WEDNESDAY
EDITION

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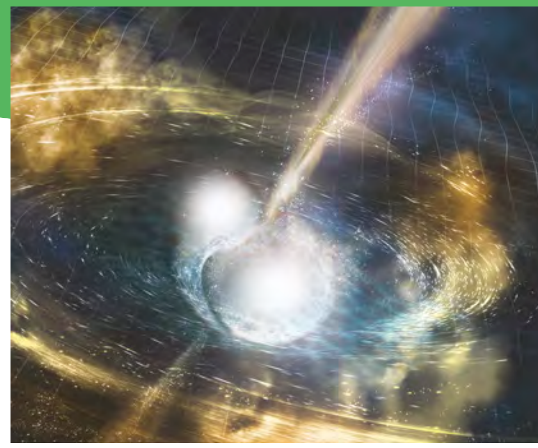
PHOTONICS WEST. SHOW DAILY

LIGO upgrade
p.25



Industry 4.0 and photonics: "the perfect fit"

In a sweeping, futuristic Photonics West keynote talk about a world of "digital twins" of real objects, Reinhart Poprawe, director of the Fraunhofer Institute of Laser Technology (ILT) in Aachen, Germany, described a new industrial revolution.

"Shadow twins" will help design production processes and in turn help shape actual products built using additive and subtractive laser techniques, Poprawe predicted. In short, the production system will help design the product. And in that future, he expects to see "practically all manufacturing processes using lasers."

Poprawe showed examples from metal cutting to beam propagation in glass, to printing of biocompatible photopolymers, saying "each individual pulse is controlled by the shadow in the computer." That shadow will tailor laser processes to the geometry of the object, for "fast and frugal simulation" in the laboratory.

All this, he said, captures the spirit of what in Germany has been referred to as "Industry 4.0" for some time, with the term now gaining more global traction. It covers an industrial approach of thinking where digital photonic production is believed to be a perfect fit. The "4.0" refers to the series of revolutions from human labor, to steam and coal, and on to electronics and computers, to today's integrated platforms for software and automated physical systems.

"It is amazing what can be done in tailoring material properties in space and time," Poprawe said. "The product functionality will be translated into design geometry and materials."

Industry will put aside standard older machines, he added, showing delegates a 3D printing approach that will use five-dot exposure systems, although the "ultimate" system would incorporate up to several hundred such dots.

As a consequence, Poprawe expects to see a remarkable 30-fold increase in productivity. In perhaps just a few months, or certainly a very few years, he said, such approaches will start to become available to the market.

The ILT director urged greater collaboration between industry and universities, following the model shown by the campus of RWTH Aachen University, where Poprawe is the chair for laser technology and director of the Center for Digital Photonic Production.

"A single source of truth is not the state-of-the-art today," he said. "We have to combine all these sources of truth."

Poprawe added: "We believe nobody can do it alone. We need a new kind of social behavior of the people. With that, we have a very good chance to match what we understand by the Fourth Industrial Revolution."

FORD BURKHART

Automotive lidar developer Luminar Technologies showcases its technology on board a Mercedes SUV outside the North Hall exhibit area. The company is at booth #1716.
Photo: Joey Cobbs

DON'T MISS THESE EVENTS TODAY.

LASE PLENARY SESSION
Ursula Keller (ETH Zurich)
Hidetoshi Katori (Univ. of Tokyo and RIKEN)
Berthold Schmidt (Trumpf Photonics)
(10:20 AM-12:35 PM, Room 21, North)

INDUSTRY EVENTS

3D PRINTING AND INDUSTRY 4.0
(8:30-10 AM, Room 21, North)

SPIE JOB FAIR
(10 AM-5 PM, South Exhibit Hall)

NIKON OPTICAL MATERIALS AND OPTICS
(11 AM-12 PM, Room 23, North)

BASICS OF LASER MATERIAL PROCESSING
(1:30-3 PM, Room 23, North)

EXECUTIVE PANEL ON THE INNOVATION ECOSYSTEM
(1:30-2:30 PM, Room 21, North)

HOW TO SPEAK "HIGH POWER DIODE LASER"
(3-4:30 PM, Room 23, North)

SPIE STARTUP CHALLENGE FINALS
(3:30-6 PM, Room 21, North)

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.

IN THIS ISSUE.

Hell, Deisseroth detail microscopy and neuroscience challenges

The BiOS plenary session proved to be a master class in super-resolution microscopy and optogenetics for studying neural circuit dynamics. Two high-profile speakers — 2014 Nobel Laureate Stefan Hell of the Max Planck Institute and optogenetics pioneer Karl Deisseroth, of Stanford University — covered a breadth of critical technologies and applications in their respective presentations.

Hell, who shared the 2014 Nobel Prize in Chemistry with W.E. Moerner and Eric Betzig for the development of super-resolved fluorescence microscopy, took a "post-Nobel" look at the current state-of-the-art in super-resolution microscopy, focusing on far-field fluorescence nanoscopy that actually achieves molecular size (1 nm) resolution.

Among other things, Hell is credited with having conceived, validated, and applied STED (stimulated emission depletion) microscopy, the first viable concept for breaking the diffraction-limited resolution barrier in a light-focusing microscope. It is one of several types of super-resolution microscopy techniques that developed to bypass the diffraction limit of light microscopy to increase resolution.

And yet, Hell pointed out in his presentation Sunday evening, these techniques still have not quite been able to obtain 1nm spatial resolution. In practice, he says, the reality is more like 20 nm.

"If you separate by focusing light, you are limited by diffraction," he said. "We had to realize not to separate features by focusing, but to separate them by molecular states. And STED microscopy was the first to do this, to sequentially separate molecules by keeping them in the off/on state."

He sees promise in MINFLUX, a new far-field fluorescence nanoscopy method that combines the advantages of STED with the principles of PALM (photo-activated localization microscopy). In PALM, single molecules are also excited by switching them on and off, but these molecules light up randomly versus being targeted as in STED.

Together, they harness a local intensity minimum of a doughnut laser or standing wave laser to determine the coordinates of the fluorophore(s) to be registered, using an intensity minimum of the excitation light to establish the fluorophore position. The result is molecular size (1nm) localization precision 100 times higher than conventional light microscopy and about 20 times higher than super-resolution light microscopy.

Hell said MINFLUX microscopes have the potential to become one of the most fundamental tools of cell biology, making it possible to map cells in molecular detail and to observe the rapid processes in their interior in real time. "So now we can track the position of the molecule with high precision and increase the speed of recording without the need for fluorescence," he said.

Deisseroth is working to shed new light on how the brain determines human behavior. While he is best known for his work in optogenetics, Deisseroth is a neuroscientist who is also a practicing psychiatrist, and this has influenced his research for many years.

"I am a psychiatrist, but I run a basic science lab, and we are interested in understanding problems and functions of neural circuits," he said. Deisseroth noted that the discovery of structural principles in a microbial protein helped illuminate

2014 Nobel Laureate Stefan Hell. Photo: SPIE

the pathophysiology of psychiatry, and now "we want to collect multiple kinds of data streams and bring them together."

For example, he said, "we collect information on brain-wide cellular resolution activity and anatomy in behaving vertebrates to help us understand how neural circuits actually work," much like a cardiologist explains a damaged heart muscle to a patient.

"Multiple individual cell control is very powerful in principle for learning to understand how neural circuits are operating," Deisseroth said. "What are these cells? We would like to know a lot more about them."

KATHY KINCADE

Super-res technique suits lithography

Min Gu of RMIT University in Australia, a leading authority in nanophotonics, nanofabrication, biophotonics, and multi-dimensional optical data storage, put his "SPIN" on overcoming the diffraction limit in nanoscale optical and photonic devices during his plenary talk at OPTO this week. The devices are used in optical data storage, optical communications, 3D nanoprinting and nanometric displays.

Pallab Bhattacharya. Photo: SPIE

"New approaches of removing the diffraction limit are needed to achieve petabytes of optical data storage," said Gu, who was instrumental in the development of SPIN (super-resolution photoinduction-inhibited nanolithography), a two-beam nanofabrication tool with a feature size of only tens of nanometers, far beyond the diffraction limit found in the popular direct laser writing (DLW) photolithography approach. As a result, SPIN is well suited to nanolithography; some SPIN-enabled nano-optoelectronics include artificial neurons, artificial grippers, artificial membranes, and 3D neural circuits.

"With SPIN, we are breaking the diffraction limit barriers," Gu said. "We use the first laser beam to induce photoinduction, then the second beam can achieve photoinhibition. If you overlap them, you can produce a much smaller focus spot with super-resolution."

Gu's team has also been looking at combining SPIN with STED (Stimulated emission depletion microscopy) — another super-resolution microscopy method — for new applications in optical data storage. "Using two-photon photoresist for SPIN and STED, we combine them to do the read and write functions together," he said.

Another talk at the OPTO plenary session focused on III-nitride nanowire LEDs and diode lasers for communications as well as silicon photonics, neural probes, and head-up displays.

GaN-based nanowire and nanowire heterostructure arrays grown on (001) Si substrates for use in visible light sources have unique properties that make them attractive for those and other applications, said Pallab Bhattacharya of the University of Michigan. Over the last 40 years, Bhattacharya has been a pioneer in the development of visible and near-infrared lasers, including most recently 600-1300nm LEDs and edge-emitting diode lasers in the 10mW power range.

This work has included the development of InGaN nanowire heterostructure arrays that his lab grows using plasma-assisted molecular-beam epitaxy. These nanowires offer some key advantages for these light sources, especially in terms of quantum efficiencies, he noted.

"InGaN nanowires have a large surface-to-volume ratio, so they are relatively free of extended defects compared to planar GaN grown on lattice-mismatched templates," he said. "In addition, radial relaxation during epitaxy leads to small polarization fields. The quantum efficiencies are quite large to start with; we optimize the growth conditions to balance the creation of defects at very low substrate temperatures with those at very high substrate temperatures."

Bhattacharya said the emission wavelength of the light sources can be varied according to the composition in the InGaN disks, which can be inserted into the nanowires. Using this approach, Bhattacharya and his collaborators recently fabricated 1.3micron nanowire lasers on 001 (Si) with lasing at exactly 1.3 microns, and a simple photonic integrated circuit on silicon using the 1.3micron monolithic nanowire array.

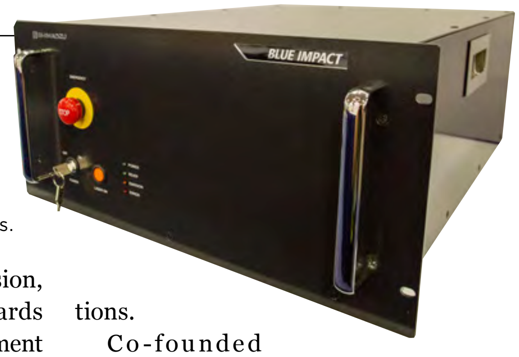
"And it all works!" he said. They are now working with researchers at NASA to develop infrared detector arrays on silicon, something he says NASA is "very excited about."

Andrew Rickman, a big name in the world of silicon photonics, made a convincing case in his talk for why bigger might be better when it comes to the design, manufacture, and integration of silicon photonics chips.

Rickman, the founder of Rockley Photonics, contends that, unlike the shrinking feature sizes in microelectronics fabrication, integrated photonics platforms should take advantage of larger geometries to boost optical efficiency and ease of coupling so that the silicon photonics industry can finally realize the promise of "silicon scale."

KATHY KINCADE

Shimadzu, Nuburu hail blue power revolution



Japan-based Shimadzu is showing off its new 100W blue industrial laser at booth #4945, as well as welding and 3D printing systems incorporating the technology co-developed with Nichia and Osaka University. Photo: Joey Cobbs.

Japanese exhibitor Shimadzu is showing off recent developments in high-power blue laser diodes at its Photonics West booth, including a 100W multi-beam module, a welding machine based around the 100W module built by development partner Marutani, and a 3D printing system using the same photonics technology.

All the systems are based around high-power blue diode emitters provided by laser chip manufacturer Nichia, which has partnered with Osaka University scientists and Shimadzu on a four-year development project to bring what Shimadzu describes as the "blue revolution" to industrial laser processing.

During Monday's conference sessions, Osaka researcher Masahiro Tsukamoto described the six-beam laser head design, which delivers power at around 455nm from multiple diodes operating at 39% efficiency. The design has been packaged into a 19-inch standard rack size format, and is on sale at booth #4945.

The equipment should prove particularly useful for welding reflective metals including gold and copper, which absorb much more strongly in the blue than at the more conventional infrared wavelengths used in laser welding. Tsukamoto outlined a development roadmap out to the end of the project in 2020, at which point a multi-kilowatt output from the six-beam head is envisaged.

During the same conference session, the Colorado-based 2018 Prism Awards finalist Nuburu described its development of what is claimed to be the world's "first revolutionary high-power blue laser". The 150W direct-diode system is based around "PLPM4" emitters provided by German laser diode maker Osram Opto Semiconductors.

Nuburu's optical design features 160 actively designed micro-optical components and an 80mm-diameter aspheric lens to couple the blue light into a 200 micron optical fiber. It also uses a set of interleaving mirrors and a beam-expanding telescope, and the setup is being aimed at welding, cutting, and 3D printing applications.

Co-founded by former Nuvonyx chief Mark Zediker and Jean-Michel Pelaprat — previously Novalux CEO and general manager at laser giant Coherent — Nuburu says the technology will enable "radical" gains in speed and quality in existing metal processes, as well as unlocking a path to new designs for both conventional laser-metal machining and additive manufacturing. Specific applications are set to include spatter-free copper welding, potentially enabling new applications not addressable with infrared lasers.

MIKE HATCHER

IMAGE-GUIDED PDT TREATS ORAL CANCER

Sunday's photodynamic therapy (PDT) BiOS conference session heard Jonathan Celli from the University of Massachusetts in Boston (UMass) describe the development of low-cost enabling technology for image-guided PDT treatment of oral cancer in resource-limited settings.

In particular, his group has been working on battery-powered LED sources to identify and treat mouth cancers in rural India that are caused by individuals chewing the stimulant known as gutka, a type of tobacco. Oral cancer represents over 30% of cancers reported in India, one of the highest oral cancer rates in the world and also the leading cause of cancer death among Indian men.

Celli told the conference, "Clinical studies of PDT for treatment of oral cancer show the ability to achieve complete epithelial necrosis with exceptional healing results."

"We were motivated by the high incidence of oral cancers in India, so we have developed a low-cost enabling technology for intra-oral ALA-PDT that can be delivered in rural sites with limited medical infrastructure."

The laser treatment is performed using a topical photosensitizer aminolevulinic acid (ALA) to selectively destroy abnormal cells. This approach involves a battery-powered, fiber-coupled LED source with interchangeable applicators for light delivery to oral lesions. An integrated smartphone-based imaging system is used for treatment guidance.

Celli also described ongoing developments and lessons learned from initial clinical implementation of the technology in Aligarh, India. The UMass development has been made in partnership with Stephen Brown from the National Medical Laser Centre at University College, London, UK.

"We have demonstrated that a prototype low-cost battery-powered LED light source for ALA-PDT achieves tumoricidal efficacy both *in vitro* and *in vivo*, comparable to a commercial turn-key laser source," Celli said. "When we first started out we took a very simple LED source operating on an alkaline battery with a super cheap LED ($20) delivering 635nm at 170mW. We have showed that we can get a very good response."

Celli's group has evaluated light delivery via fiber bundles and customized, 3D-printed light applicators for flexible delivery to lesions of varying size and position within the patient's oral cavity. The researchers have also addressed the performance requirements (output power, stability, and light delivery) and presented validation of their device for ALA-PDT treatment of carcinoma cells.

Celli concluded that this low-cost battery-operated LED device has effectively translated from a laboratory bench in Boston to a clinic in India. Further developments that are still being worked on include making improvements to smart phone based imaging attachments to achieve better resolution and positioning; and automation of the image-based feedback and light delivery parameters.

Pending clinical study outcomes, the researcher also envisions global health development that could be delivered by working with non-governmental organizations for dissemination into rural communities, patient screening and recruitment; and working with potential industry partners for a sustainable commercialization methodology.

MATTHEW PEACH

imec extends SWIR hyperspectral range

Nanoelectronics research and innovation hub imec has developed its first shortwave infrared (SWIR) range hyperspectral camera, and is demonstrating the imager this week at booth #4321.

The camera, which combines CMOS and InGaAs sensor technology, promises imaging applications as diverse as medical diagnostics, food sorting, waste management, machine vision, and agriculture.

Hyperspectral imaging filters can be integrated monolithically onto silicon-based CMOS image sensors, which typically have a sensitivity range from 400 to 1000nm — visible and near-infrared.

But as imec explains, the industry is expecting that more than half of commercial multispectral and hyperspectral imaging applications will need to manage and process data in the extended 1000-1700nm SWIR range.

Andy Lambrechts, program manager for integrated imaging activities at the Belgian research and development center, said: "The SWIR range is vital for hyperspectral imaging as it provides extremely valuable quantitative information about materials such as water, fats, lipids, and the protein content of food, plants, human tissues, pharmaceutical materials, as well as the characteristics of commercial products like plastics, paper, wood, and more."

The new SWIR hyperspectral imager developed at imec is being shown off at booth #4321. Photo: Joey Cobbs.

He adds that it was a natural evolution for imec to extend its offering into the SWIR range while exploiting core capabilities in optical filter design, to deliver robust, low-cost hyperspectral hardware.

The new cameras feature linescan stepped filter designs with 32-100 or more spectral bands, as well as snapshot mosaic solutions enabling the capture of 4-16 bands in real-time at video-rate speeds. Cameras with both USB3.0 and Gigabit Ethernet interfaces are currently in the field undergoing qualification with strategic partners.

MATTHEW PEACH

Lidar landscape shifts as big players join forces with new entrants

The emergence of lidar as a key technology for future autonomous vehicles ratcheted up throughout 2017, with major players including Ford, Airbus and Osram backing a raft of startups with their own particular takes on the photonics hardware.

By any measure the past year has been a remarkable one for lidar technology. Excitement about the prospects and potentially massive disruptive effect of autonomous vehicles has pushed this erstwhile photonics technology — lidar dates back to the early days of the laser, used in meteorology and by the Apollo 15 mission to map the lunar surface — right back up the tech agenda, with news of major investments on an almost weekly basis.

The plethora of startups, spin-outs and venture capital deals has, for some, recalled the days of the optical telecommunications boom of the late 1990s. In fact there are some more direct connections to that time, with the use of 1550 nm laser diodes first developed for optical fiber transmission, vertical-cavity surface-emitting lasers (VCSELs) generally found in data centers, photonic integration schemes, and micro-optical electrical mechanical systems (MOEMS) all touted by their proponents for a critical future role.

At the wheel: Luminar Technologies co-founder Austin Russell in a car equipped with the company's high-resolution lidar kit. Photo: Luminar Technologies.

Elsewhere in the lidar universe, October 2017 saw two of the auto industry's biggest names — Ford and General Motors — respectively acquire lidar component and systems firms Princeton Lightwave and Strobe.

Everybody working in this space has the same ultimate aim: safer driving. Global estimates from the World Health Organization suggest that 94% of the 1.25 million road deaths recorded in 2013 were attributable to human error. Although that makes a compelling argument for replacing the error-prone humans in the driving seat with robots, sensors, and algorithms, there are still big questions over how and when exactly that transition will happen. What does seem clear is that a fusion of sensor data, almost certainly including lidar, is required.

That momentum was in evidence earlier this month at the Consumer Electronics Show (CES) in Las Vegas, with lidar seen on board numerous vehicles and early developer Velodyne saying that it expected 2018 to go down as a "watershed year" for the sector.

And there could be highly significant developments right here in San Francisco this week: the lawsuit filed by Google's autonomous vehicle subsidiary Waymo against Uber's equivalent nearly a year ago is expected to reach a conclusion in a court room not far from the Moscone any day now.

With dozens of companies now working on lidar and related image processing, analysis and control technologies aimed at future self-driving applications, it seems inevitable that there will be some kind of shake-out before long. But for now, here's our selection of the startups and more established companies to have made their presence felt over the past 12 months.

Luminar Technologies

Exhibiting at Photonics West this week, the California startup appeared with a bang in April 2017, buoyed by a $36 million round of seed finance. Co-founded by the young tech entrepreneur Austin Russell and former Ocean Optics executive Jason Eichenholz, Luminar's bold claims of sensor performance are based around its adoption of a 1550 nm laser. It can take advantage of the more relaxed eye safety regulations at this wavelength to field significantly higher power — what Luminar's executives describe as the "photon budget" — and therefore greater sensing range.

While that makes the core laser technology significantly more expensive than the shorter wavelengths more conventionally associated with lidar, Eichenholz and Russell expect the market impact of autonomous vehicles to be so disruptive, with self-driving cars carrying passengers on a near-continuous basis, that the higher price of multi-channel indium phosphide (InP) lasers and associated hardware will be acceptable to car makers.

The Luminar team followed up on its debut in the summer, showing off their technology atop a Mercedes van outside the Laser World of Photonics event in Munich, before in September Toyota's research wing announced that it was testing out the technology on its "Guardian" and "Chauffeur" development vehicles.

Since then, Russell has further burnished his credentials with inclusion in both the Forbes "30under30" list of influential young entrepreneurs *and* the Massachusetts Institute of Technology (MIT) Tech Review's "35under35" equivalent. At CES 2018, Toyota showcased its latest, "third generation" autonomous platform, which combines the 200 meter-range Luminar kit with

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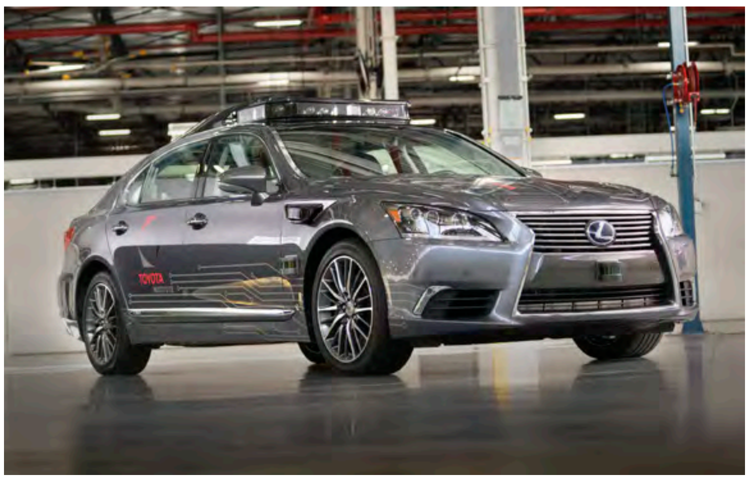
a number of shorter-range sensors. Luminar is actively hiring for dozens of positions at its twin facilities in Palo Alto and Orlando, Florida, and will be demonstrating its lidar solution outside Hall D of the Moscone Center this week. Eichenholz will give a keynote talk on the subject in Room 21 on Thursday at 11am.

AEye

While most of its rivals are deploying lasers emitting at shorter wavelengths, Luminar is not the only lidar company working with 1550nm light. Pleasanton-based AEye is another California startup to adopt InP-based technology, with its pitch to provide the hardware, software and algorithms that will come to represent the "eyes and visual cortex" of future self-driving vehicles. In essence, that means combining a lidar-generated 3D point cloud with 2D machine vision, to generate a more recognisably "human" view of a car's surroundings.

In June 2017, AEye — previously known as "US LADAR" — said that the venture wings of both Intel and Airbus were among the investors in its $16 million round of series A financing, alongside the high-profile venture capital group Kleiner Perkins Caulfield and Byers.

Headed up by Luis Dassan, a graduate of the University of Central Florida's famed College of Optics and Photonics (CREOL), and with strong US military expertise in its ranks, AEye went on to demonstrate its 360 degree, MOEMS-based, solid-state system in September, claiming a range of 300 meters in live metropolitan tests. "This is just the starting point for AEye," said Dussan at the time. "Our system's use of intelligent sensing and software-definable lidar (SDL) will catalyze rapid innovation and world class perception capabilities, enabling OEMs, Tier-1 suppliers, and mobility companies to successfully tackle their toughest corner cases."



This Lexus car, fitted with a rooftop lidar system from Luminar and built by Toyota Research Institute, made an appearance at CES 2018 in Las Vegas.
Photo: TRI.

In December, that was followed by the launch of a partner development program for what AEye calls "iDAR", short for "intelligent detection and ranging". Said to mimic the way that the human visual cortex evaluates potential driving hazards, the approach uses beam-steering hardware and other proprietary tricks to dramatically increase the frequency with which objects in the field of view are "hit" with a laser pulse.

Potential adopters of AEye's approach got a chance to evaluate it at CES, where the company unveiled its "AE100" system. It is described as the world's first agile MOEMS lidar, "pre-fused and bore-sighted with a low-light HD video camera". Customizable with specifications including a range of up to 400 meters and frame rates of 200 Hz, it is slated for initial release by mid-2018, with a wider commercial launch shortly after.

LeddarTech

Also attempting to make an impact in Vegas was Canada's LeddarTech, spun out of the local National Optics Institute (INO) more than a decade ago. In September the Quebec City company revealed that Osram had acquired a 25% stake in it, as part of a $101 million round of series C finance.

Investing alongside Osram are parts giants Delphi (now Activ), Magneti Marelli, and sensor specialist IDT Automotive and Industrial. LeddarTech CEO Charles Boulanger expects the lidar sector to become a multi-billion-dollar business by the end of the decade, with his company playing a lead role.

Though it is also developing solid-state lidar, and claiming long-range capability, where the Canadian firm seems to diverge from rivals AEye and Luminar is its focus on lower-cost hardware. At the CES event in 2017, the company even raised the possibility of future lidar sensors for automotive applications costing just $100.

In a white paper penned by Pierre Olivier, its VP of engineering and manufacturing, LeddarTech says the key is optical time-of-flight signal processing, with claims that the company's algorithms are able to calculate accurate ranging information from only a very weak photonic "echo".

"When combined with a photodetector, a pulsed light source and optics, it forms a complete sensor system that can easily be integrated into a small footprint at low cost," wrote Olivier of the firm's "LeddarCore" product, adding that LEDs, VCSELs, and edge-emitting diodes were all compatible with the design.

With two CES 2018 innovation awards for LeddarCore in the bag, LeddarTech headed to Vegas this year with engineering samples and demonstrations of lidar systems showcasing "LCA3", the latest version of LeddarCore. "More key suppliers and Tier-1 manufacturers are turning to us over other lidar vendors because we deliver on our promises," boasted Boulanger ahead of the event.

Joining forces with the firm at a dedicated exhibition pavilion in Vegas were the other members of what LeddarTech describes as its "Leddar Ecosystem". As well as Osram, they included optical component supplier Hamamatsu Photonics and Albuquerque-based VCSEL specialist TriLumina — the latter showing off a solid-state 3D lidar system built around its flip-chipped 940 nm emitters and patented monolithic microlenses.

Innoviz and Oryx

Israel has turned out to be something of a hot-house for lidar startups, thanks in part to past investments in sensor technology development by the country's military. Among the most successful thus far is Innoviz Technologies, which in the past 12 months has landed series B venture backing of $73 million alongside partnerships with car-parts giants Activ and Magna, contract manufacturer Jabil, and an unspecified "top-tier" auto maker.

In September, the Kfar Saba firm said that it had grown to employ some 75 workers, and that its first lidar

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product was in production and would become available in the first quarter of 2018. CEO and co-founder Omar Keilaf is able to draw on the expertise of "chief photonics officer" David Elooz — previously head of physics within the elite technology unit of the Israeli Defense Forces — and welcomed Samsung Catalyst and Softbank Ventures Korea as strategic investors in the latest round of financing.

"With our lidar solutions moving into mass production and getting ready to begin shipping in early 2018, the backing from companies such as Samsung, SoftBank Ventures Korea and all the rest will enable us to scale our operations as we focus on not only lidar but the entire autonomous vehicle stack," said the CEO in October.

Innoviz was another to demonstrate its latest advances at CES 2018, and although it is yet to reveal too much technological detail about its MEMS-based lidar sensors in public, the company has indicated that it is targeting the lower-cost end of the emerging market. Initial versions of its "InnovizOne" sensor are expected to sell for a few hundred dollars at first, with a price below $100 even envisaged as the partnership with Jabil's optics division begins to scale up.

Another Israeli startup in the sector is Oryx Vision, which in August 2017 raised $50 million in a series B round of financing. Oryx stands out for its adoption of what are described as "far-infrared nano-antennae", rather than conventional laser emitters, in its coherent flash lidar. It is said to operate well in challenging conditions posed by adverse weather and low, bright sunlight at dawn and dusk.

Also with strong connections to Israel's military technology base, Oryx said it would put the funding towards accelerating its development work and intensifying commercial engagements with car OEMs and top-tier-auto part suppliers. The company expects to ship units for car-mounted testing during the second half of 2018.

Both Innoviz and Oryx can take inspiration from compatriot Mobileye. Though not a lidar company, its camera-based systems for advanced driver assistance features are also expected to find widespread use in autonomous vehicles, prompting Intel to acquire the firm last year for a cool $15 billion.

Touted for a commercial release this summer, this self-driving taxi from French startup Navya is fitted with multiple lidar units from Velodyne, alongside radar units and cameras. Photo: Velodyne Lidar.

Velodyne and Quanergy

For early trendsetters Velodyne Lidar and Quanergy Systems, whose solid-state lidars have been widely used in developmental efforts by car OEMs, 2017 priorities included scaling sensor production at new facilities. Following lucrative venture backing for both firms in 2016, last year saw Velodyne open its lidar 'megafactory' in San Jose, while Quanergy began mass production of its 'S3' sensors at its highly automated factory in Sunnyvale, California.

"With the commissioning of this facility, Quanergy is now the only company to mass produce solid-state 3D lidar sensors," boasted the firm in December 2017, adding that the production line features high-precision photonic IC processing tools and a conveyor system connecting machinery that turns a silicon wafer cassette into a finished lidar sensor.

"We fully expect that these sensors will play an integral role in bringing self-driving vehicles to the road," said Quanergy's CEO Louay Eldada, also predicting that the price of the S3 will eventually drop below $100. Meanwhile the company's former head of engineering, Angus Pacala, has started up his own venture in the form of San Francisco-based Ouster. With a $27 million series A round banked in December, Ouster is aiming to ramp production of a 64-channel sensor this year, as headcount grows from 40 to an expected 100 by summer.

Not to be outdone, Velodyne has slashed the price of its "VLP-16" sensor in half, and used its CES 2018 event booth to host what is described as the first fully autonomous taxi to hit the market. Navya's "Autonom Cab" can carry up to six passengers and features no fewer than ten lidar sensors, alongside six cameras and four radar units.

Velodyne president Mike Jellen said in advance of the event: "We expect 2018 to be a watershed year for both Velodyne and the industry, laying the foundation for autonomous vehicle deployments around the world in just a few years."

TetraVue

At last year's Photonics West TetraVue — another Californian startup in the automotive lidar space — revealed that it had raised $10 million in venture backing, and the firm was actively hiring on its dedicated Careers Center booth during the event. Since then, it has emerged that the financial backers include the likes of semiconductor equipment giants KLA-Tencor and Lam Research, alongside the venture wing of industrial sensor firm Robert Bosch and the Samsung Catalyst Fund.

"TetraVue cameras uniquely merge digital video with lidar technology by capturing multi-megapixel images at up to 30 frames per second with accurate depth for each individual pixel," explained the company ahead of the technology making its debut appearance at CES 2018. "As a result, a TetraVue camera has the ability to process 100 times more real-time data describing object location and motion in the surrounding environment."

MIKE HATCHER

Students seeking jobs in the optics and photonics industry are encouraged to broaden their horizons beyond niche academic disciplines: learning a foreign language is one way to stand out from the crowd. Photo: Adam Resnick/SPIE.

Optics and photonics jobs: what it needs, what it takes

The SPIE Photonics West Exhibition offers optics and photonics companies the opportunity to meet qualified engineers and technical talent. The Job Fair, held in conjunction with the exhibition, gives students and other job seekers a chance to discuss their skills and talents with leading companies.

SPIE spoke with companies looking to recruit at the Moscone this week, as well as students and professors, about finding and filling jobs in photonics. Companies told us what they are looking for in candidates, while students shared the experiences of their job hunts.

According to Alexis Vogt, Endowed Chair and associate professor of optics at Monroe Community College (MCC), the global optics, photonics, and imaging industry is growing faster than the overall economy. Coupled with industry reports suggesting that one-fifth of experienced technicians and engineers are approaching retirement, the need for skilled optics and photonics technicians is clear.

Vogt adds that in upstate New York, three-quarters of skilled optics technician job openings go unfilled annually, due to insufficient numbers of optics and photonics graduates. That shortage is not isolated to New York — or even the US. In a survey of 1700 small- and mid-sized German companies, about three quarters said the shortage of skilled workers impairs their innovation activities. Some German optics companies have contacted MCC to hire skilled optics technicians. “Our entire industry needs highly skilled optics and photonics technicians,” said Vogt.

Universities and training programs are working hard to match skilled applicants with jobs, but there are issues to be worked out.

Nicholas Wong is a recent PhD graduate from the Optoelectronics Research Centre at the University of Southampton in the UK, and is actively looking for work. He says that in his experience, a PhD trains one technically, but offers limited preparation for tackling the job market.

“I have had to do a large degree of finding my own way and learning as I go when it comes to knowing the current state of where these relevant jobs are available, and how to approach the search for them,” said Wong.

Mike McKee is associate director of Academic Support Services in the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida, and recognizes the difficulty seen by Wong. “While the job market is strong for photonics engineers, the problem has been trying to navigate to find those positions,” he says. “Often the positions are not called out as “optics or photonics engineering” positions, making it difficult for students to search using those key terms.”

One surprising resource McKee has pointed prospective students towards is the US Department of Labor website, which carries a large number of jobs forecast to be available in the optics and photonics industry over the next eight years.

He adds that several companies approached CREOL last year at Photonics West, asking them to refer engineering students to their organizations. To help get the word out, McKee and others created the “CREOL Undergraduate Blog,” (http://creolundergrad.blogspot.com/) which posts job opportunities.

“Start-up scrappy”

The consensus among exhibitors and recruiters is that candidates need life skills as well as technical skills. Job requirements are likely to include interpersonal skills relating to teamwork, organization, and flexibility. Employees who excel are those who are technically sound, can change gears quickly, adapt to a variety of situations, and understand how to work in a collaborative environment.

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Optics and photonics jobs

Nick Herringer, US Engineering Services Manager at Zemax, says his company looks for smart people who have a strong technical background in optics, physics, or a related field. But those people also need the social skills for building meaningful relationships in a collaborative work environment.

"Typically, a degree in an optics or physics discipline will provide candidates with the appropriate technical skillset, but that is only part of the equation," said Herringer. "We also need candidates to be able to communicate effectively with co-workers, be flexible with their work, and have the creativity to develop new solutions."

In some cases, companies are simply looking for more experience than some recent graduates can offer. The human resources group at Quartus Engineering, who are looking for "optical and opto-mechanical engineers at all experience levels," notes that while many candidates have worked on very small projects, they are frequently looking for people with experience designing at a much larger scale.

Candidates often have a great deal of research experience, which is valuable, but Quartus would like candidates to have more real-world, application-related experience. "It is sometimes challenging to find candidates with the work experience in optical system development that meets our broad needs," they told us.

While this may sound negative, the group encourages optics and photonics students to apply, saying: "We have found that as technology progresses, optical systems are becoming more and more ubiquitous, with countless opportunities to be on the cutting edge of technological progress."

The lidar equipment company Luminar Technologies also looks for candidates with some experience. A job description for a Vehicle Integration Engineer not only asks for two to three years' experience, but also that the candidate be "start-up scrappy" — having the experience and drive to work with a developing technology.

"While we have seen some great talent, finding top professionals in the optical community is always competitive and requires active networking," says Jason Eichenholz, its co-founder and CTO. "Our ideal candidates have a combination of real-world and academic experience in optics and photonics."

Help yourselves

Nick Herringer encourages students to

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ensure their degree(s) do not trap them into a niche track. He believes students should broaden their horizons through activities such as computer science courses, foreign languages, or tutoring other students. Taking on subjects outside one's field of study requires learning to think in different ways, something helpful in the working world.

"Don't corner yourself into one way of thinking or approaching challenges," advises Herringer. "Your major or specialization will speak for itself. It is the other things you do and study in school that will separate you from your peers and help you be successful in the long run."

Among the big names actively recruiting in the Moscone this week are Oculus Research, Apple, Intel, and Trumpf, alongside a slew of startup companies working in cutting-edge fields. Photo: Adam Resnick/SPIE.

Eichenholz points out that a degree is more valuable if you know how to use it. "While you are getting an education, it is critical to do two things: obtain real-world work experience, and find a mentor," he says. "Get out there and get an internship or job in a space relevant to what you will be doing. Candidates with some work experience are always more attractive because we know they can hit the ground running."

Also useful is a mentor who is an expert in communication and navigating corporate waters. "Soak up as much knowledge from them as you possibly can," Eichenholz says. "Doing these two simple things will pay off in more ways than you can imagine, and immediately put you ahead of the pack."

Barry Silverstein, who manages optics research at high-profile exhibitor Oculus, adds that job candidates need to be culturally and intellectually diverse individuals with the ability to use and enhance their skills into unforeseen challenges. The goal at Oculus is to invent, master, and commercialize AR and VR technologies. "That will require skills and science that doesn't exist today," says Silverstein. "Candidates need to be able to thrive in this uncertainty. Optics and photonics skills are fundamental to this goal."

Katelynn Bauer is a recent graduate of University of Rochester, and currently a research associate in the Laboratory for Laser Energetics at the same institution. Bauer did not apply to any job without first talking to someone who worked at that company to gauge if that person enjoyed working there. She wanted to spend her working time with people who felt they did meaningful work. "This mostly came from a gut feeling," says Bauer, "but just listening to someone talk about their work can tell you a lot."

Bauer also suggests looking beyond the first couple of years at a potential job, and to consider if the company offers room to grow, or the opportunity to learn new things from experts in the field. Does the job align with an applicant's 10-year or 15-year goals? These questions can also help form some of the questions a candidate might ask during an interview.

Diversity and intervention

A growing concern among the optics and photonics community is addressing diversity in STEM. The SPIE Women in Optics program and the SPIE Diversity Committee regularly holds events for networking, discussion, and advancing the mission of diversity and inclusion in optics and photonics.

There are programs at high schools and universities that encourage women and minorities to be interested in science, but many educators, and even students, feel these programs may be starting too late. "Intervention should occur earlier," says Cathy Chen, a senior associate at Exponent, Inc. She notes several studies that show girls are discouraged from entering STEM fields long before they reach college.

When Chen was working on her PhD in electrical engineering at Columbia University, she worked with a bi-annual outreach program offering elementary and middle-school girls the opportunity to participate in science activities on campus. Chen says there was a "definite difference" in the two age groups, in terms of how much they were willing to be openly interested in science. By middle school, the disconnect from STEM subjects was already apparent.

When boys and girls are really young, says Alexis Vogt, they can have an equal interest in science. "At age five, there's no notion a girl can't do what a boy can do," she says. But somehow, even by elementary school, girls are getting the message that they either can't or shouldn't be involved in STEM.

As a female in a male-dominated field, Vogt often found herself as the only woman in a class, meeting, or presentation. She credits her parents as teaching her to view that situation as an opportunity, rather than challenge. Not all girls or kids from under-represented communities get such encouragement.

Last year, MCC received $550,000 through a National Science Foundation award called Optics & Photonics Technology Innovation!, or "OPT IN!" for short. Over the next three years, the program will provide education and training for area high school and college students, increase internship opportunities, and expand outreach efforts. As part of this program, Vogt is putting together an Optics Road Show to present science to the general public and targeted audiences including low-income and underrepresented racial and ethnic populations, veterans, and women.

"As we move forward and grow our optics program to meet the increasing regional and national optics workforce demands, I want more families to encourage their children to pursue interests in science and physics, especially their daughters," says Vogt.

And she adds that while most of the attendees at Photonics West this year will be white males — because they are the ones who mainly represent the optics and photonics community today — "it doesn't have to stay that way."

KAREN THOMAS

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product focus

The Moscone Center, Moscone North and South
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30 January - 1 February 2018

Welcome to the optics.org Product Focus which we have published specifically for Photonics West 2018 in partnership with SPIE and the Photonics West Show Daily.

Here you will find an effective at-a-glance guide to some of the latest products available on the market with booth numbers if available making it easy for you to check out the products for yourself.

All this information and more can be found on the optics.org website. Simply go to **www.optics.org** for all the latest product and application news.

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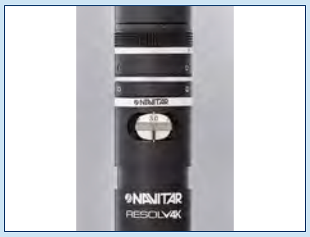

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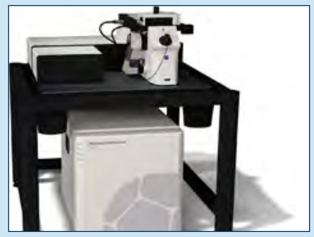

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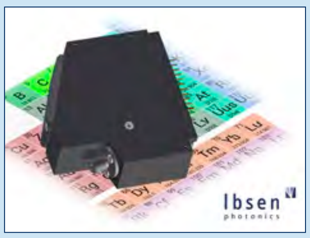

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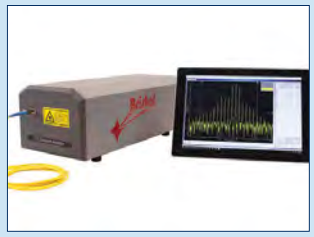

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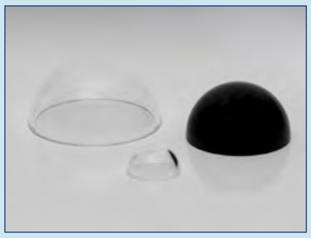

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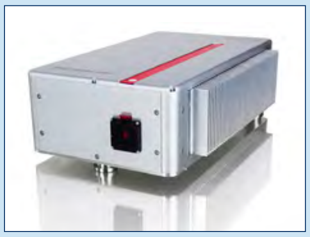

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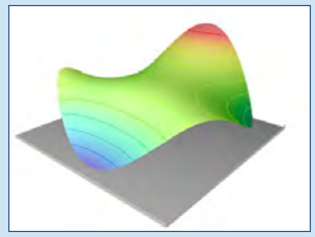

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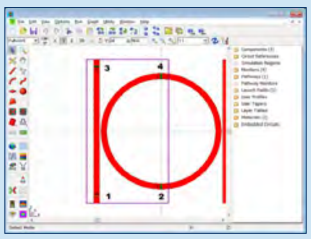

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Optical lattice clocks: time for miniaturization

Photonics West plenary speaker Hidetoshi Katori is at the forefront of a move to develop the latest generation of optical lattice clocks. But how do these ultra-precise timepieces work, and where might they be used?

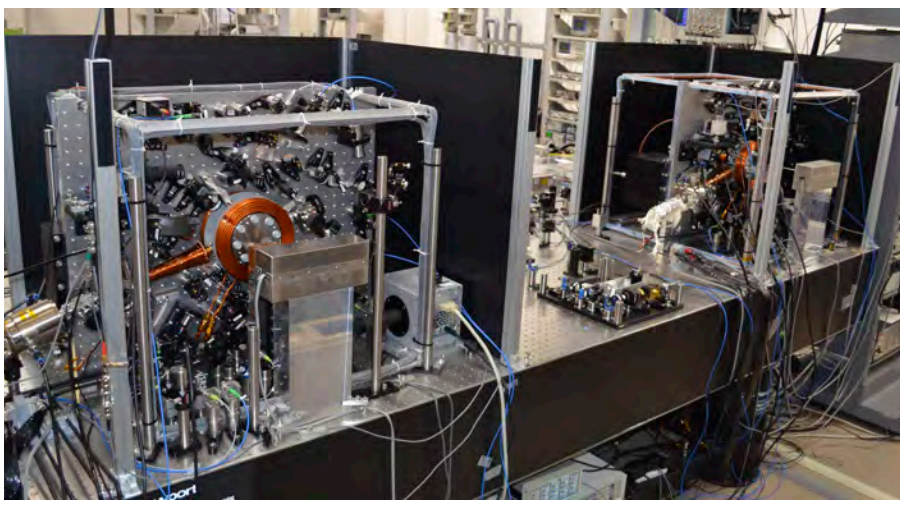
In recent years, organizations including the US National Institute of Standards and Technology (NIST), the University of Tokyo, and the UK's National Physical Laboratory (NPL) have devoted increasing attention to the development of optical lattice clocks — in essence new and even more precise versions of atomic clocks.

These cutting-edge timepieces have a wide range of potential applications, from improved tracking of deep-space probes and better satellite navigation systems to more accurate tests of fundamental physics. Even more fundamentally, they could facilitate a change in the definition of the SI unit of time.

In simple terms, an atomic clock works by tracking the oscillations of an electron bound to an atom — using those oscillations as the basis for time metrology. In optical clocks, those oscillations are very fast, and correspond to frequencies in the optical domain of the electromagnetic spectrum. These ultrafast oscillations divide time into very fine intervals, helping to improve the precision of the clock.

As Hidetoshi Katori, chief scientist in the Quantum Metrology Laboratory at the University of Tokyo, explains, an optical lattice clock interrogates thousands of atoms trapped at the anti-nodes of a standing optical wave. Compared with a more conventional ion clock, which typically interrogates a much smaller number of ions, an optical lattice provides much better stability.

Andrew Ludlow is a physicist at NIST in Boulder, Colorado. He says that optical lattice clocks are made particularly special because the atoms at the heart of the clock are confined in a specially engineered laser "trap" that is also known as an optical lattice. This lattice serves the purpose of holding atoms so that they can be measured more effectively — without compromising relativistic effects.



Ultra-precision time metrology: optical lattice clocks can achieve a fractional time uncertainty to a remarkable 18 decimal places — equivalent to measuring the age of the universe to within a single second. Photo: University of Tokyo.

"Many atoms can be trapped throughout the optical lattice, so that measurements of the atoms generate a relatively large signal, also improving the precision of the clock," says Ludlow. These optical lattice clocks, now being actively developed in research labs around the world as a next-generation, high-performance atomic clock, are the subject of Katori's LASE plenary talk — entitled "Optical Lattice Clocks: Reading the 18th Decimal Place of Frequency".

Hidetoshi Katori from the University of Tokyo and RIKEN is giving a LASE plenary talk on the subject of optical lattice clocks. Photo: University of Tokyo.

Optical lattice clocks were conceived about 15 years ago, and much of the development work since then has focused on developing and refining the techniques required to make one work, as well as in experimentally assessing the limits of their performance, both in practice and fundamentally. According to Ludlow, as knowledge about and experience with these systems has improved, so has the ability to leverage their properties for "ever-increasing" timekeeping performance.

One such project is ongoing at NPL in London, where staff are busy designing and implementing an optical lattice clock based on strontium atoms. According to the team, strontium is a particularly promising element for such applications because it contains a relatively high abundance of both odd and even isotopes (including 87-Sr at 7% and 88-Sr at 82%). Another advantage is that strontium atoms can be cooled in ways that are ideally suited for loading into an optical lattice — largely because they possess a broad (fast cycling) transition that is very useful for Doppler cooling of odd isotopes, as well as a narrow (slow cycling, but not too slow) transition that enables sub-Doppler cooling in the even isotopes.

Ytterbium lattice

Over at NIST, work has been focused on an ytterbium lattice clock. In common with the best optical lattice clocks, it is currently capable of a measurement precision equivalent to one part in 10^{18}. In fractional terms, says Ludlow, that corresponds to measuring the age of the universe to within one second.

Although many different developments have made such remarkable progress possible, Ludlow highlights some notable recent ones: these include new techniques for cooling the atoms down to ultra-cold temperatures near absolute zero and detailed investigations into physical phenomena that can alter the electronic oscillation rate — including electrical polarization due to the optical lattice or ambient blackbody radiation, or collisions between the atoms trapped in the optical lattice. In addition, the generation of ultra-frequency-stable optical sources using very high finesse optical cavities have enabled atomic measurements at or near the fundamental limits set by quantum mechanics.

In Ludlow's view, there's plenty more to improve on. "Optical lattice clocks have — and continue to — push the state-of-the-art for time [and] frequency measurement capability," he said. "What's more, their unprecedented levels of performance have not hit any fundamental limits yet: both experiment and theory suggest better performance is still possible. So there's a lot of interesting and exciting research still to come."

NIST's Andrew Ludlow sees applications for optical lattice clocks emerging in gravitational metrology, advanced communications and navigation systems. Photo: NIST.

Despite that exciting prospect, he still sounds a note of caution and points out a critical limitation of such systems. They remain, in his words, essentially laboratory experiments, do not operate all of the time, and need regular, careful adjustment by scientists.

"As a research community, we are working to mature the experimental apparatus not just towards higher performance, but also towards more robust operation outside the laboratory setting," Ludlow added. "While some of the key applications of these optical clocks can be realized in the lab, many applications require operation outside the laboratory, so we want to move this quantum technology to the places it is most needed."

Tick rates and relativity

Meanwhile, Katori and his team at the University of Tokyo's Quantum Metrology Laboratory have developed an optical lattice clock at an uncertainty level of 10^{-18}. At this level, he explains, they are able to distinguish between the tick rate of one clock placed just a centimeter above or below a second clock — because relativistic effects dictate that the higher of the two clocks will "tick" very slightly faster.

"Using this gravitational red-shift, we have measured the height difference of two remote clocks with [an] uncertainty of five centimeters," said Katori. "We are now miniaturizing these clocks to take them outside the laboratory."

According to Katori, designing an atom container in such a way that it did not perturb the atomic pendulum

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Optical lattice continued from page 21

was a key challenge. However, the problem was solved by tuning the trapping laser frequency to the so called "magic frequency" — where the dipole polarizability of trapped atoms becomes equal for the clock states.

Katori reveals that his Photonics West plenary talk will focus on describing exactly how he and his team have worked on controlling systematic uncertainty at 10^{-18} — and provide an update on recent progress made with the development of transportable clocks. "These are important steps for optical lattice clocks to be practical and useful devices," he says.

Looking ahead, Ludlow observes that there are a handful of innovations and developments on the horizon. First, he highlights the fact that although a lot of recent work has focused on radically improving the performance of optical lattice clocks, it can still be quite a challenge to assess how good they really are.

This is largely because observers need a very good reference to compare it against — and of course optical lattice clocks are now better than all other time or frequency references. To address this he reveals that some efforts now focus on achieving what is possible within a laboratory or research institute — but also points to the fact that some measurements or assessments "greatly benefit" from remote comparison between distinct types of optical clocks.

"Because of the high level of performance of these clocks, remote comparisons are challenging and sometimes even impossible," Ludlow said. "But there is presently a good deal of effort around the world aimed at making optical lattice clocks comparisons in order to rigorously evaluate all aspects of their performance."

On a related note, Ludlow also predicts that a good deal of work over the next few years will be focused on how best to get this quantum technology, and the associated complex research apparatus, outside of the lab. Such applications could include relativistic geodesy — using clocks to measure gravitational potential — as well as advanced communications or navigation systems.

"Some early efforts have started exploring additional quantum phenomena that could improve the performance of lattice clocks even more. A good example is the implementation of quantum correlations to enhance clock measurement signal-to-noise, often referred to as 'spin squeezing'," he adds.

A number of groups have also started exploring next-generation, ultra-stable laser sources. These are used to drive the electronic oscillations in the clock, and take advantage of cryogenic optical cavities and new mirror technologies.

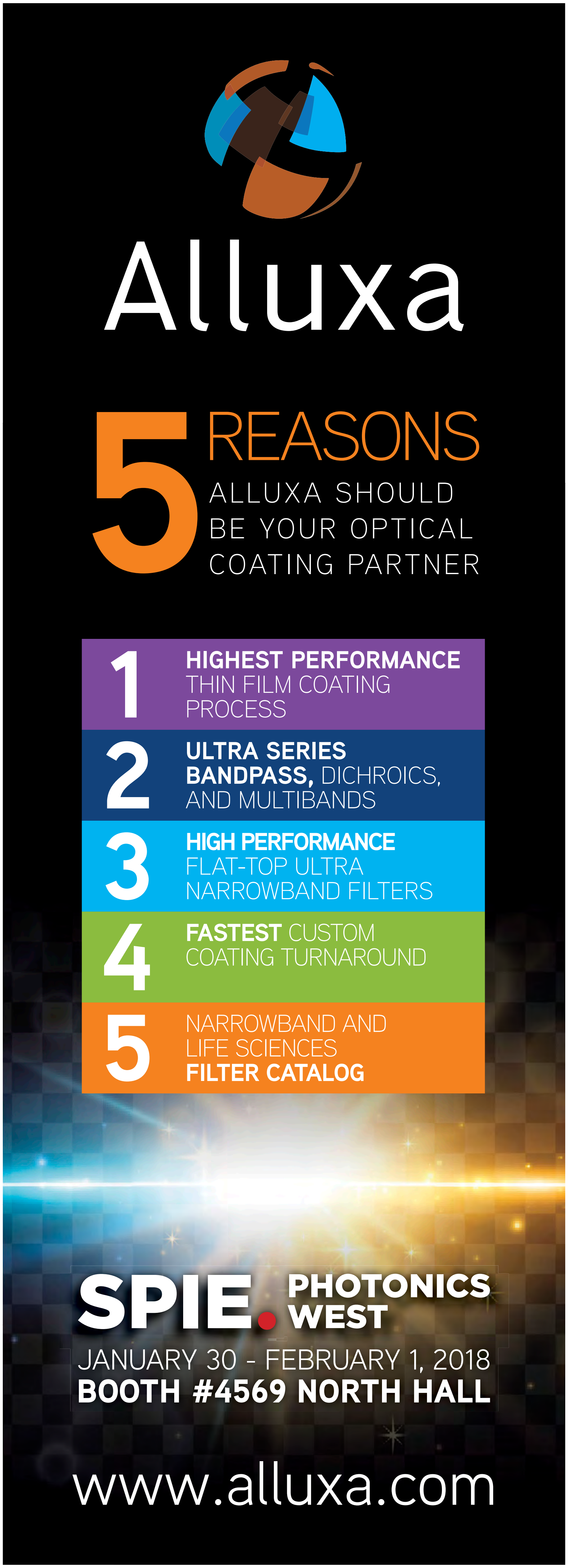
"With all of the advances that have already happened, plus more to come, there is an expectation that at some point in the future, optical clocks will become the new basis for the definition of the SI second," Ludlow suggests. "Clocks like these are being aggressively developed by talented research groups around the world, and while it may be impossible to predict what innovations to come will have the most value, I'm confident that these systems will only get better and more useful."

Meanwhile, Katori reiterates that the ongoing realization of miniaturized clocks — with stable operation extending to a month, or even perhaps an entire year — will be among the critical innovations over next few years.

"These efforts will make optical lattice clocks practical instruments that open up new physics and new innovations armed with its unprecedented measurement capability," he predicted.

See Hidetoshi Katori's LASE plenary at 11.15am in Room 21.

ANDREW WILLIAMS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Collaboration key as LIGO is prepped for future breakthroughs

Developing the optics behind LIGO's gravitational wave detectors saw photonics engineers and vendors collaborating on ground-breaking technology. Now those systems are being upgraded further.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has to date made five confirmed observations of gravitational waves from its two sites in Washington and Louisiana, a spectacular success for the teams of engineers behind LIGO's optics. But developing those systems and making observations possible was a demanding operation for the researchers and industrial partners involved.

At the heart of gravitational wave detection inside the Advanced LIGO sites is a system of test masses — the 40 kg mirrors, each 34 cm across and 20 cm thick, against which the laser beam is reflected during the instrument's operation. These mirrors, along with an arrangement of compensation plates, recycling mirrors and beam splitter components, are collectively termed the "Core Optics" subsystem, and form the cavity optics where observation of a gravitational wave occurs.

GariLynn Billingsley, LIGO senior engineer and manager of the Core Optics subsystem, confirms that development of an optics system able to meet the requirements of LIGO was a far from trivial matter, demanding the combined efforts of engineers from the LIGO project and several industrial partners from the optics sector.

> "Our research has developed what I think we can fairly call the most stable lasers in the world."
>
> BENNO WILLKE, ALBERT EINSTEIN INSTITUTE.

"We were aware of how challenging the specifications were, but at the same time we knew that every gain we made in these optics would have a direct impact on the final noise floor of the instrument in use," commented Billingsley. "The effort needed to make the Core Optics as good as possible would ultimately be worth it when advanced LIGO was operational, so we worked 'hand in glove' with the vendors involved."

The design challenges were ultimately met through the use of test masses made from ultra-high purity fused silica and coated with layers of doped tantala (tantalum oxide), with a micro-roughness of less than 0.16 nm RMS in order to meet stringent restrictions on acceptable light scatter.

Billingsley explained that the fused silica used was a Heraeus Suprasil material, with the test masses all super-polished at Coastline Optics in California, and then ion beam figured at what is now Zygo Extreme Precision Optics at Richmond, formerly the ASML Optics facility.

Other partners involved in the project included Laboratoire des Matériaux Avancés (LMA) at the University of Lyon in France, where the core optics were coated, while a now-dissolved group at CSIRO in Sydney, Australia, carried out coating operations on LIGO's Michelson interferometry optics and certain other components — efforts that Billingsley characterized as "spectacular" work.

The target was a final Core Optics design capable of delivering acceptably low losses for the optical signal when taken across the complete sub-system, requiring a delicate balancing act from the engineering team.

Acceptable losses

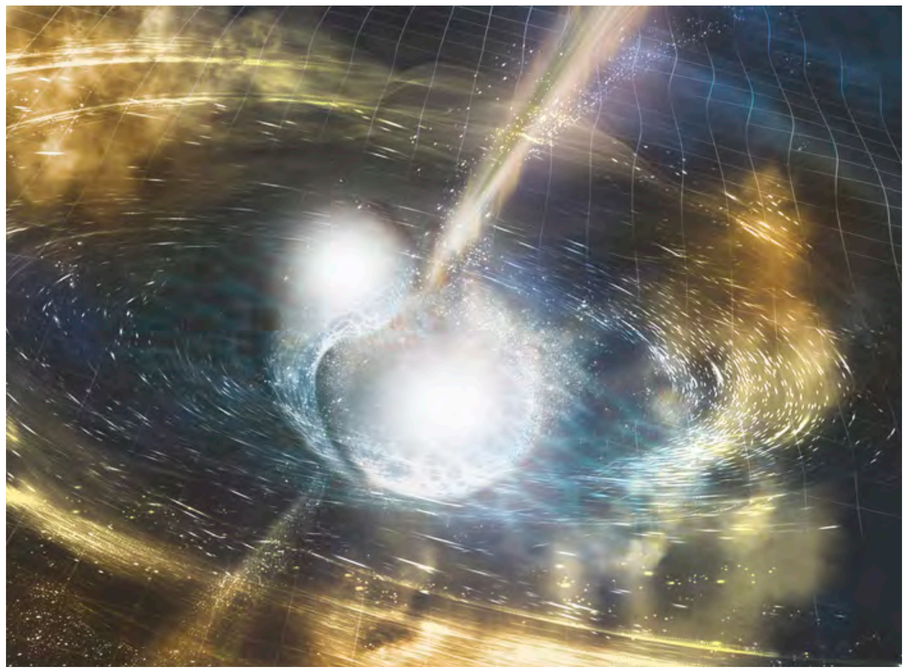
"Our budget for allowed loss was 75 ppm — that's 75 ppm total loss in a cavity four kilometers long, a very stringent requirement when allocated among the different sources of loss that we knew we were likely to be dealing with," observes Billingsley. "A standard approach would be to divide up the allowable defect losses per measurement instrument type and allow a certain number of ppm in each defect size range, but in reality it turned out that the optical defects were mostly point defects, with very few scratches. This allowed us to re-allocate the loss budget based on what we were actually finding."

In the end the team achieved losses of around 60 ppm, better than they were aiming for, with the quality of the final ion-beam polish playing a significant part in the achievement.

"We posed a significant challenge when we set our RMS limit for the polishing operation, knowing that it was a very tough specification," Billingsley recalled. "In the end, many pieces were delivered at 0.1 nm RMS over an area of 160 mm diameter, which is excellent work."

The coatings on the test masses were a further challenge, and LMA's engineers were tasked with producing a coating uniformity that was, in Billingsley's words, "at the far end of anyone's experience."

The recipe for the final coating arose from the need to tackle thermal noise, one of the most sensitive and important factors, while also retaining all desired optical properties from the test masses. A titania-doped tantala coating, layered with silica, was ultimately developed for the purpose. Tantala/silica is a known material for mirror coatings, but the exacting demands of LIGO turned out to require the addition of titania, in order to both reduce internal friction within the coating itself, and lower the thermal noise of the final coated component.



Just a couple of weeks after Rainer Weiss, Kip Thorne and Barry Barish were awarded the 2017 Nobel Prize in Physics, the LIGO and Virgo teams revealed that they had detected the first direct gravitational-wave evidence of a neutron-star collision; the cataclysmic cosmic phenomenon that was then confirmed by observations of a resulting gamma-ray burst and spectacular signals across the electromagnetic spectrum. Credit: NSF/LIGO/Sonoma State University/A. Simonnet.

Future generations of LIGO could employ radical new approaches to the thermal noise problem, perhaps by using silicon test masses cooled to cryogenic temperatures, while several different concept designs for the Core Optics sub-system as a whole are under consideration, to tackle the inherent trade-off between cost and sensitivity.

In the meantime, 2018 will see LIGO begin its third observation run, termed "O3", and in preparation a program of modifications and enhancements to the existing instrument and its optics is currently under way.

"Development of the Core Optics subsystem has taught us a great deal about what's needed in the search for gravitational waves, and the existing system has produced some great results," said Billingsley. "But for O3 we are putting in the latest-greatest test masses, combining the same optics design with the most uniform coatings of the bunch. We now have the opportunity to put in our best technology, and that's what we will be doing."

Laser stability

The specifications of the LIGO interferometer also posed significant challenges for the team tasked with developing a pre-stabilized laser subsystem suitable for use in the hunt for gravitational waves.

Design parameters for LIGO's multi-stage Nd:YAG laser, intended to be capable of supplying power in the 200 W range with exacting limits on the allowed frequency, intensity fluctuations and spatial impurities, meant that the simple purchase of a commercial laser system for use in the observatory was out of the question.

Instead, a development team at the Max Planck Institute for Gravitational Physics (the Albert Einstein Institute, AEI) in collaboration with Laser Zentrum Hannover (LZH) selected a Mephisto laser source from Innolight as its starting point. After Innolight, now part of Coherent, had made some initial

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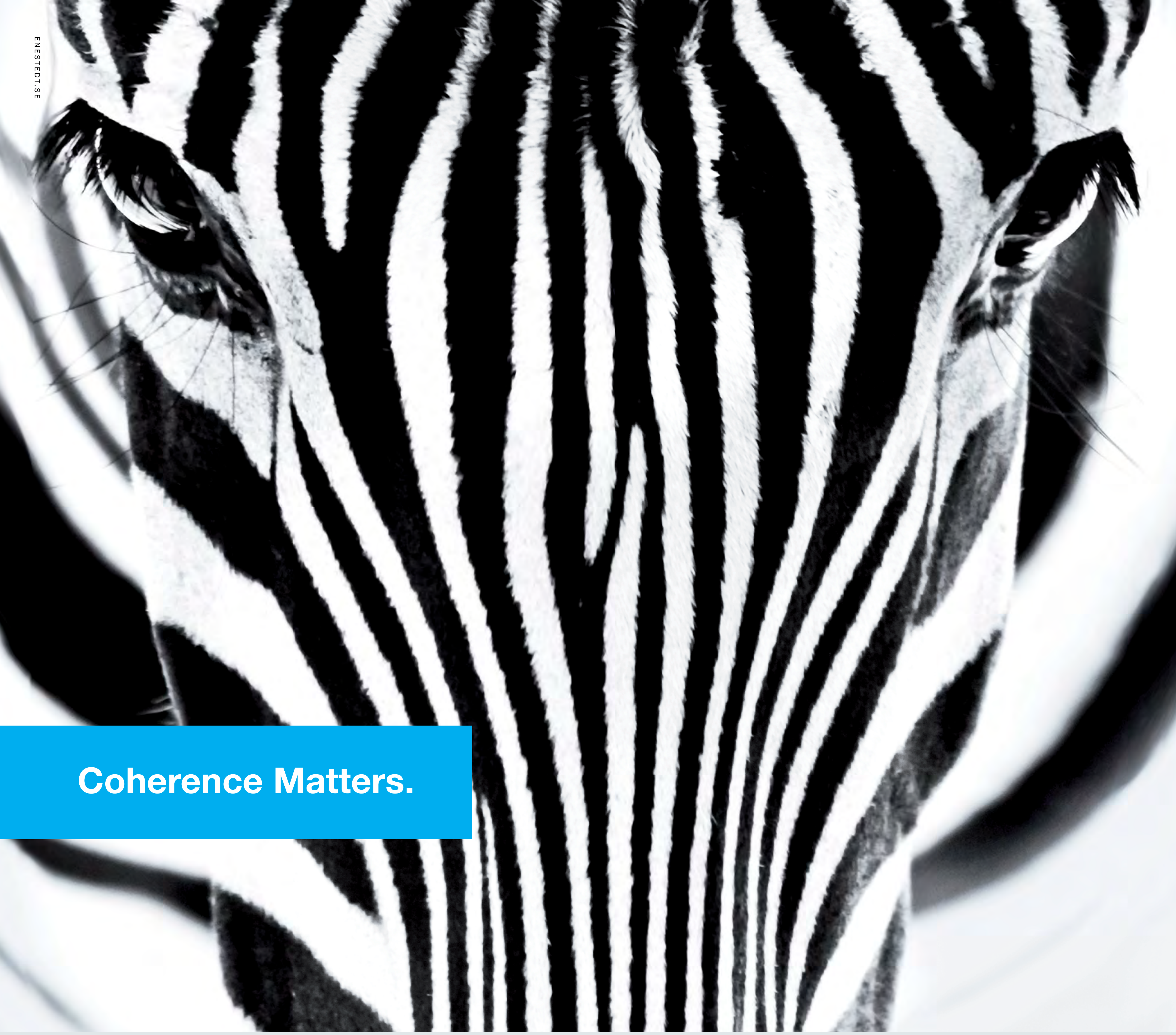
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Ligo continued from page 25

modifications to the source's diagnostic channels and driver electronics, the two German centers took the Mephisto laser as a seed source for their high-power laser development process, and set about creating a laser suitable for use in LIGO.

"It would be difficult for a commercial vendor to develop a laser with the specifications we needed, as it is unlikely that there would be any large market for such a source," commented Benno Willke from AEI, the leader of that development project. "We essentially took a commercial 2 W output seed laser with a very stable frequency and narrow linewidth, and then carried out the rest of the work ourselves."

The subsequent development program saw LZH design and build amplifiers able to boost the laser's output power in two stages, first from 2 W to 35 W, and subsequently from 35 W up to the 200 W capacity demanded by the full LIGO specifications. AEI then designed the systems needed to stabilize and characterize the laser output, which in practice included an effort to reduce the laser noise by orders of magnitude compared to what is considered acceptable for a commercial source.

"We were greatly helped by having experience of an existing gravitational wave interferometer, the GEO600, situated south of Hannover," explained Willke. "This 600-meter Anglo-German instrument, construction of which started in 1995, has helped us to understand what is actually required in terms of not just

One of the 40-kilo test masses installed in the twin US LIGO facilities. The massive mirrors form part of the "Core Optics" subsystem that is critical to the detection of gravitational waves. Photo: LIGO/NSF.

stability and reliability of the laser sources, but also the diagnostics. Adequate monitoring and diagnostics are essential, in order to rule out laser glitches in any meaningful observations of gravitational waves."

Even with this prior experience of gravitational wave observatories, the laser development program was a challenging one, with requirements approaching the limits of what was known to be possible in certain areas. Power stabilization, in particular, is one field where the expertise gained by AEI during its LIGO work has subsequently made it a world leader, according to Willke.

"We found that our LIGO targets could only be reached if we detected roughly 200 mW of light with a photodiode, which is typically not possible," he said. "So our solution was to split the light power onto several photodiodes and then combine the photocurrents. That was the only way to achieve sufficiently low noise levels for our control systems and allow the power stability we needed."

O3 upgrades

For LIGO's upcoming O3 operational run, some changes are being made to the pre-stabilized laser subsystem, building on lessons learned during the interferometer's previous operations. One significant alteration is a change to the laser power levels used. Although the source

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developed by LZH and AEI has a design capability of 200 W, significantly lower powers were actually used during the successful operational runs that saw LIGO detect the distant black-hole and neutron star collisions that prompted last year's physics Nobel.

"Due to thermal loading and certain noise coupling mechanisms, the LIGO interferometers have not been able to operate with the laser at its highest power levels, and instead used around 20 W during O1 and O2," said Willke. "The plan for O3 is to increase this figure to something like 50 or 60 W."

That intermediate goal was itself challenging, as the interferometer has proved to be more sensitive to fluctuations in laser beam pointing than the designers had expected. An initial theoretical limit on the beam pointing had been calculated, based on the team's simulation of how it would influence the output of the detector, but studies of the completed LIGO runs have shown that the beam pointing was in fact limiting the overall sensitivity of the instrument.

For O3, the solution will be a change to the second laser amplification stage. At present a master oscillator-power amplifier (MOPA) handles the first amplification stage from 2 W to 35 W, with an injection-locked high-power oscillator then employed to boost the 35 W output towards the full 200 W capability. For O3 the plan is to replace this second amplifier stage with a modified version of the first amplifier, doubling the 35 W input into a 70 W beam.

LZH's work on the initial 35 W amplifier has already led to the creation of a spin-out company, neoLASE, to exploit the commercial potential of this amplifier architecture for fields other than gravitational wave astronomy. Now LIGO intends to build further on neoLASE amplifier technology, and use it to generate a 70 W laser beam with the low beam pointing needed.

"Maik Frede, co-founder of neoLASE, was group leader of the solid-state photonics group at LZH, and neoLASE is now providing its Nd:vanadate amplifiers for current LIGO upgrades and to other potential end users," said Willke. "There are several possible applications in picosecond laser amplification and other areas that could be exploited commercially, using the technology neoLASE now has."

Virgo, the Italian gravitational wave observatory working alongside LIGO, is also set to benefit. Although its optics are generally similar to those at LIGO there are some differences, including a shorter interferometer arm and some consequent differences in Virgo's Core Optics sub-system, compared to those in the US facilities managed by GariLynn Billingsley.

The laser and vacuum equipment area at the Hanford, Washington, LIGO facility. For the forthcoming "O3" observation run, the laser power is being increased with a new amplifier stage that will reduce fluctuations in beam pointing that has limited overall sensitivity in previous runs. Photo: LIGO/NSF.

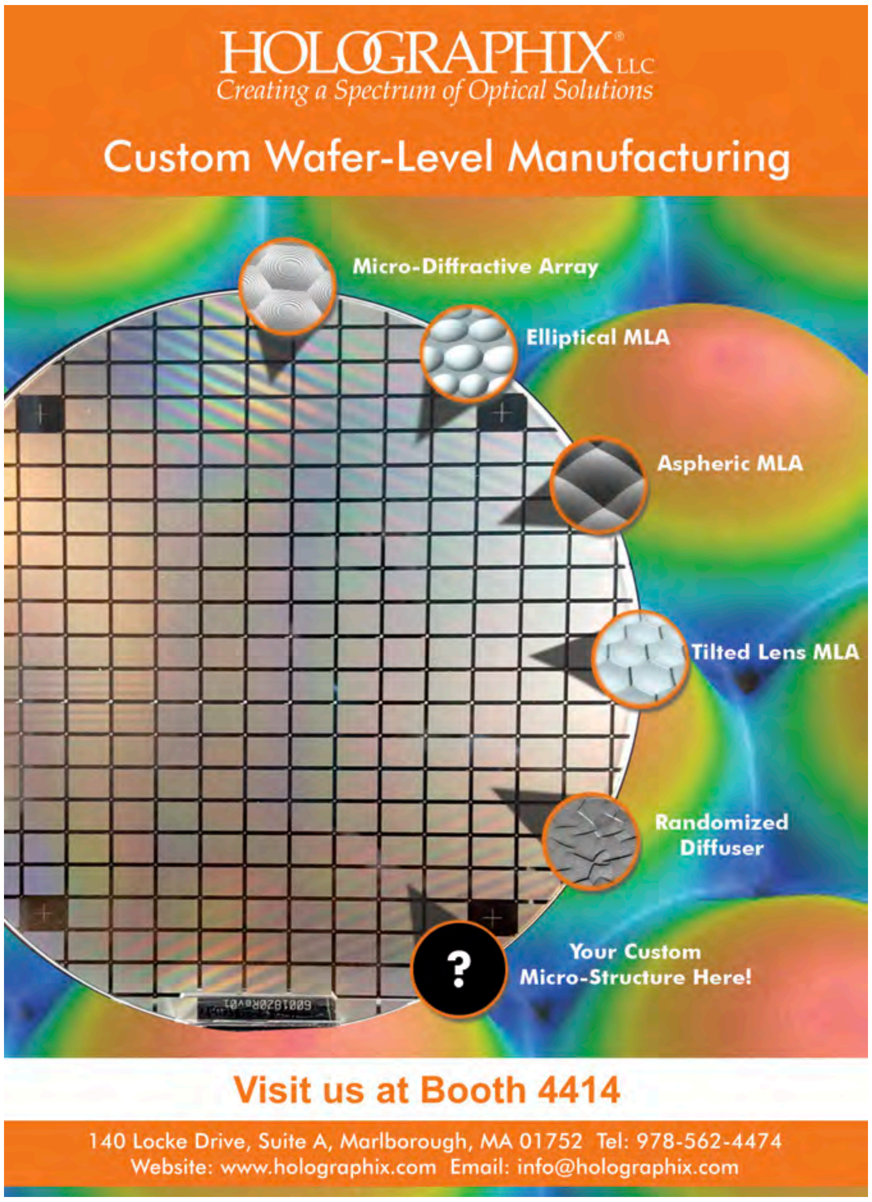
The pre-stabilized laser is another point of difference, with Virgo requiring a source delivering 100 W, rather than the 70 W intended for use in LIGO's O3. But the neoLASE laser amplification technology has been modified to suit this goal, and the company has shipped a unit to Virgo for installation.

This kind of collaboration and shared expertise is likely to be a hallmark of future gravitational wave research, an evolution from earlier patterns of more isolated development work carried out by individual groups, according to Willke.

"The collaboration between the AEI, LZH, and neoLASE is unique, as it provides an environment with all the skills required for the development, fabrication and test of stabilized lasers for gravitational wave observatories," he said.

"Our research has developed what I think we can fairly call the most stable lasers in the world, and other facilities can start to benefit. Now that real gravitational wave astronomy is being carried out, there is an effort under way to bring the different groups currently working in the field together, and coordinate their laser research and development. That is the right approach, to ensure a bright future for lasers in gravitational wave detection."

TIM HAYES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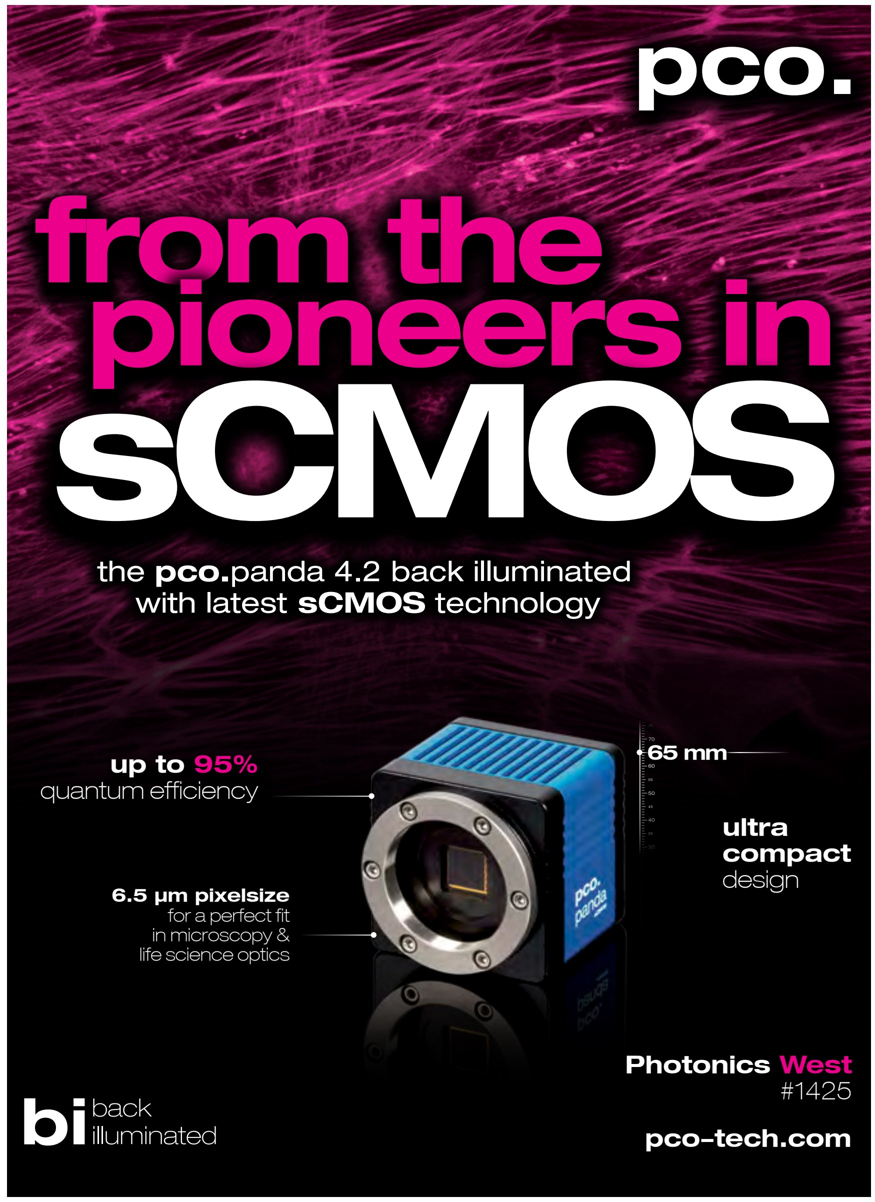

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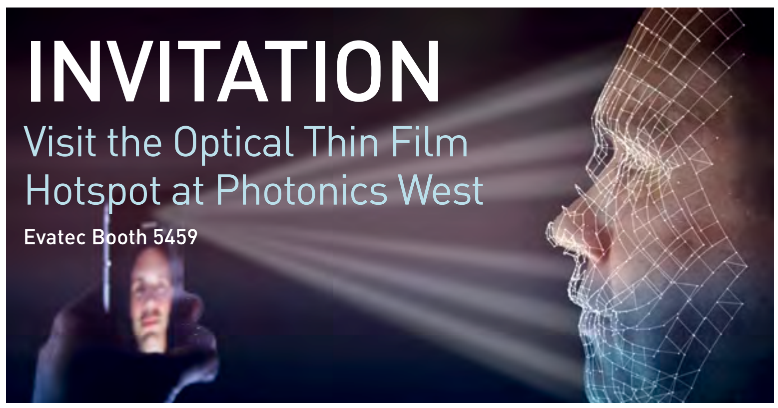

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Analysts 'bullish' on diode sector prospects

The past, present, and future of high-power laser diodes was the theme of the keynote presentation at this year's Laser & Photonics Marketplace Seminar, organized by Pennwell's *Laser Focus World*.

The illuminating talk was presented by Scott Keeney, founder of nLight, who showed how this increasingly essential laser technology, as he put it, has developed and what we can expect in the future.

Starting in 1962 with the laser diode's invention, Keeney looked at the business side of developments in high-power emitters diodes and the impact they are having as they displace other technologies and create new markets.

He said, "As the technology has improved the diode markets have expanded into industrial, medical, entertainment, military, and scientific applications."

Sticking with the business theme, Keeney looked at the fluctuating stock prices of laser diode manufacturing companies as the cost-per-watt of emitters has decreased over the past 20 years. Focusing on the telecom sector bubble around 2000, he commented, "I think that the industry bubble in 2000 was a horrible, crazy time. It was arguably the largest destruction of capital in history. So should we be concerned about it happening again? I think we should always be concerned when equity prices are high on a historical basis, as they are again today."

The nLight CEO continued: "If you look underneath this, then the company that dominates laser diode stock price data is IPG Photonics, which has done phenomenally well from an economic point of view."

But Keeney said he was not too alarmed about the market situation in 2018, compared with that of 2000. "From a fundamental valuation analysis, the stock prices today are certainly high but it is supported by some fundamental analysis and the market picture actually goes beyond IPG Photonics," he told the seminar. "If you aggregate them together, all of the companies in this space are doing well at the moment."

"No doubt there will be a market correction at some point," Keeney added, before joking: "That's not financial advice for anybody so don't short the market."

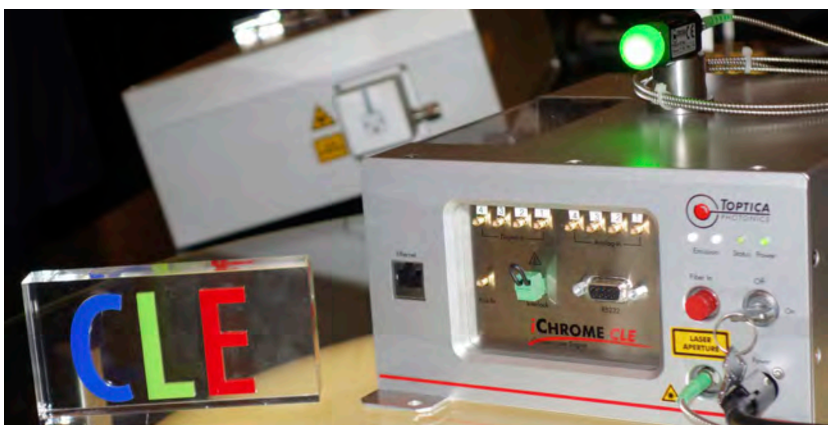
He concluded, "I think in the past five years investors have really woken up to this technology, and understand that we are doing something that is more profound than it was. So I am bullish in the long term."

Keeney's talk was followed by a Laser Marketplace staple, the "Worldwide Laser Market Review & Forecast", as ever presented by seasoned analyst Allen Nogee, president of consultancy firm Laser Markets Research.

Nogee's assessment and predictions were positive about both last year's performance and this year's prospects. He described 2017 as a "standout year" for lasers, with 19.5% growth over 2016.

Considering 2018, Nogee forecast rapid growth in the sensors and instruments, medical, and lithography sectors.

MATTHEW PEACH



iCHROME COVERS THE COLOR BASES

With its ever-broadening portfolio of laser sources and photonics products, Toptica Photonics' 2018 marketing message is "offering all wavelengths". It can now provide coverage from deep-UV at 190 nm through to terahertz radiation at 0.1 THz, corresponding to a wavelength of 3 mm. The lasers support multiple applications across microscopy, materials metrology, and quantum technology.

First presented at this year's BiOS exhibition, Toptica's iChrome CLE (short for "compact laser engine") provides 405, 488, 561 and 640nm with 20mW output at the end of the fiber — suitable for biomedical imaging applications. The source is especially compact thanks to its 561nm green-yellow diode emitter, matching the other chip-scale color sources. Photo: Matthew Peach.

NEAR-IR SPECTROSCOPY REVEALS GAMBLER BRAIN ACTIVITY

Scientists at the University of Macau have used functional near-infrared spectroscopy (f-NIRS) to show apparent differences in the neural responses of problem gamblers and a control group.

"We found a significant difference in pre-frontal activation with our gambling addiction group versus the healthy control group," concluded Zhen Yuan in his presentation, part of the Clinical and Translational Neurophotonics conference during the weekend's BiOS sessions.

The small-scale study, which looked at responses in three problem gamblers and three control subjects, used near-infrared emitters at 690nm and 830nm wavelengths and a sampling rate of 50Hz to monitor levels of oxyhemoglobin and deoxyhemoglobin in the area of the brain associated with personality traits and decision-making.

Yuan and colleagues set up a series of win-lose scenarios, finding a particularly striking difference between the gamblers and the control group when comparing signals from the brain's right frontal gyrus during a "lose" scenario.

The team at the University of Macau's Bioimaging Core, part of the Faculty of Health Sciences, has now begun using the same technique to compare frontal lobe activity in children with Down syndrome to those without the condition. The genetic disorder has a range of physical effects, including to gross and fine motor skills, and Yuan told delegates that the Macau team has measured different responses in initial studies.

MIKE HATCHER

Simplicity the key for at-sea laser links

Getting secret US Navy data flowing between ships, or ship to shore, on stormy seas, without distortion, with the tightest security, remains a top optics challenge, even after 20 years of work on the topic at the Naval Research Laboratory (NRL).

One option for the Navy these days is the line-of-sight method employing free-space optics (FSO), also known by some as atmospheric laser communications. Linda M. Thomas, a researcher in electronic engineering from the Advanced Space Systems Technology Branch of NRL, explained in a Photonics West presentation on Monday how in the last ten years engineers have put together a user-friendly system that has surprised some of its early testers.

"What surprised us at recent demonstrations was the feedback from people, who said, is that all I have to do?" she said. The key attribute seems to be simplicity. "The hard part is building the system around the technology," Thomas told delegates. "Making things straightforward to operate is really key. We don't want six months of learning how to use them."

Cost is another challenge. To keep systems affordable, Thomas said her team is using readily available, commercial products including controllers and gimbals. "To custom-make a detector will never get us to the price point," she noted. "We use off-the-shelf products."

Since 2005, the NRL has been testing laser subsystems at its Chesapeake Bay facility. One forum photo showed a compact FSO unit in a Trident Warrior experiment in 2008, with an operator on the bridge.

Other images showed successful 50km tests of Ethernet modems with the TALON, or Tactical Line-of-sight Optical communications Network, near Laurel Mountain.

In 2013, they took their FSO system to China Lake for tests of data transfer at up to 95 Mbps. With line of sight between laser and receiver, FSO can use infrared lasers to send data at rates as high as 10Gb/s over 45km, and at 200km for air-to-air.

By comparison, commercial systems can have limits of just a few kilometers — shorter for high bandwidth — for a TV truck to a station.

The US Navy currently has a share of a $45 million, three-year FSO development grant from the Department of Defense for advanced laser communication, optical time transfer and quantum communication, and more.

Thomas said her team takes a wide view of the future. "High bandwidth is great," she said, "but the big driver is moving outside traditional limits of FSO. This is changing the narrative, within the US and globally."

FORD BURKHART

BRAIN Initiative breeds imaging tools

Interest and investment in optical technologies that can unravel the mysteries of the brain continue to heat up, thanks in part to the US government-supported BRAIN Initiative launched in 2014 and the resulting BRAIN 2025 report guiding that initiative.

Reflecting the seven priority goals outlined in the BRAIN 2025 report, the current focus in neurophotonics R&D is on developing new types of photonics-based imaging tools and techniques. All have a common purpose: to glean ever more detailed information about how the brain and its myriad components work, individually and as a whole.

> "The idea is to have a 'tool-driven revolution'"
>
> EDMUND TALLEY, NIH

"The focus [of the BRAIN Initiative] is on mapping neural circuits and understanding how they function in health and disease," said Edmund Talley of the US National Institutes of Health in his presentation at Sunday's Neurophotonics "Hot Topics" plenary session. "The idea is to have a 'tool-driven revolution' that will enable new discoveries to unlock the mysteries of the brain. We don't know what we're going to find, but with these new technologies will come new discoveries."

The early fruits of these efforts took center stage at the plenary, which featured nine 10-minute presentations on the state-of-the-art in optical brain imaging at the micro and macro levels. First up was Ed Boyden of the Massachusetts Institute of Technology, whose group has developed a method they call "expansion microscopy" that enables commercially available, diffraction-limited microscopes to study neural circuits in a large-volume, multiplexed fashion. Using this approach, they can image large, 3D specimens with nanoscale precision by embedding them in a "swellable" polymer, homogenizing their mechanical properties, and exposing them to water. "We can do extended nanoscale imaging at high speed on ordinary microscopes, and it's pretty easy," he said.

Na Ji of the University of California, Berkeley discussed her team's efforts to develop an alternative to two-photon fluorescence microscopy for imaging the brain: fast *in vivo* volumetric imaging using a Bessel beam — a non-diffracting light beam with an infinite number of rings — to achieve video-rate (30 Hz) quality images with synaptic resolution. According to Ji, one current goal in brain imaging is to understand the input-output relationship for neural circuits and the anatomical and functional relationships between individual neurons.

"We want sub-micron spatial resolution to resolve individual synapses in a scattering sample. And while two-photon fluorescence microscopy has the potential to satisfy this, the problem is it is a little slow because of the serial 3D scanning of two-photon-excitation focus," she said.

Elizabeth Hillman of Columbia University described another innovative and proprietary imaging technique developed in her lab: SCAPE (swept confocally aligned planar excitation), a high-speed cellular imaging technique that combines the benefits of light-sheet imaging with confocal descanning principles to capture the activity of large numbers of neurons throughout the brain. "SCAPE is a hybrid between light-sheet microscopy and spinning-disk confocal microscopy that enables high-speed 3D imaging that can tolerate natural movements," Hillman explained.

The efficacy of this method has been demonstrated on a range of organisms, including zebrafish brain, the awake mouse cortex, and the whole brain of fruit flies. "We can do a lot of genetic manipulations of Drosophila, including imaging its whole brain through a little cranial window," Hillman said. "It doesn't sound like much, but we have never had a modality where we could image every single neuron in an active animal. So this is an exciting new platform for understanding these behaviors in animals."

Takeharu Nagai of Osaka University made a case for bioluminescence imaging in analyzing activity in the brain. Calling it the "gold standard" for biological study due to its superior signal-to-noise ratio and capacity for long-term measurement, Nagai said that bioluminescence could be the next-generation modality for bioimaging in combination with multiple optogenetics. It allows researchers to use bioluminescent proteins rather than fluorescent proteins for live-cell imaging, eliminating the need for excitation light sources that can cause phototoxicity, autofluorescence, and photobleaching.

Photoacoustic microscopy (PAM) also shows promise for studying brain functions such as cerebral microvasculature, according to Song Hu of the University of Virginia. Hu's lab has developed multi-parametric PAM for label-free simultaneous imaging of blood perfusion, oxygenation, and flow at the microscopic level *in vivo*.

"We have demonstrated PAM for cerebral blood perfusion, oxygenation, and flow in the mouse brain," he said. "By combining these parameters, we can certify the regional oxygen extraction fraction at the microscopic level and the cerebral oxygen metabolism." Recently his group extended this technology into the awake mouse brain via a first-of-its-kind head-restrained PAM to directly visualize and quantify the cerebrovascular response to general anesthesia.

Sergio Fantini of Tufts University also discussed cerebral blood-flow monitoring, focusing on cerebral autoregulation, a homeostatic mechanism that maintains a relatively constant cerebral blood flow in the presence of changes in cerebral perfusion pressure. While transcranial Doppler ultrasound has been used for many years to study this, "optical techniques offer the potential to address the challenge of continuous monitoring of local cerebral autoregulation at the bedside and in a critical care environment," Fantini noted. His group has been using near-infrared spectroscopy and coherent hemodynamics spectroscopy for potential clinical impact in assessing and monitoring stroke, traumatic brain injury (TBI), neurovascular disorders, and more.

KATHY KINCADE

Blue photons set to tackle MRSA menace

Pu-Ting Dong, with Translational Research Forum chairs Gabriela Apiou and Bruce Tromberg. Photo: SPIE

The mighty superbug MRSA has met a worthy adversary in Boston University's Pu-Ting Dong, who is armed with blue light. The graduate student, who won SPIE's Translational Research Award for 2018, including a check for $500, described her work in a half-hour talk during Sunday's conference sessions.

She was drawn to the battle against methicillin-resistant *Staphylococcus aureaus*, commonly known as MRSA, because of its growing threat. "MRSA is indeed a huge problem," she said. "The bacteria have developed resistance to all beta-lactam antibiotics."

Increasingly found in hospitals, MRSA is now ranked second as a cause of death by drug-resistant bacteria in the US. The beta-lactam antibiotics it resists include penicillin and methicillin.

Under an optical microscope, she accidentally found the mechanism for how blue light kills MRSA, and ran a series of experiments over the last one and a half years, using blue light under various conditions.

Incorporating irradiance using blue light at specific wavelengths, she achieved the annihilation of MRSA by photobleaching staphyloxanthin, the pigment that gives *S. aureus* its golden color.

"A 30-year-gap has formed between the emergence of this resistance and the clinical introduction of antibiotics," she said. "There is no effective solution right now and novel approaches are needed."

She developed her strategy along with the Cheng research group at Boston University. "It uses a drug-free photonic approach to photobleach the staphloxanthin, which is a very important virulence factor." Their findings, she said, pave the way for reusing an old class of antibiotics.

FORD BURKHART

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