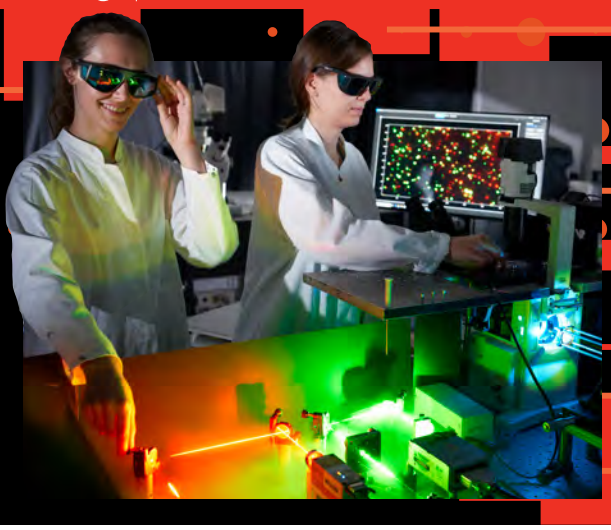
2024

SPIE. | optics.org | JANUARY 27 – FEBRUARY 1, 2024

PHOTONICS WEST PREVIEW



BiOS Hot Topics p. 10

Kernel Flow takes neuroimaging out of the lab and into society

Ryan Field will tell the BiOS Hot Topics audience how advances in optics hardware are creating the first commercially viable functional neuroimaging applications.

Non-invasive neuroimaging techniques are established elements of diagnosis and therapy — but not of everyday clinical care. Although functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) are primary ways to visualize brain activity, neither of them could realistically be called low-cost compact instrumental platforms, and both require operators with a suitable level of training in their use.

This landscape may now be changing courtesy of functional near-infrared spectroscopy (fNIRS), in which near-IR illumination is used to monitor hemodynamics as a way to measure brain activity. The technique was one of two optical technologies, the other being diffuse correlation spectroscopy, identified by a 2022 report in SPIE *Neurophotonics* as being all set to make a major impact in human brain

Kernel has developed a head-worn time-domain fNIRS (TD-fNIRS) spectroscopy system named Kernel Flow. Credit: Kernel.

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Tackling the complex, multifaceted puzzles presented by fusion energy

Ahmed Diallo discusses the present and future impact of carbon-free primary energy.

"If we're talking about making a real impact on the world, fusion energy could be a game-changer," says Ahmed Diallo, program director for the Advanced Research Projects Agency-Energy (ARPA-E). "Fusion energy is essentially the universe's natural power plant: it's the same process that lights up the stars and our sun, and it promises a vast supply of carbon-free energy."

The sun takes elements like hydrogen and fuses them together under extreme conditions to release a massive amount of energy. Diallo's team at ARPA-E is trying to replicate this stellar performance in the lab by creating the right conditions — a vacuum, like that of space, super-high heat, and a way to keep that scorching "soup" in place long enough to harness energy from

continued on page 04

Ahmed Diallo, program director for the Advanced Research Projects Agency-Energy. Credit: Michael Livingston, PPPL.

DON'T MISS THESE EVENTS.

SATURDAY

BIOS EXPO
10am – 5pm Moscone Center, Hall DE (Exhibit Level)

GOVERNMENT FUNDING IN BIOPHOTONICS
1pm – 2:30PM Moscone Center, Expo Stage, Hall DE

BIOS HOT TOPICS
7pm – 9:20 pm Moscone Center, Room 207/215 (Level 2 South)

SUNDAY

BIOS EXPO
10am – 4pm Moscone Center, Hall DE (Exhibit Level)

QUANTUM SCIENCE MEETS BIOLOGY: OPPORTUNITIES ENABLED BY THE NQI
1PM - 2:30 Moscone Center, Expo Stage, Hall DE

NEUROTECHNOLOGIES PLENARY
3:30PM - 5:30PM Moscone Center, Room 207/215 (Level 2 South)

BIOS POSTER SESSION
5:30PM - 7PM Moscone West, Room 2003 (Level 2 West)

BIOPHOTONICS FOCUS PLENARY: CLINICAL APPLICATIONS
7PM - 8:30 PM Moscone Center, Room 207/215 (Level 2 South)

For the full schedule, see the technical program and exhibition guide or download the SPIE Conferences app. Some events require registration.

IN THIS ISSUE.

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Welcome to Photonics West 2024

Dr. Kent Rochford is CEO and Executive Director of SPIE. Credit: SPIE.

I am excited to say this year will be the largest Photonics West of all time, and I look forward to welcoming you all back to the Moscone Center for the greatest event in photonics. And our field consistently shows — in numerous ways — how it enables the most impactful technologies of our era.

Once again, we saw photonics being honored with Nobel prize announcements in November of last year, with Nobels in both physics and chemistry being awarded to researchers in our community for generating attosecond light pulses and the discovery and synthesis of quantum dots, respectively. The US, Europe, and Asia are all investing heavily in semiconductor manufacturing, quantum technologies, and materials research – all leveraging and requiring continued advancements in optics and photonics. Telescopes and space exploration are once again capturing the minds of both young and old, and countries across the globe have reinvigorated or started programs to leave Earth's orbit. Smartphones and wearables are commonplace, more powerful due to optics and photonics technologies. We find examples of photonics impacting our lives everywhere we look, and the impact is growing.

This increase in applications and awareness is helping our industry stay strong and vibrant in an increasingly unpredictable economy and business environment. SPIE has seen record demand for our exhibits, our membership is at its largest in history, and our Digital Library has exceeded 600,000 pieces of content – all signs showing a healthy and growing optics and photonics community. What's more, the SPIE Global Industry Report, which will be released at our new Global Business Forum on Monday of Photonics West, shows that photonics-enabled products and services account for $16 trillion annually, or more than 15% of the global GDP! I'd say photonics (read: you, Photonics West attendee) is making an impact!

Photonics West is the best place to experience that impact firsthand and deepen your engagement with the broader community and industry. Whether you are searching for a supplier for a crucial component of your optical system, hoping to find an investor for your new biophotonic diagnostic tool, trying to take the next step in your career, or trying to solve a complex problem from your lab, you can be successful wandering the exhibit halls or conference rooms and striking up conversations at Photonics West.

This year's exhibits — now four — will take up 15% more space than last year and are once again sold out. They include nearly 1,600 booths representing companies from more than 35 countries! Combined with the AR|VR|MR conference, which your paid Photonics West badge gives access to, there are over 5000 technical presentations and attendees from over 70 countries. This week will be packed with things to do, people to meet or reconnect with, and companies and products to interact with.

Among the many new offerings this year are the Quantum West Expo and the Quantum West Business Summit, further bolstering the growing Quantum West conferences, which include over 350 presentations. Additionally, the Quantum West plenaries feature some of the brightest minds in quantum computing, atomic clocks, and quantum biology to complement the other 20 plenary presentations happening throughout the week.

I invite each of you to actively participate and engage wholeheartedly; whether you're a seasoned veteran in the field or a newcomer eager to absorb the wealth of knowledge around you, your unique perspective adds value to the vibrant mosaic of our community. Take advantage of the numerous networking opportunities scattered throughout the event. Engage in conversations during coffee breaks, exchange ideas in the bustling exhibition hall, and participate in the social events designed to foster connections. You never know where a chance encounter might lead — a partnership, a collaborative project, or even a lifelong friendship. The collaborative spirit of Photonics West is not just about the present; it's about planting the seeds for your career successes while also ensuring photonics will continue to have an increasingly profound impact.

I hope your time at Photonics West is filled with enlightening conversations, innovative discoveries, and lasting connections. Here's to a conference that not only informs but inspires, and to the shared journey of pushing the boundaries of what's possible in photonics.

And yes, the dog park will be back.

KENT ROCHFORD

Kernel Flow

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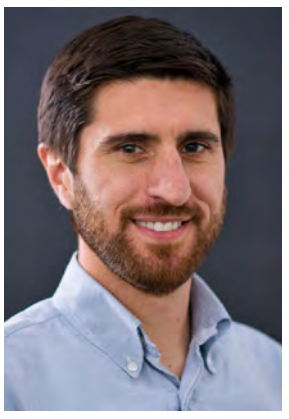
imaging. "The fNIRS technique has opened doors to explore unanswered questions in several fields, ranging from neurodevelopment to social and cognitive sciences to populations that are hard to assess with more conventional neuroimaging techniques like MRI," wrote the SPIE authors.



Ryan Field, CEO and CTO of neurotechnology developer Kernel. Credit: Kernel.

Ryan Field, CEO and CTO of neurotechnology developer Kernel, agrees. Founded in 2016, the California company has developed a head-worn time-domain fNIRS (TD-fNIRS) spectroscopy system named Kernel Flow, which could see the technology enter the consumer space to solve a pair of pressing societal health challenges. Field will be discussing the device and its impact in the BiOS Hot Topics Plenary Session. Kernel Flow earned its place in the session by virtue of having the most highly cited paper published in the *Journal of Biomedical Optics* in 2022

"Kernel started from the idea of building neuroimaging products that are targeted at consumers; devices that you can potentially buy and use in your home," said Field. "As we went through development, we identified that TD-fNIRS was an interesting route to low cost neuroimaging. The technology offers a way to record neural activity in the visual cortex, frontal cortex and motor cortex of the brain. And if technically it might record perhaps 80 percent of the functional measures that a full fMRI investigation would, it can do so at about 20 percent of the cost and complexity."

Neuroimaging modules you can hold in your hand

Development of the Flow device was partly facilitated by recent strides in consumer electronics, as well as progress in the lidar sector where Field has previous experience. The advanced sources and detectors now used in platforms such as the iPhone and in automotive sensing are built on breakthroughs in components and integration that Kernel has now mapped onto its own requirements, while designing a successful TD-fNIRS device intended specifically for imaging of the brain.

"Our initial Flow1 platform was built with off-the-shelf components, and the system involved several boxes of equipment and a table-top of space," commented Field. "But for the current Flow2 device all the hardware is proprietary. Kernel now uses custom sensing chips that we have designed and manufactured working with a commercial CMOS foundry, custom laser drivers, and our own firmware and control algorithms to make sense of the brain activity. As a result the technology is now contained in a module you can hold in your hand."

The objectives of the company have also shifted, from an initial goal of devices for any users who wished to image neural activity, to a current focus on two specific clinical research uses where more readily available neuroimaging could have a dramatic impact for patients.

One of these is the monitoring and treatment of depression, including the evaluation of available therapies to determine which are the best and most effective for different patients. The other application is the early detection of cognitive decline, to spot individuals likely to progress to dementia, and to assess treatments for conditions such as Alzheimer's disease.

"Around 300 million people suffer from depression and tens of millions suffer cognitive decline, and both numbers are growing," noted Field. "Mental health is a critical and global societal challenge, and as we live longer it is our brains that are starting to bear the brunt. What can we do to maintain brain function for longer and extend a good quality of life? These are the areas where we are building products to actively help clinicians."

The goal is for a convenient and easy to use TD-fNIRS system such as Flow2 to help clinicians as they hunt for those biomarkers already identified from fMRI as being predictive for depression and cognitive decline, and Field is confident that his platform will detect them. But the Flow2 platform could well reveal previously unknown and valuable information about neural behavior, by virtue of the platform's novel capabilities.

"Our TD-fNIRS is unique, giving us different data than fMRI would do," Field commented. "We get absolute measures of hemoglobin concentrations, information about heart rate variability of the patient as they are

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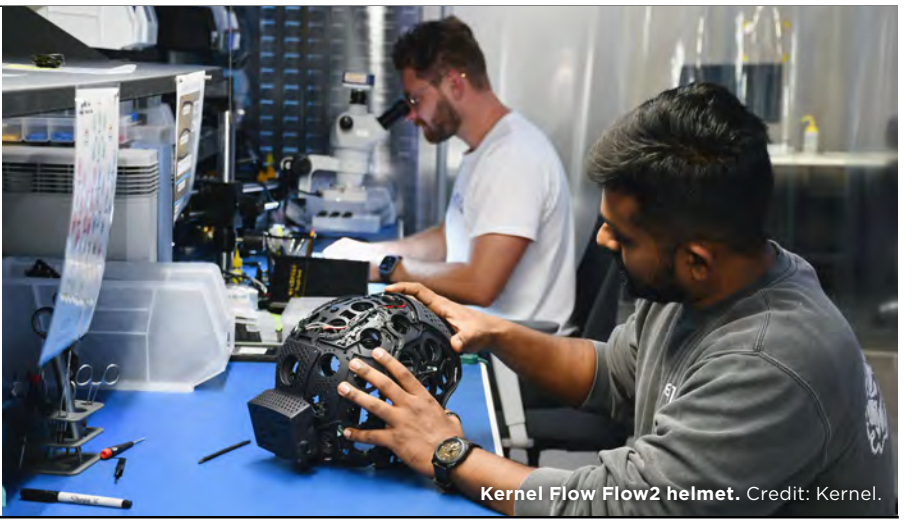
Kernel Flow continued from page 03

measured, and we can easily track people longitudinally over time. It is not practical to receive a fMRI scan every time you see a doctor, but an examination with Kernel Flow2 could take place during each visit. This ability to gather a lot more data about individual patients will drive discovery of additional biomarkers that could not be identified with other tools."

Kernel is now starting to bring the Flow2 device to the medical research space, and is collaborating with clinical partners on observational studies and the gathering of data from patients.

"We have built a technology that has never existed in this form before, enabling the scientific community to ask new questions," said Field. "Functional brain imaging has to date had a hard time finding its application and its market. Success for Kernel will be finding that first really big market, and demonstrating that functional neuroimaging has a place in society as well as in research labs."

TIM HAYES



Kernel Flow Flow2 helmet. Credit: Kernel.

Diallo continued from page 01

it. "It's tough to do," says Diallo, "but it's also what makes it safe. If confinement ceases, the reaction simply stops, making it a potentially safer alternative to other forms of power."

On 29 Jan, as part of the LASE conference at SPIE Photonics West, Diallo will give a summary of current ARPA-E programs and ideas for future projects.

The mission of Energy ARPA-E is to advance high-impact technologies that have the potential to transform the energy industry. A key aspect is accelerating the development of enabling technologies for fusion energy regardless of the concept. Diallo's focus is on transformative research and development to enable commercial fusion energy. As program director, Diallo plays a critical role in shaping the future of energy research and development, driving innovation, and fostering collaborations that can lead to breakthroughs in energy technologies. His responsibilities include identifying and developing high-impact transformational energy research areas, creating funding opportunities, and evaluating proposals for technical merit and potential. In addition, he also manages funded projects, ensuring they meet objectives and promote collaboration among stakeholders. He also oversees dissemination of knowledge, sharing project results with the scientific and energy communities. "I'm genuinely thrilled about the projects under my purview," says Diallo, "especially the ones that pave the way for new startup ventures."

Enriching experiences and experiments

Diallo joined ARPA-E in 2022 and is currently "on loan" from Princeton Plasma Physics Laboratory (PPPL) where for the last 14 years he has served as a principal research physicist and head of the Advanced Diagnostics Development Division. "I hold a special fondness for a multitude of projects that I had the privilege to contribute to at PPPL," says Diallo. "Notably, in 2010, I was deeply involved with PPPL's flagship project, the National Spherical Torus Experiment (NSTX)."

His time at PPPL was particularly enriching as he collaborated on a variety of fusion devices across the US and internationally. This exposure proved instrumental in broadening his experience and professional growth. The PPPL years also presented the invaluable opportunity to work alongside a host of talented scientists, engineers, and students — a more personal facet of Diallo's career that he cherishes deeply. "As I look back, it's clear that these experiences didn't just shape my professional trajectory, they also enriched my collaborative spirit and technical acumen."

A profound journey through education

Seeking to solve the world's energy problems has led Diallo around the world, an experience he began early on. A native of Burkina Faso, he earned his Diplôme d'Etudes Universitaires Générale from the University of Ouagadougou (UO); he received BS and PhD degrees from the University of Montana and the University of Iowa respectively.

Some of his early experiences include serving as a Research Fellow at the Australian National University, where he co-developed and installed imaging polarization interferometers to perform proof-of-principle of 2D magnetic field pitch angle and flow measurements on fusion devices. As a post-doc at the Swiss Plasma Center (EPFL), he developed an antenna system to launch electrostatic waves in plasmas.

"Moving across continents for my education and career has been a profound journey, enriching my work as a scientist in unexpected ways," says Diallo. "Initially, I didn't fully grasp the opportunity that lay in engaging with diverse perspectives and backgrounds. However, as my career progressed, I recognized the depth it added to my professional life. Living and working in different parts of the world has broadened my understanding and approach to scientific challenges, particularly in fusion energy, a field inherently dependent on collaboration. These experiences have not only been personally gratifying but have also honed my ability to collaborate effectively across various cultural and disciplinary boundaries."

In Burkina Faso, Diallo's early interest in science steered him towards studying math and physics at UO, where he was introduced to plasma, a fourth state of matter that encompasses 99% of the visible universe. His education in the US catalyzed his fascination with fusion energy. While still an undergraduate, he delved further into the subject during a research internship at PPPL where he recognized its potential as a carbon-free and abundant source of primary energy. "This was particularly resonant for me, given Burkina Faso's critical energy needs," says Diallo. "The prospect of contributing to fusion energy both as a researcher and as a program director with such transformative potential for the world at large is immensely fulfilling."

Support for a multifaceted career

In 2020, Diallo was named a PPPL Distinguished Research Fellow for "his groundbreaking studies of tokamak edge plasma dynamics and his development and utilization of novel plasma diagnostics." When receiving such accolades, Diallo is quick to point out that he's been fortunate to have numerous mentors, and that their support gave him the space to explore and learn throughout his journey in life and in research. He adds that his family's unwavering encouragement has been the cornerstone of his resilience and adaptability, especially as he has traveled across continents. "Their support during these transitions and choices has been nothing short of extraordinary, fortifying my resolve and enabling me to embrace each new chapter with confidence," says Diallo.

Diallo has transformed these experiences into his own mentorship of others. At PPPL, he served as a mentor to numerous students doing hands-on research through the US Department of Energy's Summer Undergraduate Laboratory Internship program, and today, mentorship plays a central role in his professional philosophy. "I am committed to guiding students and early career scientists, a responsibility I view as central to cultivating the next wave of innovators," says Diallo. "Through mentoring, I aim to impart more than knowledge — my goal is to influence their holistic development, empowering them to navigate both their careers and lives with a sense of purpose and capability. It's a way to invest in the future by equipping the emerging generation with the tools and wisdom to excel and, in turn, inspire them to continue this legacy of mentorship."

The future of fusion energy

As many researchers can attest, the journey from idea to working product isn't always smooth. One of the obstacles Diallo has come across in his work is the concept of successful storytelling — getting your idea or theory across to those who are providing funding or experimental facility. "Your idea may not be accepted immediately," says Diallo. "You may have to go through multiple staff, convincing several people along the way. This can add unnecessary delays in a project with otherwise good ideas." Diallo adds that while the concept of getting your ideas across through its story works well in the US, "that's not what I grew up with. I've had to learn this "storytelling bit" along the way." He notes that you may have a great idea, but not be able to make others understand its value. Sometimes you need someone who can take the seed of your idea and wrap a story around it.

Fusion energy is just too important a subject to get lost in the shuffle of explanations. Diallo remains steadfast in his belief that fusion energy stands as the pinnacle of sustainable primary energy solutions, with the potential to furnish humanity with a boundless, carbon-free power supply. His aspiration is to see a concerted global effort converging to address the intricate challenges of fusion energy by accelerating the development and deployment of fusion energy plants within the next decade. "This unified approach would mark a monumental stride towards an era of clean energy prosperity," says Diallo.

KAREN THOMAS

SPIE expands its journal portfolio across biomedical and translational optics with Biophotonics Discovery

Helmed by Editor-in-Chief Darren Roblyer, the Gold Open Access publication will encompass a wide array of topics, complementing the annual BiOS conference at SPIE Photonics West.

Biophotonics Discovery will augment the existing SPIE portfolio of peer-reviewed biomedical journals. Drawing from the wealth of topics covered at BiOS, the new journal will highlight novel and emerging biophotonics technologies and their impacts on basic and clinical science as well as medicine. "We're going to be focused on the realized potential of technologies that are being developed by our community," says Editor-in-Chief Darren Roblyer, an associate professor of biomedical engineering at Boston University. "People who are developing methods and techniques, they might publish that research in SPIE's *Journal of Biomedical Optics*. But if your work is focused on biophotonic *applications*, and if you're taking that technology, modifying it, and then using it to explore discoveries in basic science or trying to tackle an unmet clinical need — if you're using this technique clinically for an application that could change healthcare — those are the types of reports and manuscripts that we're looking for." For the journal's inaugural year, open-access fees will be waived for all submissions.

In part, SPIE is launching *Biophotonics Discovery* to provide a peer-reviewed outlet for the extensive range of innovative research presented at the Photonics West BiOS Symposium each year. *Biophotonics Discovery,* like all SPIE journals, will support the transition of conference proceedings to an expanded journal manuscript.

The publication also complements the Society's other biomedical journals: the *Journal of Biomedical Optics,* which focuses primarily on optical device development; the *Journal of Medical Imaging,* which publishes research on medical imaging related applications; and *Neurophotonics,* with its focus on neuroscience-related optical technology. *Biophotonics Discovery* will cover the entire breadth of BiOS topics, including the more application-specific conferences. In doing so, it follows a very successful model established by SPIE journals such as the *Journal of Astronomical Telescopes, Instruments, and Systems* and *Journal of Medical Imaging,* both of which are well-supported by their research communities and were born from conference programs.

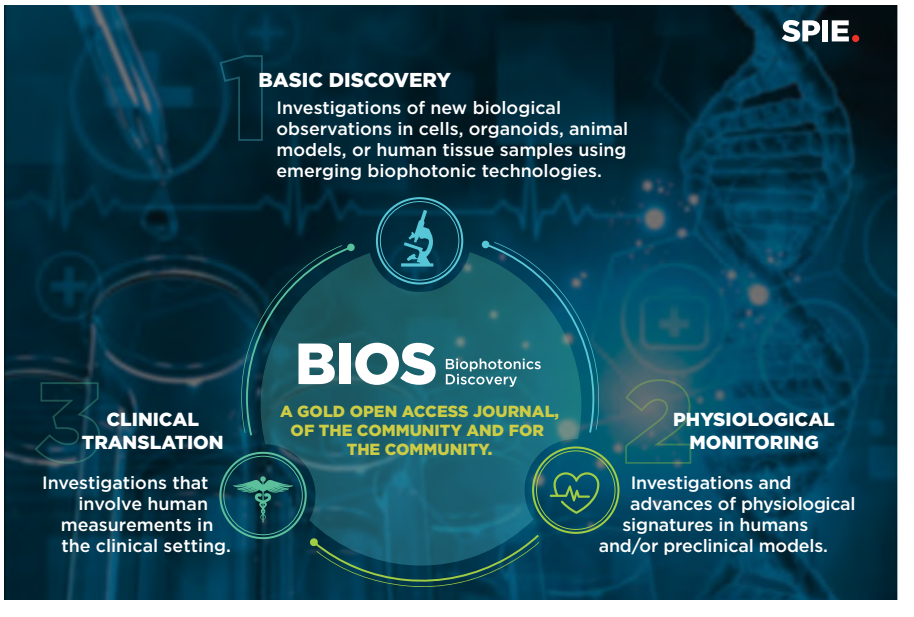
But *Biophotonics Discovery* will also implement new elements of its own. As well as the usual advisory board and teams of deputy editors and associate editors, Roblyer is appointing an early career editorial board. "This is something that is different to other journals in the biophotonics field," notes Roblyer. "These are people who we think are going to be the next assistant professors, the next independent investigators in the field. They're going to be still in training — typically as postdocs or research staff members in a lab — but they will have their names on the journal and will be providing us with feedback on the content. We're going to keep our eye on them; they are who we consider to be the next stars. And as they pursue their own independent research careers, if they're interested in being associate editors, they're going to be very high on our list of people to consider."

In developing this approach, Roblyer had the critical input and backing of 2022 SPIE President Anita Mahadevan-Jansen, widely recognized for her proactive support of students and early-career researchers. "She is one of the journal's senior editorial advisors," says Roblyer. "Anita is the first person in my Rolodex in terms of coming up with ideas. And she really pushed this idea, that we should include postdocs early in their career. This is a different idea for this journal that I'm really excited about."

Another new element Roblyer points to is a requirement for open data. In support of SPIE's commitment to open-access science, he says, each author will be required to share any data necessary to replicate the study's findings. "Aside from the fact that we see this coming down the pipeline — funders like the NIH and others are starting to mandate this as a requirement when you submit grant proposals — this will allow others to better leverage and build on the work we publish," he says. It will encourage rigor, right, and reproducibility, as well as an enhanced process to help alleviate possibilities of plagiarism.

"I think this journal fits in a very large niche that hasn't been fulfilled by the community yet," says Roblyer. "A lot of these basic-science discoveries in clinical translation end up in journals outside our field that are run by for-profit publishers. I'd like to bring that research directly to our community. SPIE helps our biophotonics community by running conferences, by providing opportunities for leadership and mentorship. So rather than giving this research away, I say, let's keep this in-house — that's a major vision and goal of the journal. I hope that some of the most exciting discoveries in translational research show up in this journal over the next few years, and I'm pretty confident they will."

DANEET STEFFENS



Bringing brain imaging up to laser-speckle speed

The $75,000 SPIE-Franz Hillenkamp Postdoctoral Fellowship will fund the development of Simon Mahler's multi-channel brain-imaging device

It was a particular aspect of his doctoral work in nonlinear optics that led Simon Mahler to his current position in Changhuei Yang's Biophotonics Lab at Caltech. "For my PhD at the Weizmann Institute, I was studying the synchronization of coupled lasers," says Mahler. "Part of that was studying laser speckles so that I could generate a clean laser beam." If you want to synchronize a large group of lasers, he explains, they have to be of uniform phase, a key element for intensity modulation. "As a side project, I was studying laser speckles to improve the quality of the laser beams," says Mahler, "and somehow, while I was studying speckles, I discovered more and more about them, and that small project became bigger and bigger." By the end of his PhD in 2021, Mahler had spent nearly half of his time studying speckles in order to generate clean laser beams and manipulate them. "Then I found out that you can use speckles to image bio samples," he says. "And I thought, 'That sounds very interesting.'" That interest led to Mahler's pivot into biomedical optical imaging, combining photonics and biomedical engineering research; his role at Caltech with the lab's focus on brain imaging; and high-level recognition: In December, Mahler's project — designing a multi-channel helmet which utilizes near-infrared laser speckle imaging to non-invasively monitor cerebral blood flow in the human head across several locations simultaneously — garnered him the $75,000 SPIE-Franz Hillenkamp Postdoctoral Fellowship in Problem-Driven Biomedical Optics and Analytics, an annual award that supports interdisciplinary research, providing opportunities for translating new technologies into clinical practice for improving human health.

Simon Mahler, Caltech.

Yet another benefit to switching his path from fundamental to applied research was seeing the results of his work with more immediacy. "When you do fundamental research," Mahler says, "you often don't see the real-life application before a long time; when you do engineering or applied research, you see the outcome much more quickly, so you can really see how and why the application is useful. It has a more immediate impact."

At the moment, the immediate impact of his multi-channel laser device translates to observing the blood flow in brains of people who have suffered a traumatic brain injury from, say, a car accident or a sports-related fall. If the accident damaged part of their skull, that might have required a transparent implant to replace a broken or missing piece. "Right now, I have two subjects with transparent implants on one side of their brain," says Mahler. "I compare the way my laser device monitors blood flow through the implant and through the skull, looking to see if the device acts the same or different." This type of blood-flow imaging, he notes, is important because when it comes to surgery, having clear information about blood flow is critical. "I really enjoy working on this project because it's not only about being in the lab and building a device — it's not only my experiment," says Mahler. "We are also bringing people to the lab and scanning their brain, and I get to see if my device really works and *how* it works. It's pretty rewarding to see that my research can help people."

Interest in imaging brain blood flow is not new, and laser speckle imaging is just one technique alongside others such as MRI and ultrasound, but, as Mahler notes, this is a case of technology catching up to and advancing research. "I think the reason it became famous the last couple of years is because lasers can be made so cheaply now, and you can have such a small compact version. At the same time, cameras and detectors have advanced a lot because we use them every day, as example with our phones." These recent technological advancements allow researchers to apply laser imaging to the brain that simply wasn't possible previously, opening up exciting opportunities for biomedical engineers and researchers.

"It makes it pretty competitive too," says Mahler. "We are not the only ones working on this technology. But it's also interesting because you have such a wide choice of technology to explore — there are so many different types of lasers and detectors and cameras that you can build your own system and it still will be unique."

While his Hillenkamp fellowship provides financial support, Mahler envisions many other transformative outcomes. "SPIE is so active in helping to develop our area of research," he says. "I went to Photonics West last year and found out that I'm not alone; I found many other people using the same imaging technique, and I was really happy to see that. At the conference, we had a place to connect, to share our science, and to have ideas. This fellowship will help me to improve my network, and also to be part of the SPIE community." Another outcome, he says, will benefit the global field of brain imaging using laser techniques: "The fellowship will provide a higher profile of my work and, in turn, give more exposure to other research. I think science research is about sharing ideas with each other and making them work. If you're all alone, it's hard and sometimes impossible to succeed; if you are with people, whether you're collaborating or in competition, it drives you to engage, to work harder, and, ideally, to find new ways to apply your work."

DANEET STEFFENS

Apple's 'star power' heralds return to growth for AR — eventually

Analyst reports paint a mixed picture for the immediate future, while developers work towards mass production of novel microdisplay and optics technologies.

Jeonghun Ha, CTO of 2024 Prism Award finalist LetinAR, will present details of the Korean firm's "PinTILT" technology, including progress towards mass production of injection-molded plastic AR waveguides. This image shows Jorjin smart glasses that use LetinAR's optical technology. Image: LetinAR.

After what has been a difficult couple of years coming down from "peak Metaverse," the extended reality (XR) sector received a substantial shot in the arm in 2023 when Apple announced details of its forthcoming "Vision Pro." The launch of the potentially game-changing hardware is now imminent — although reported shortages of key optical components look set to limit shipment volumes for a while.

Even so, the wider market for XR is expected by one forecaster to enter a serious growth phase this year. In its June 2023 report, analyst firm CCS Insight was anticipating volume shipments of 9.8 million units in 2023 — a slightly lower figure than in both 2021 and 2017. For 2024 that total was expected to jump to a record-breaking 16.2 million, marking the start of a "hockey-stick" rise towards an anticipated 75 million shipments — and a value of $40 billion — in 2027.

CCS' Leo Gebbie, the firm's principal analyst for connected devices, wrote following Apple's initial announcement of the high-end headset: "Apple has the star power to reignite excitement about a technology that has struggled in recent times. A foray into virtual and mixed reality would be the biggest shift in the company's strategic direction for years and a huge statement of intent to explore the next generation of computing."

But Gebbie also pointed out that the launch was unlikely to move the needle too much in terms of global unit shipments of XR devices. "Apple's repeated its classic trick of taking a technology and making it simple, streamlined and accessible for everyone to use. But we have to remember that this really isn't a mass market consumer device yet. It's an ultra-premium, experimental device aimed at businesses, developers, and enthusiasts, and it may be years before an Apple headset truly hits the mainstream."

Rival analyst Omdia appears to agree about Apple, although its more recent outlook — specifically for the consumer VR sub-market — does not sound so promising. In December it predicted only "marginal" growth through 2028, pointing out: "Headset sales suffered a 24% decline in 2023, plummeting to 7.7 million units from 10.1 million in 2022. Further declines of 13% are expected in both 2024 and 2025, marking a challenging period for the VR industry before a projected resurgence from 2026."

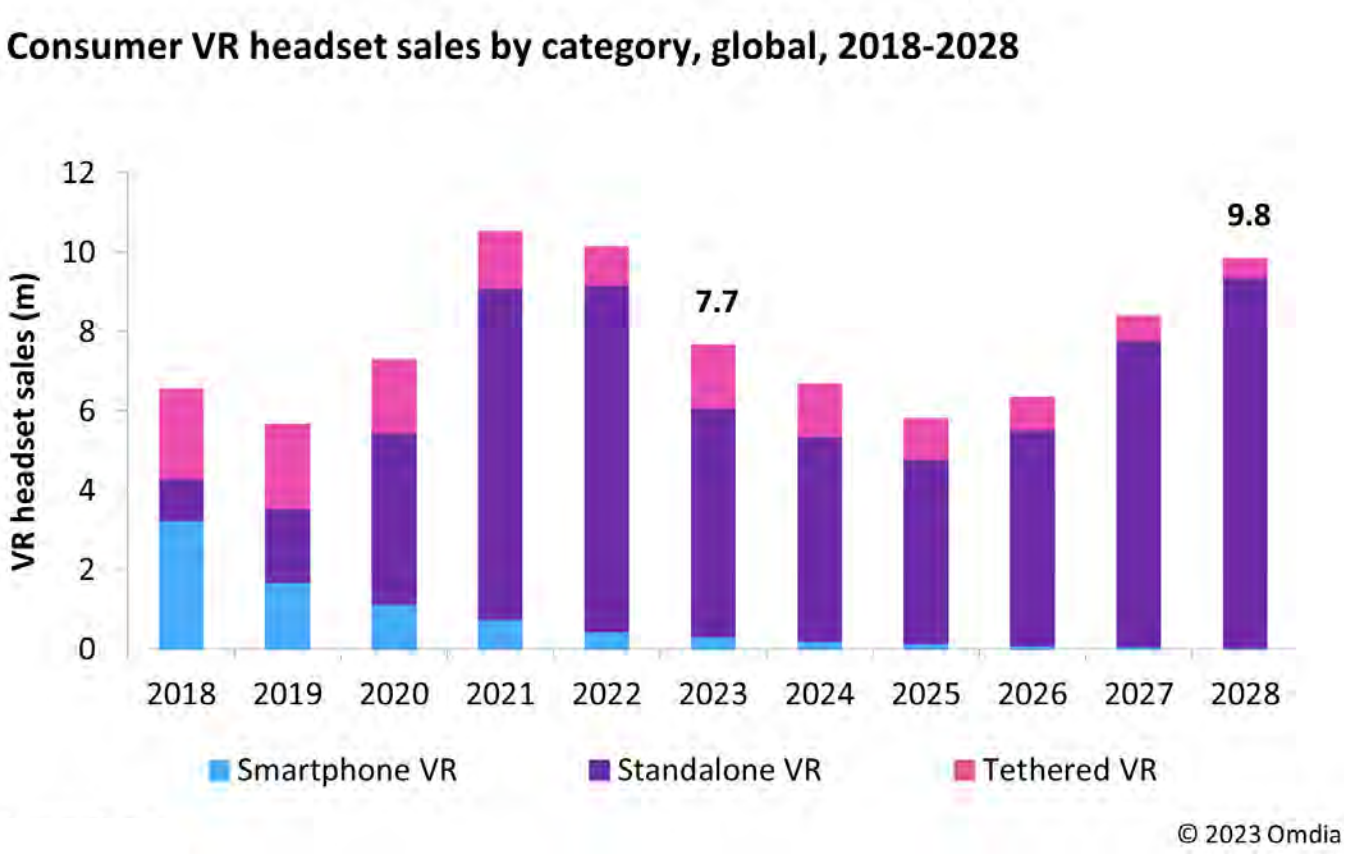
Omdia's senior principal analyst George Jijiashvili added: "Amidst tech giants refocusing on AI, the lack of substantial investments in VR (apart from Meta) is set to result in a slump for the industry over the next two years — that's despite Apple Vision Pro launching in 2024, which will have a limited impact until at least 2026."

The Vision Pro certainly features some optical innovations — notably twin micro-OLED displays featuring 23 million pixels, Zeiss prescription inserts, and customized catadioptric lenses. But reported difficulties with the manufacturing yield of the displays are expected to restrict the number of units Apple can deliver in the first year of availability, possibly informing Omdia's hesitant outlook.

A key part of the problem is that only a handful of companies are able to produce micro-OLED displays. Aside from Sony, key contract manufacturer Luxshare is one of the few to have volume capability, with BOE Technology and SeeYa also rumored to have engaged with Apple.

Among the others is Grenoble, France, headquartered Microoled, which last year revealed a EUR21 million funding round led by Jolt Capital. Spun out from nearby CEA-Leti back in 2007, Microoled says it is perfectly positioned to cater to the various needs of what it calls "light AR" applications. The company offers a range of tiny but high-resolution AMOLED displays with power demands as low as 1mW.

The latest financing round is intended to support scaling of dual-use technologies, including the development of full-color, high luminance displays, as well as expand manufacturing capabilities in Grenoble.



The market for micro-LEDs will grow from an almost negligible total today (2023) to just over 50 million units per year by 2030. Source: Omdia.

GaN options

Another Apple-related development has seen its long-time partner and iPhone manufacturer Foxconn agree to a strategic collaboration with UK-based micro-LED startup Porotech. The University of Cambridge spin-out has a unique approach to the technology, thanks to its development of porous gallium nitride (GaN) semiconductor material that can be engineered on silicon to emit light across the visible spectrum. If that can be scaled up to mass production, the result may be a game-changer for micro-LED displays, whose high costs mean they have so far only appeared in very high-end TVs from the likes of Samsung and a handful of other products.

In its December announcement of the Porotech deal, Foxconn said: "The micro-LED has great potential for AR applications, but at the same time is

quite challenging. It involves multiple disciplines including semiconductor wafer manufacturing, hybrid bonding, IC design, optoelectronics, quantum physics, and optics. Integration across these different fields is difficult and progress has been slow. In the past, no single company possesses such a big portfolio of expertise.

Scale-up plans

"With this partnership, we expect to expedite the research and productization of micro-LED technology and push the AR application to a new era. Foxconn's strength in supply chain management is also expected to contribute at the mass production stage."

Attendees at the SPIE AR|VR|MR conference may hear more about plans for scale-up during Porotech's presentation on the firm's "DynamicPixelTuning" technology for microdisplays, while the company is also a Prism Awards finalist in the AR/VR/MR category.

One of the other XR displays startups to secure significant investment in 2023 was Mojo Vision, which raised nearly $44 million in mass production, implying that there were still some hurdles to overcome before micro-LEDs emerge from a few high-end niche applications. Both Mojo and Digilens are presenting at this year's AR|VR|MR conference.

According to yet another recent forecast, this time from IDTechX analyst Sam Dale, the XR display market will grow to a value of $4.6 billion over the next decade, while the equivalent future figure for XR optics is put at $5.1 billion.

"The specialized optics required by AR headsets have so far proved to be a stumbling block for the industry," wrote Dale in a November 2023 report. "In VR headsets, there is rapidly growing usage of unconventional lens types to solve the deficiencies of the Fresnel lens architectures that previously dominated. For AR, an industry of specialized, often fabless, optics firms has sprung up, offering a diverse range of technologies to headset manufacturers that are just as active in this space."

A quick glance at either Dale's report or the SPIE AR|VR|MR program appears to confirm that view, revealing just how many different

Slated to launch February 2nd, Apple's VisionPro may help re-energise the AR sector, although reported shortages of its twin micro-OLED displays are expected to limit the headset's impact on the overall market for some time. Photo: Apple.

support of its quantum-dot micro-LEDs. Like Prorotech, Mojo uses GaN material to deliver red, green, and blue light, with quantum dots providing the wavelength conversion.

Mojo is also working with waveguide optics developer DigiLens to integrate its micro-LEDs with surface relief gratings — something expected to "raise the bar" on display performance and efficiency, and to move AR glasses closer to volume production for consumer applications.

Mojo quotes Omdia figures from a different report suggesting that the market for micro-LEDs will grow from an almost negligible total today to just over 50 million units per year by 2030. Omdia reported that, so far, only a handful of companies are capable of optics technologies are being pursued, from metamaterials and micromirror arrays to liquid crystals and holographic combiners. They include Digilens and Korea's LetinAR — the two finalists competing in the same category as Porotech in this year's Prism Awards.

LetinAR's "PinTILT" approach integrates the pupil expansion and pupil forming function into a unified design, and is said to overcome limitations in thickness, size, and power consumption, while Digilens was shortlisted for its "Argo" smart glasses for enterprise applications. Porotech and LetinAR are also among more than 60 companies taking part in the AR|VR|MR Expo in Moscone West this week.

MIKE HATCHER

Hot Topics to showcase the latest in biophotonics

Ways to capture data sets that feature higher spatial and temporal resolution are also providing richer information content, SPIE's BiOS Hot Topics hosts say. To that end, they have selected a blue-ribbon line-up for the 2024 Photonics West program.

Topics will range from optical microscopy to OCT to photoacoustic imaging and diffuse optics. Not to mention some intravital spectroscopy and Raman spectroscopy at super-resolution. And even Brillouin spectroscopy.

In all, it's "just amazing," according to the co-moderator of the session, Sergio Fantini, interim chair of biomedical engineering at Tufts University and a professor there since 1999.

In his own research, Fantini pursues diffuse optical imaging of tissue, with a focus on the study of cerebral hemodynamics and functional imaging of the brain. Fantini, along with Paola Taroni of the Politecnico di Milano and Marilyn Gorsuch of SPIE, selected speakers who could represent the cutting edge in their fields. They gathered input from the chairs of all the BiOS conferences, nearly 50 of them.

"We tried to have diversity in all senses, by topics, gender, geography, and career stage," Fantini said, putting excitement and wide-ranging scope on display.

"What's striking about this program is that in just about two hours you can get a snapshot of the entire biomedical optics field," he said. "Besides 'wide-ranging', this session will be fast-paced and inspiring."

Taroni agreed, adding that this lineup "goes beyond the specific field of research of each of us but at the same time would present some exciting and unexpected advancement, even in our own field."

Attendees will learn about new clinical applications, methods of surgical guidance, diagnostic techniques, and dynamic characterization of DNA nanostructures and spatially targeted RNA sequencing.

Fantini predicted strong interest in a common theme across the eight listed talks and two special presentations from SPIE award recipients: "It's the quest for higher resolution, and for richer temporal and spatial information content of the data collected with various techniques."

Philip Tinnefeld is working on the use of graphene in energy transfer processes. Credit: LMU Munich.

Speakers and topics

Listed speakers include **Paul Beard** of University College London, who is speaking on "High Resolution Photoacoustic Imaging in Humans."

Beard is "really a pioneer in the field of photoacoustic imaging and tomography," Taroni said. "His work covers different technical aspects of photoacoustics and contributes to the development of this technology, making high spatial resolution available for real applications in humans."

"He has a wonderful track record in photoacoustic imaging," Fantini added. "His methods employ Fabry-Perot ultrasound sensors, and keep in mind: these sensors can out-perform conventional piezoelectric ultra-sound sensors."

Ben Vakoc, of the Wellman Center, at Massachusetts General Hospital and Harvard Medical School: "Circular Ranging for 4-D Intraoperative OCT."

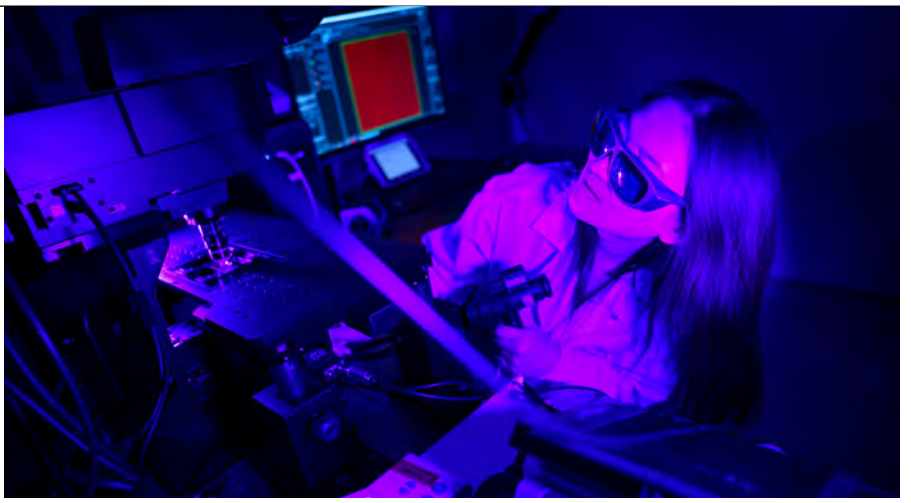
Circular ranging in OCT involves acquiring images from multiple angles, providing enhanced 3D visualization of tissues. This implies complexity and high costs. Vakoc's work, Taroni said, aims at addressing those limitations for applications in intraoperative imaging.

He will talk about his new methods making use of a variant of Fourier-domain OCT, based on a time-stepped frequency comb source, which features a number of spectral lines. "This allows for 4-D real-time tomographic visualization of surgical interventions," Fantini said.

Michelle Digman, University of California Irvine: "Single-Cell Organelle Phenotyping."

Digman investigates the spatial topology of organelles in cancer cells, seeking insights into cellular processes, with special attention to understanding breast cancer and more generally cancer biology.

Digman, Fantini said, "is an outstanding researcher in biomedical



Lingyan Shi has developed a super-resolution approach using stimulated Raman scattering. Credit: University of California San Diego.

fluorescence imaging." Her approach here is to use environment-sensitive probes and hyperspectral imaging for single cell biological studies to characterize their metabolic state. "This work has high significance," he said, "for example in studies of the role of cellular metabolic states in cancer metastasis, resistance to chemotherapy, and tumor recurrence."

Philip Tinnefeld, at LMU Munich, Germany: "Beyond FRET: Graphene Energy Transfer for Single-Molecule Biophysics and Super Resolution."

"Working beyond conventional FRET, Tinnefeld has explored the use of graphene in energy transfer processes, which has implications in various fields, including high resolution biosensing and DNA nanotechnology, which makes his work specially interesting as a hot topic," Taroni said.

Tinnefeld's work in biophysics illustrates a common theme in the Hot Topics list: enhanced spatial localization and resolution. "And this is at the single molecule level," Fantini said.

Tinnefeld will present his "novel dynamic structural biology tool that we term GETvNA (Graphene Energy Transfer with vertical Nucleic Acids). It helps to determine angles of nucleic acids on single molecules as well as to visualize the movement of proteins on DNA with single nucleotide resolution."

His Hot Topics title: "Beyond FRET," illustrates his aim to go beyond the standard Förster Resonance Energy Transfer approaches, Fantini said. He aims to achieve super-resolution microscopy in three dimensions, Fantini said, using the energy transfer between a dye and the graphene layer to achieve detailed axial localization, better than 2 nm.

The concept of Image-seq (Image-guided single cell capturing and RNA sequencing). Courtesy of Charles Lin.

Charles Lin, at Boston's Massachusetts General Hospital, Center for Systems Biology, and at Harvard: "Image-seq that combines intravital microscopy with single-cell sequencing."

"The combination of the two techniques allows one not only to investigate the properties of single cells but also to know exactly where each investigated cell is located in tissue. Tissue function depends on cellular organization. So, preserving the spatial information on the investigated cells is a key aspect," Taroni said.

"It's a cool technique for image-guided cell isolation," Fantini added. It is based on a multiphoton microscope for combined imaging and tissue ablation, the latter to create access for a micropipette to aspirate a cell for which spatial information is known, Fantini said. This technique allows for RNA sequencing of a single targeted cell.

Lingyan Shi, of University of California San Diego. "Super-Resolution Using Raman Spectroscopy."

continued on page 12

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Hot Topics

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Shi is the most junior member of the Hot Topics group of speakers, Fantini said, "and she is definitely a rising star in the biophotonics field." She will talk about her super-resolution approach using stimulated Raman scattering.

Her approach provides chemical imaging of metabolic dynamics that, in combination with fluorescence spectroscopy, allows for studying the nanoscopic distribution of proteins and lipids at the cellular and subcellular levels.

She proposes a multimodal approach to microscopy with super resolution. Various techniques (stimulated Raman scattering, multiphoton fluorescence, second harmonic generation) can provide complementary pieces of information on single cells and tissues, visualizing macromolecules, proteins and lipids, with a quantitative and label-free approach. "This can really be helpful in the investigation of metabolic changes in aging and pathologic processes," Taroni said.

Giuliano Scarcelli, of the University of Maryland. Credit: U Maryland.

Giuliano Scarcelli, University of Maryland: "Multiplexed Brillouin Microscopy."

Brillouin microscopy is a type of optical elastography that is based on interactions between light and thermal acoustic phonons. "This is a field not as crowded as others that are represented in the Hot Topics session," Fantini said, but he termed Scarcelli's work an exciting area that opens a new window in the mechanical characterization of biological samples.

Stiffness variations are associated with various diseases (including cancer). Scarcelli's work aims at investigating those mechanical properties of tissue. His multiplexed approach makes Brillouin microscopy much faster, Taroni said, and allows the characterization of the sample with significantly lower phototoxicity and damage.

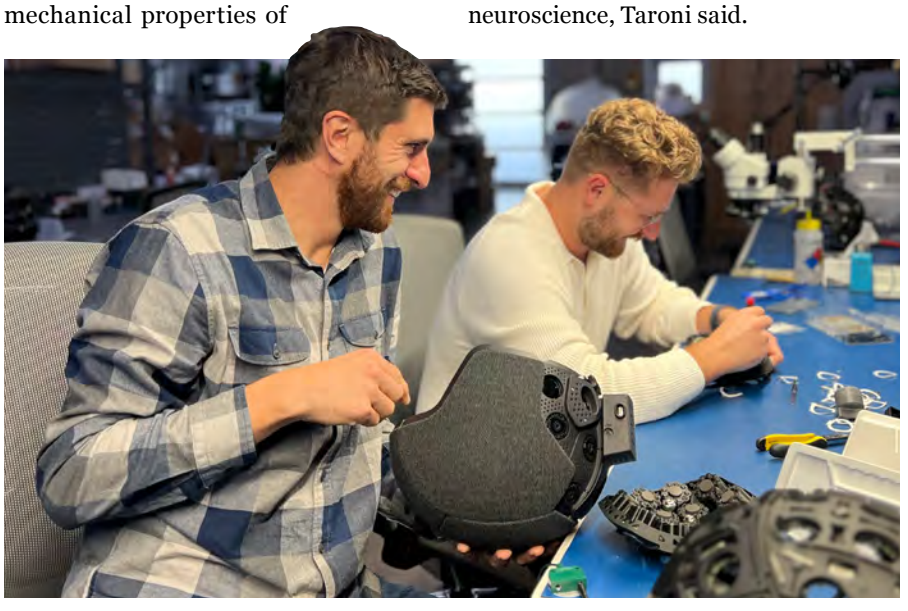
"Scarcelli has been a very active and innovative researcher in the field for many years," Fantini said. The goal, he added, has been "improve acquisition speed using a multiplexed dual-line illumination approach."

Ryan Field, CEO of Kernel, a company based in Culver City, California. This speaker was nominated by the editor-in-chief of SPIE's *Journal of Biomedical Optics,* Brian Pogue, based on having received the highest number of citations among articles published in the journal in 2022. "That shows that there is a lot of interest in the time-domain (TD), diffuse optics brain imaging system that Kernel, his company, is developing," Fantini said.

This year the company has produced its second-generation instrument, Flow2.

"Flow2 is our production grade TD-fNIRS system and the next generation of our prototype, Flow1," the company said. Flow2 has nearly twice as many channels and provides even higher sensitivity and dynamic range, all while using less power. The Flow2 headset has also been redesigned for superior fit, Kernel said, and maintains better coupling in the presence of hair, and provides a more uniform image of functional brain activity across the whole head.

As the company says, with Flow2 they aim at producing "the world's most comprehensive portfolio of brain-based biomarkers," which could open new paths for neuroscience, Taroni said.



Ryan Field, left, in the lab working with the novel Flow2 helmet, which provides a uniform image of functional brain activity across the entire head. Credit: Kernel.

SPIE President Jennifer Barton assesses the Hot Topics talks

Photonics West's 2024 BiOS Hot Topics talks will be far ranging, reflecting both basic technology advances and how they are being adopted into clinical use. That notion came from Jennifer Kehlet Barton, the 2024 SPIE President and director of the BIO5 Institute at the University of Arizona. She said she was eager to hear the lineup and pick up on a few pervasive sub-themes.

From circular ranging to multiplexed Brillouin microscopy, one consistent theme running through all the talks, she said, will be "the big one" — AI and ML, artificial intelligence and machine learning.

Barton commented, "You don't hear talk of 'AI for super resolution'. It's kind of a given now, over just the last couple of years. It's gotten to the point where those tools are actually useful. It used to be that they would maybe underperform compared to conventional image processing algorithms, but now you can get 10 percentage points better, which in image processing is huge."

And they are easy to apply. "There's published algorithms out that that you don't have to be an expert to use the tool."

Another element that has made these algorithms so useful in all the Hot Topics areas is the idea of cross training. "One of the problems in optical imaging is that you don't have millions of images, like you do have in CT or MRI, because these aren't big standardized machines that are available in every hospital yet," she said.

Now, Maryellen Giger of the University of Chicago and a Past-President of SPIE is in charge of a nationwide initiative to curate those images and make them more available to anybody, Barton added.

Near-infrared spectroscopy is an emerging technology with lots of FDA-approved systems," Barton added. "People are using it more and more, but there's not millions of data points out there for it."

The point of cross training is that we can get an AI algorithm and train it on one set of data, say CT images. "That algorithm is pretty smart. It's like a kindergartner who can't quite do calculus yet, but knows one plus one equals two. That's actually a long ways toward getting more specialized."

One could take pre-trained AI and train it on hundreds or thousands of optical images, using, say, CT imaging. "Then we can figure out how to transfer that knowledge so that AI can be useful for optical imaging," Barton said. "You don't tell it what to look for, you just give it enough examples that it figures it out itself."

Jennifer Barton holds the falloposcope, a sub-mm diameter endoscope capable of imaging the fallopian tubes. The device contains multispectral fluorescence imaging and optical coherence tomography, with the goal of early detection of ovarian cancer. Credit: Deanna Sanchez, University of Arizona.

Optical imaging, Barton said, is getting to a point where researchers are beyond saying, "Oh wow. Look at what a wonderful image I took. We are getting to a point where we make it actually useful for a clinical problem."

For example, Ben Vakos, who talks about circular ranging for 4D interoperative OCT — 4D as three dimensions in space and one in time, will need real-time feedback for something that operates over larger ranges of space. "Usually with OCT we talk about millimeters. Well, you don't do operations in millimeters, you operate in large spaces — inches. That's huge."

"If you have high resolution, you have a small field of view. To have something that has high resolution over large field of view is really hard to do. But that's what you need for interoperative imaging for actual clinical, hospital work. To make it useful to the surgeon in the operating room, you have to break that field of view/resolution dependency."

Ben Vakos's circular ranging idea will help with that, Barton said.

Barton was also looking forward to learning about Brillouin microscopy in the talk by Giuliano Scarcalli of the University of Maryland. "It's an area where you have a weak signal, so we're going to have to figure out its place," Barton said. "It's at the opposite end of the spectrum. Things like OCT, that are moving in to clinical usefulness, they are just going to start getting incorporated into surgical tools."

"With Brillouin microscopy, they are still finding the space where they are going to provide the most value to the community. I am going to learn about it," she added.

And Charles Lin, she said, "always does the most amazing cutting edge work in microscopy." He works on intravital microscopy, on a living system, "not just a set of pickled cells on slides."

"I am looking forward to seeing what amazing work he's done next."

FORD BURKHART

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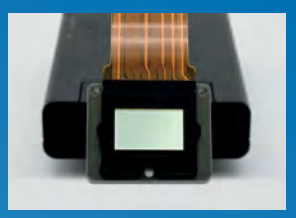

PLUTO-2.1 Spatial Light Modulator

New version optimized for 1700 - 2500 nm (Short Wavelength Infrared).

ERIS analog SLM driver update

The updated driver for the ERIS SLM offers real 120 Hz operation. Refresh rates for both, input frames via the HDMI graphics interface and the output on the phase SLM display are boosted to 120 Hz.

GAEA Spatial Light Modulator driver update

The updated driver for the 4K resolution SLM enables addressing of 3 x 8 bit within a frame (180 Hz) for Color Field Sequential (CFS) operation.

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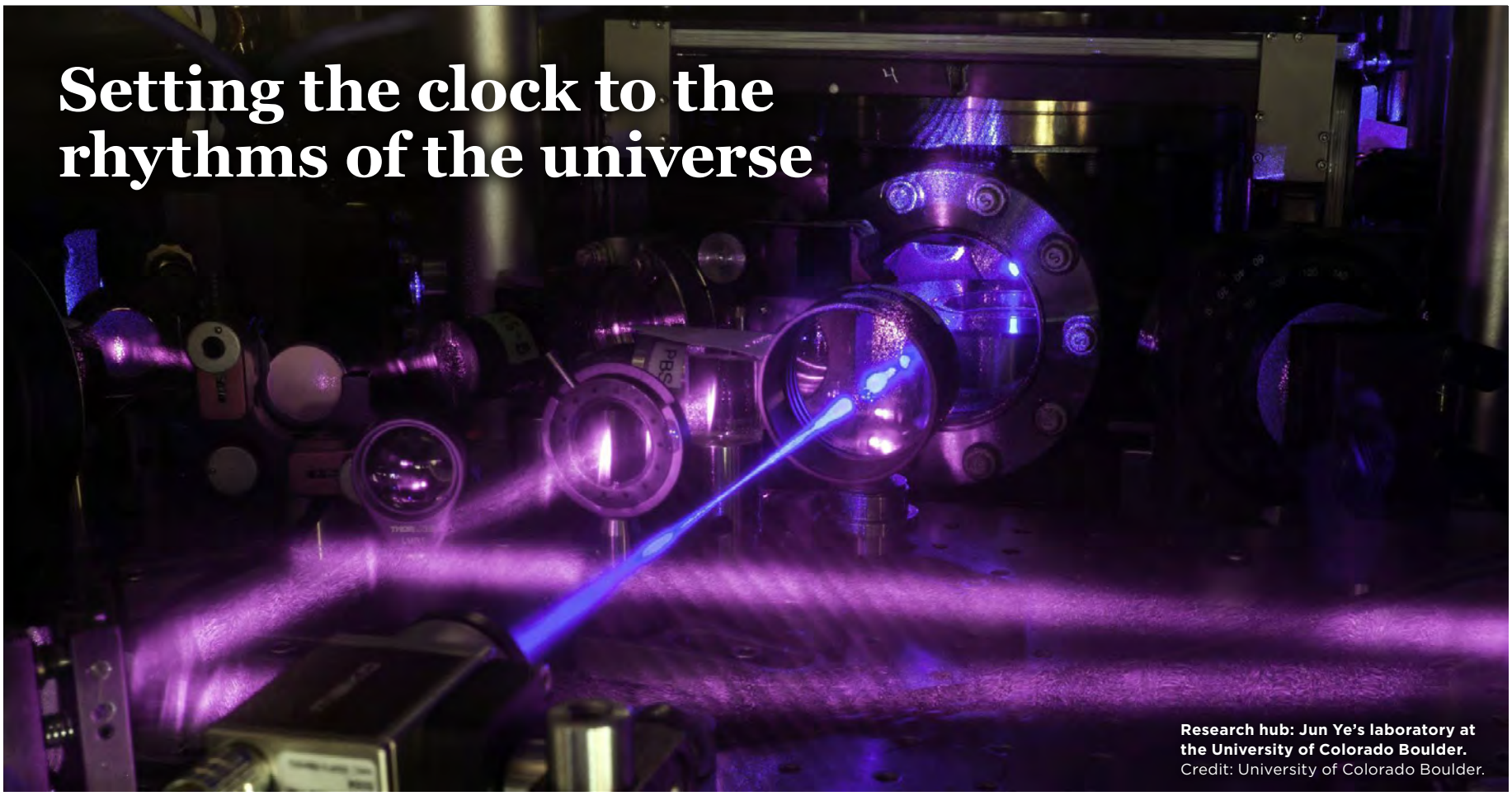
Setting the clock to the rhythms of the universe



Research hub: Jun Ye's laboratory at the University of Colorado Boulder. Credit: University of Colorado Boulder.

Jun Ye's Quantum West Plenary promises to set out the wide-ranging benefits to science, engineering, and society of ever more accurate timekeeping.

If you ever find yourself needing to know the time, there is no better person on the planet to ask than Jun Ye. A physicist working at JILA, a joint research institute of the University of Colorado and the National Institute of Standards and Technology (NIST), Ye's group recently built the world's most advanced and precise clock.

The device is so accurate that it would neither gain nor lose a second over the age of the universe. It is so precise that, because of the connection between space and time on Earth, if you move it by a millimeter, you can tell the time has changed. "This sounds like science fiction," adds Ye. "But the clock accuracy is so good now, we can tell within 1 cm where we are with respect to the Earth's gravitational potential, thanks to Einstein's general relativity that connects time and gravitational potential."

The clock is the culmination of a career developing and refining precise measurement tools with an array of talented scientists. Ye earned his Master's at the University of New Mexico while also studying in the renowned quantum optics group led by quantum optics theorist (and fellow Quantum West Plenary speaker) Marlan Scully. In the mid-1990s, Ye's PhD advisor at JILA was John 'Jan' Hall. Hall joined NIST in 1961, just after the birth of the laser, and spent most of the rest of his career making lasers increasingly stable. Under Hall's mentorship, Ye developed the world's most sensitive instrument for measuring the wavelengths and quantities of light absorbed by different molecules.

After a two-year postdoctoral stint in trailblazing quantum optics experimentalist Jeff Kimble's laboratory at the California Institute of Technology, where he developed an optical system to trap individual atoms in a small cavity, Ye was lured back to JILA in 1999, where Hall was still working. "Jan was considering retirement," recalls Ye. "And so he basically said, 'Well, since you're coming back, maybe you can have my lab'."

But Hall wasn't quite done yet. He had recently co-developed a new technology called the optical frequency comb, a type of laser that produces a series of pulses with a very precise delay between them whose spectrum, zoomed in, looks like a discrete rainbow, with sharp spikes of the different colors at precise, evenly spaced intervals — much like the teeth of a comb (hence the name).

The comb is an extremely accurate ruler for measuring the frequencies of light waves, and Hall was eager to explore its applications. For four years, Ye worked with Hall and colleagues on developing the optical frequency comb and utilizing it in a broad range of spectroscopy applications. But when Hall finally officially retired in 2003 — two years before receiving a share of the 2005 Nobel Prize in Physics for his optical frequency comb work — Ye sought a new challenge.

Combining his experience of trapping and cooling atoms with his knowledge of optical frequency combs, Ye wanted to build optical atomic clocks with laser-cooled strontium atoms (where the tick of the clock comes from the atoms' electrons undergoing optical transitions between two stable orbitals) in order to surpass the accuracy of incumbent atomic clocks. The technique turned out to be a great success. "It has been a very exciting journey for the last 20 years where we have been able to improve optical atomic clock precision by five orders of magnitude," Ye says.

Ye's Plenary talk at Quantum West could easily focus on the many groundbreaking discoveries he and his collaborators have made to reach this exquisite level of timekeeping accuracy. But he feels this would be a wasted opportunity. "I want to focus on what are we doing right now," he says. "The atomic clock is the core of a quantum revolution where we can perform very precise quantum state engineering, bring many atoms together to work as a team of

continued on page 16

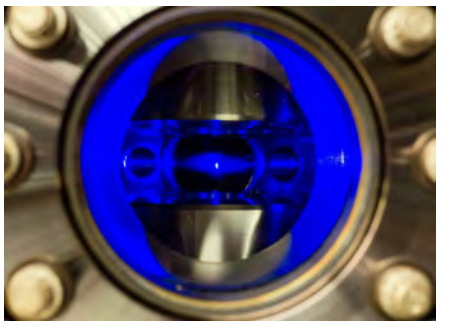
Jun Ye, Professor Adjoint at the University of Colorado Boulder and a JILA Fellow. He says of his work: "The atomic clock is at the the core of a quantum revolution." Credit: University of Colorado Boulder.

Quantum West continued from page 15

quantum particles."

So far, Ye's group has brought together tens of thousands of strontium atoms and controlled their interaction at the quantum level to build extremely precise optical atomic clocks. His current work aims to add to the number of atoms in these systems significantly. "We want to scale the systems up to 1 million atoms. We will need to understand all the intricacy of atomic interactions in a many-body setting and, in parallel, we may need to now put entanglement into the quantum systems so that we can hide away some of the quantum noise," he says. "And that's really where quantum information science is heading — can we really build a system with so many quantum particles working together, keeping their entanglement, keeping their quantum coherence to use this to take a measurement or process information?"

In one sense then, Ye's clocks are like microscopes peering down into the quantum world and revealing all sorts of important insights for various applied quantum fields, like quantum information processing, quantum communication, and quantum sensing. In another sense, the clocks are like telescopes. "We want to see how far we can push the clock precision to the next two orders of magnitude or better because then we can start to measure the gravitational effect across a quantum mechanical wave function," Ye explains. "And that happens to also be the point where you can use the clock itself to listen to gravitational waves, using time to directly detect these spacetime ripples."



Optical setup in Jun Ye's laboratory at the University of Colorado Boulder. Credit: University of Colorado Boulder.

Perhaps the most exciting role for atomic clocks in the coming decade will be as probes of the fundamental nature of the universe.

But perhaps the most exciting role for atomic clocks in the coming decade will be as probes of the fundamental nature of the universe. "In the end, it's the spacetime fabric that the clocks are measuring, but you need quantum physics to make those clocks," says Ye. Therefore, the clocks are like a bridge between the macroscopic world governed by Einstein's theory of general relativity and the microscopic world governed by quantum mechanics. With sufficient precision, this could mean atomic clocks play a pivotal role in unmasking the nature of dark matter, challenging Einstein's conception of determinism in motion, and finally understanding the connection between, and perhaps even eventually reconciling,

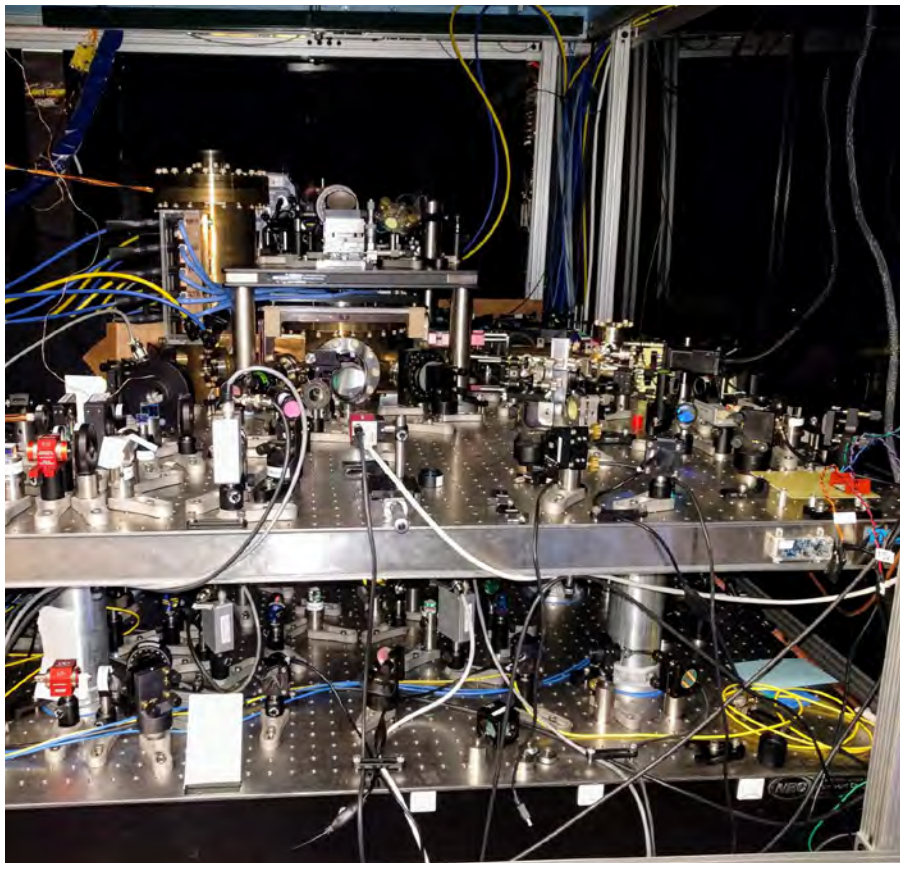
Work in progress: Ye's group has brought together tens of thousands of strontium atoms and controlled their interaction at the quantum level to enable extremely precise optical atomic clocks. Credit: University of Colorado Boulder.

our currently incompatible theories of the macroscopic and microscopic worlds.

To realize this potential, Ye's atomic clocks — at present, consisting of myriad mirrors, miniature lenses, optoelectronic devices, and lasers arranged on a 4 x 12 ft optical table — need to be made more practical so that they can be used in the field and eventually space. And to do this will require innovations in miniaturizing the clocks' components. "The engineering itself is going to require a lot of creativity and novel ideas," Ye says. "How do we use integrated photonics to shrink the system to a much smaller size? There will be a lot of interesting science and technology coming out of those efforts." Ye hopes to connect with experts in integrated photonics at Photonics West who can help him make miniaturized optical atomic clocks a reality.

And, although cautious of making predictions, knowing the talent that resides within the scientific community makes Ye optimistic that the necessary precision, accuracy, and portability will be achieved to realize optical atomic clocks' full potential in the next 5–10 years. "Past performance cannot guarantee future success, but let me just say that over the last five years, we achieved a factor of nearly 100 accuracy improvement," he says. "It may take a lot of effort, we may need to develop another new interesting technology, and there will be surprises (that I know for sure), but I don't see any fundamental limiting factor for why we cannot achieve another factor of 100," he says.

BEN SKUSE



Research hub: Jun Ye's laboratory at the University of Colorado Boulder. Credit: University of Colorado Boulder.

UK aims for global reach with QKD security and future quantum networks

Inward investment from key player Toshiba, satellite development with Singapore, and Nu Quantum's Cisco collaboration all support "Moonshot" mission to establish and scale quantum links.

How well is the UK commercializing its advanced quantum research and expertise? That was the tricky question posed by the House of Commons Science, Innovation and Technology Committee in a series of hearings during 2023.

As the MPs on that committee soon discovered, there's no straightforward answer: quantum technologies remain at an early stage of development around the world, although the UK's early move to fund them does appear to have established key elements of a domestic supply chain in support of the nascent industry.

On the very same day that the committee last sat, the UK government announced five Moonshot-style "missions" to be targeted under its National Quantum Strategy — covering efforts dedicated to computing, sensing, medical imaging, navigation, and networking.

"Mission 2" centers on quantum networks. "By 2035, the UK will have deployed the world's most advanced quantum network at scale, pioneering the future quantum internet," is the headline goal. "The opportunities are global and the UK will work with at least five other countries to collaborate on developing underpinning technologies and connectivity with international quantum networks, including through satellite links," stated a policy paper from the Department for Science, Innovation, and Technology (DSIT). "The UK will also take a leadership role in developing quantum networking standards."

With national and international networks on the agenda, enabled in part by satellite connections, the ultimate goal is for the UK to have the capability to send quantum information locally and globally, by 2035. "This will be 'year zero' for what will become known as the quantum internet," proclaimed DSIT.

So how are we getting on? An indication of the progress being made came shortly before that announcement, at the latest iteration of the UK National Quantum Technologies Showcase, an event that has grown massively since its 2015 inception. Opening the event, then science minister George Freeman — who has since resigned and been replaced by Andrew Griffith — highlighted how quantum technology officially now sits alongside AI, semiconductors, engineering biology, and telecommunications as one of five critical technologies regarded as key to the UK's prosperity and security over the next decade.

That recognition had already seen the quantum sector awarded its £2.5 billion decadal funding commitment, but unlike the other four technologies there is little certainty about the size, timing, or precise nature of the market opportunities awaiting computers, sensors, networks, or imaging techniques directly exploiting quantum phenomena.

Held at the larger venue of the Business Design Centre for the first time, the UK Quantum Technology Showcase took place in November 2023, with the UK government outlining five quantum "missions" shortly afterwards. Photo: UKRI.

Toshiba invests big

But there are some clues. Freeman highlighted Toshiba's £20 million investment in quantum key distribution (QKD) encryption technology as the most significant development in the UK's quantum sector in 2023. According to the September announcement, the move immediately created 30 new jobs at Toshiba Europe's Cambridge Science Park facility, where the Japanese technology giant has been working on quantum cryptography since 1999. Citing research suggesting that the QKD market could be worth more than $3 billion by 2028, Toshiba said that its new Quantum Technology Centre would manufacture QKD systems, and be a "fully commercialized business" operating under its Digital Solutions unit. "Commercialization of QKD put in the hands of businesses throughout the UK would represent a big step forward in realizing the UK's ten-year vision to become a leading quantum-enabled economy and science and technology superpower," stated Toshiba at the time.

Part of the reason for its UK investment is a long-standing partnership with telecoms giant BT, which has already seen QKD deployed in London and tested by the global banking group HSBC. That collaboration has resulted in the quantum-secure transmission of test data over fiber-optic cables connecting HSBC's global headquarters in Canary Wharf with a data center 62km away.

Speaking during the most recent UK Showcase, HSBC's Philip Intallura said that the bank saw the effort as a relatively small, low-risk investment in a technology that may or may not turn out to be critical in the future, depending on whether future quantum computers are able to "crack" conventional cryptography systems used to secure everyday transactions. And while HSBC appears to be one of only a select few banks actively looking into quantum cryptography, Intallura said it was one area where regulation could eventually force widespread deployment.

Toshiba officials mark the official opening of the firm's new £20 million Quantum Technology Centre at the Cambridge Science Park, alongside UK business and trade minister Lord Johnson, and Hajime Hayashi, Japan's ambassador to the UK. Photo: Toshiba.

Free-space QKD

Toshiba's pioneering work has centered on QKD deployments over optical fiber, but as BT's Andrew Lord explained at the same event, applications in free-space optical communications both short — and long-range represent the next frontier. BT was a participant in the recently completed "AirQKD" project, funded via the UK's wider quantum program. With Lord as project manager, the three-year, £5.8 million effort aimed to demonstrate QKD over short to mid-range communications, with pilot demonstrations suitable for "last-mile" 5G deployment, and potential future use in autonomous vehicles that would rely on fully secure high-speed data connectivity.

According to Lord, AirQKD was largely successful. Project partner and Cambridge spin-out Nu Quantum played a major role developing novel single-photon sources and detectors suitable for free-space QKD, with further photonics-related involvement from the Fraunhofer Center for Applied Photonics (CAP) and Bay Photonics on system integration and packaging respectively. Pilot demonstrations on the roof of BT's Adastral Park research center and the University of Warwick's autonomous vehicle test track have provided proof of principle with a prototype setup, over free-space links extending to hundreds of meters.

Lord is confident that the approach can be advanced towards commercial requirements, telling delegates at the London Showcase: "[We] know how to cut cost by a factor of ten or more for ubiquitous systems, such as lamp-post connections." That future development

A rendered image showing how a future quantum networking rack from Nu Quantum may look. The Cambridge, UK, startup is working to develop the technology with Cisco, among others. Image: Nu Quantum.

would involve scaling the technology down to the level of the photonic integrated circuit (PIC), something that Lord thinks could be achieved within two years, while simultaneously improving reliability.

The unknown factor remains exactly how much future demand there will be for free-space QKD, precisely what the "sweet spot" will be in terms of required link distance, and whether there would be enough market pull to justify investing in PIC-scale development. "The jury is still out on how cheap [it needs to be]...but in principle free-space [QKD] is very powerful," Lord said.

The AirQKD success also seems to have proved significant for Nu Quantum, with the startup's announcement of £7 million in "pre-series A" investment led by Amadeus Capital coinciding with the London showcase event.

Nu Quantum, whose CEO and co-founder Carmen Palacios is a panellist in this week's Quantum West Business Summit, has also been involved at the other end of the free-space optical spectrum — at least in terms of distance — with quantum-encrypted satellite connections, under the Arqit-led £4.5 million project to create a UK sovereign capability in the manufacture of satellite QKD payloads. As Tim Spiller, director of the quantum communications "hub" hosted by the University of York, said at the London showcase, optical fiber is inherently distance-limiting when it comes to QKD because of the need for signal amplification. "If you need amplification then you're stuffed," he said, while a satellite payload offers the potential to launch a "trusted node."

UK Space lab prepares for lift-off

Recent satellite QKD developments were also discussed in London by David Pearson from RAL Space, the UK's national space laboratory. It has developed a system using a 780nm wavelength and a narrow beam to demonstrate space-ground connections. Longer-wavelength versions are likely in the future, with a view to improving atmospheric transmission.

RAL Space is also working on the "SPEQTRE" project — a collaboration with Singapore startup SpeQtral — to fly a satellite QKD testbed, with CubeSat testing anticipated this summer, and hopes for a launch later in the year. SpeQtral has also extended an existing collaboration with Toshiba, after the startup won a contract to build Singapore's "National Quantum-Safe Network Plus (NQSN+)" nationwide quantum-safe network alongside telecoms firm SPTel.

SpeQtral co-founder and CEO Lum Chune Yang said of the Toshiba collaboration: "This enhanced partnership is a significant milestone for SpeQtral, particularly in light of our involvement in the NQSN+ project.

"With SpeQtral's satellite QKD capabilities along with Toshiba's fiber QKD deployments, we eagerly anticipate the opportunities that this partnership will further unveil, and remain committed to pioneering state-of-the-art quantum solutions that safeguard Southeast Asia's digital future."

Toshiba's Shunsuke Okada added: "We are thrilled to take our partnership with SpeQtral to the next level, building on the foundation established a few years ago. We are committed to supporting businesses in the quantum-safe network market, beginning with NQSN+, across Singapore and Southeast Asia, with our advancing expertise and know-how."

Quantum networking

With QKD the most evidently commercial quantum application at this point, Spiller hinted at what may come next for quantum communications, in the form of distributed entanglement — going beyond encryption and key sharing to establish the kind of future network envisaged in the UK government's "mission 2." Achieving that will rely on some novel photonics — not least the wavelength conversion that may be required to connect light-based quantum computers and repeaters over optical fiber. "The quantum internet is on the horizon, [but] it's a long way away," Spiller said.

Moving towards that horizon is however the topic of another UK-funded research project, this time involving Nu Quantum and the telecoms giant Cisco. The £2 million "LYRA" effort, which began in October 2023 and runs for 18 months, is aiming to deliver a deployable prototype of a data center-compatible rack-mount 'quantum networking unit'.

"Nu Quantum is partnering with Cisco as the lead customer and end-user for the project," stated the startup, with Cisco committing to evaluation of the final prototype system at a new UK-based facility. "The aim is to move away from highly controlled and fragile laboratory experiments towards real-world deployment in more industrial and data-center like environments, where quantum computers will ultimately need to operate resiliently and at scale."

Supported via UKRI's small business research initiative (SBRI) competition, LYRA is aiming to deliver two separate 19-inch rack-mount modules, for system control and optical interfacing. "This modular architecture allows in-field upgrades to support different quantum computer modalities and alternative wavelengths," explains Nu Quantum. The solution also incorporates a new high-precision timing-architecture and digital control bus, allowing the system to easily scale to support a large cluster of quantum-compute nodes.

"It is increasingly recognised that fault-tolerant quantum computing can only be delivered by networking together tens to thousands of discrete quantum computing cores," added the firm. "Project LYRA will develop an engineering-led, field-deployable prototype of this critical infrastructure, leading to a future where quantum networking will be as essential to quantum computing as classical networking is to today's cloud and HPC environments."

Nu Quantum's management team, led by CEO and co-founder Carmen Palacios (third from left), alongside VP of IP, legal, and operations Sam Funnell (far left), VP of product Ed Wood, and VP of quantum Claire La Gall. Photo: Nu Quantum.

Ed Wood, the startup's VP of product, told *Show Daily* that aside from Cisco, the project involves companies working on two different approaches to quantum computing — superconducting and trapped-ion — as well as a data center provider, a large aerospace firm, and a leading tech multinational. "More parties are interested in joining the project," Wood added.

If all goes well, Nu Quantum will deliver a complete system comprising rack-mount control electronics (the control module) and optical assembly, including discrete single-photon detectors (the optical module). "The combination of the control module and optical module form a complete 'quantum networking unit'," Wood explained. "The optical module is wavelength-specific, it is produced typically to match the native emission wavelength of the ion or atom used as a communications qubit.

"This is required, as wavelength conversion is to be avoided where possible — it is a lossy process that will damage the overall performance of the system. But the modular nature of the system means that the control module can be retained and a new optical module at a new wavelength installed."

Circling back to the original question posed by that House of Commons committee, perhaps Toshiba is in the best position to provide an answer. "Efforts over the past few years to commercialize quantum computing marks a shift from pure R&D, taking what's been learned in the lab and applying it to real world commercial situations," said the firm at the official inauguration of its new Cambridge facility. The time has come to use these powerful technologies to protect our future data, suggests Okada. "The quantum era is not some distant future constrained to the walls of a research lab," he said. "It is here, and the technology is ready to safeguard the most sensitive of commercial data."

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A quantum leap for biophotonics

Conference exploring the use of quantum technologies in biology debuts at Photonics West.

Each year, BiOS kicks off Photonics West with conferences covering biophotonics and biomedical optics along with the BiOS Expo. The conference always has some of the largest sessions of the week and sets the stage for Photonics West. Looking to replicate the success of the tandem conference and expo, SPIE has added the Quantum West Expo to its young and growing Quantum West conference program, hoping to build a similarly robust program for the exciting and growing field of quantum.

Going one step further, SPIE is combining the two buzzing disciplines, quantum and biophotonics, into a new conference, *Quantum Effects and Measurement Techniques in Biology and Biophotonics,* running 27 to 30 January. From all indications, it's a program the community has eagerly awaited and a good sign of the increasing maturation of quantum technologies.

"We were overwhelmed by the response," says one of the conference chairs, Sergey Polyakov of the US National Institute of Standards and Technology (NIST), of the conference call for papers. For a new conference, 20 abstract submissions would be enough to put together a one-day program. "We had 50 or 60 submissions — and three days were not enough. We have expanded a little bit into a fourth day for the conference." Clarice Aiello of the Quantum Biology Tech (QuBiT), and Paige Derr of the US National Institutes of Health (NIH) are also conference chairs.

The field of "quantum biology" has emerged through theoretical and experimental progress over the past few decades with the development of quantum tools like quantum sensors. The conference will cover how these devices — among other modalities of quantum for biology — take advantage of nonclassical phenomena to deliver new measurement capabilities beyond what is achievable classically, and how they are being developed specifically for biological and biomedical applications. Many of these sensors are photonics-based or have an optical readout.

At the same time, the conference chairs note, quantum effects have been shown to play a defining role in relevant biological processes such as photosynthesis, spin-dependent chemical reactions, and enzymatic activity. The area of quantum-related biology and medicine is new and growing rapidly, attracting interest from both theorists and experimentalists and with huge commercial and therapeutic potential.

"We are really talking about two fields that are closely intertwined," says Polyakov. One part of quantum biology revolves around instrumentation and is a bit closer to fruition in terms of practical benefits like disease monitoring, diagnosis, and even treatment. "And the other part is really exploratory, fundamental research in biology. And while it remains fundamental for the time being, there is huge potential for the future."

Aiello adds, "even though quantum biology is not as developed, it's not just a basic science curiosity. There might be a few applications coming up, especially as we understand more."

Polyakov says, "there are several translational technologies, some of them I am proud to say have originated from NIST." For example, he says quantum technologies might be used to replace the very cold liquid helium needed in MRI to keep the magnetic current superconductive. Another example would be breathalyzers based on frequency comb technology. Last April, scientists at NIST and the University of Colorado, Boulder reported a new laser-based breathalyzer powered by quantum technology and artificial intelligence that can detect COVID-19 in real time with excellent accuracy. While frequency combs themselves are not exactly a quantum technology, "you need frequency combs for a lot of the quantum action," Polyakov says. "One technology pulls the other and becomes a driving force for something completely different."

In a commentary for the American Physical Society, Aiello wrote, "Quantum biology findings could enable the development of new drugs and of noninvasive therapeutic devices to heal the human body, as well as provide an opportunity to learn how nature builds its own quantum technologies."

One of the questions that quantum biology is trying to answer, Aiello says, "is, can quantum phenomena survive long enough in the wet, messy biological environment *for them to matter for biological function*? We're not talking about minutes. We're talking about nanoseconds to microseconds. I mean, nobody doubts that biologically relevant compounds can remain quantum for femtoseconds. But for some biological processes to incontestably rely on quantum mechanics, they would need to survive for a bit longer. For example, if birds truly sense the weak magnetic field of the Earth to migrate as proposed by quantum biologists, quantumness inside their cells should remain for almost a microsecond. This type of data has never been unambiguously proven or refuted in a single living cell."

The conference chairs say that the US National Quantum Initiative (NQI) has contributed to increased interest in quantum effects for and in biology. On the one hand, emerging quantum technologies offer unprecedented advantages for sensing. New quantum-enhanced measurement modalities are being harnessed for medicine and biotechnologies ("quantum for bio"). On the other hand, in-vitro bio compounds exhibit profound quantum effects. If these quantum effects survive in living cells, quantum mechanics might be used by biology for function ("quantum in bio").

On January 28, Derr will moderate a panel discussion, "Quantum science meets biology: Opportunities enabled by the National Quantum Initiative." The panel will feature key representatives from federal agencies tasked with implementing the NQI in areas where physics and biology interface.

Aiello, Derr, and Polyakov also credit SPIE for boosting quantum biology. "The impact for the future will go well beyond the talks here," Aiello says. "Having SPIE recognize and support the field helps these scientific communities form and grow in a sustainable way."

To get a sense of the conference highlights, the conference chairs recommend checking out the keynote papers, including, *Probing photosynthesis with single photons* by Birgitta Whaley, and *Quantum imaging of molecular vibrations* by Warwick P. Bowen. The plenary sessions on 29 January are also not to be missed: *Quantum science and atomic clocks* by Jun Ye, JILA; *Silicon colour centres* by Stephanie Simmons, Photonic Inc.; and *New quantum theory applications in biology* by Marlan O. Scully, Texas A&M University.

"I think it's important that we start thinking about quantum literacy," says Polyakov. By that he means taking knowledge of quantum beyond physicists to include, for example, bio-engineers and biochemists. "We want to get the message heard by the medical doctors and other bio professionals who frequent Photonics West. We will service this community as much as we can."

Running January 27 - 30, 2024, *Quantum Effects and Measurement Techniques in Biology and Biophotonics* features over 40 presentations and will be held in room 158 of the Moscone Center.

WILLIAM G. SCHULZ

(L-R) Conference chairs, Clarice Aiello of the Quantum Biology Tech, Sergey Polyakov of the US National Institute of Standards and Technology, and Paige Derr of the US National Institutes of Health.

A bold concept for 2024 from Hamamatsu

Visitors to the Vision Suite will "see the future of optics," say its developers.

Hamamatsu Photonics is a significant global developer and manufacturer of optical sensors, ranging from its photomultiplier tubes to electric light sources and other devices that are used in medical applications as well as in basic science. The company originated in Hamamatsu City, Japan, in 1948.

Show Daily interviews Dr. Stephanie Fullerton, Hamamatsu's Life Science Manager, responsible for camera and systems product development, marketing & communications at the company. Dr. Fullerton has more than 20 years of experience in the life science imaging industry, from technical sales to marketing strategy and product development.

Dr. Stephanie Fullerton, Hamamatsu's Life Science Manager, responsible for camera and systems product development, marketing & communications. Credit: Hamamatsu.

At Hamamatsu, she focuses on camera technology including the transition from CCDs to scientific CMOS and has worked on advanced imaging for PCR, DNA sequencing, whole slide scanning, light sheet, flow cytometry and super resolution. She graduated from the University of Rochester with a B.S. in biochemistry and has a Ph.D. from Duke University in neurobiology.

Show Daily: What is the 2024 message from Hamamatsu for Photonics West?

Stephanie Fullerton: That's a very relevant question. Every year at the show, we have displayed new products and presented various experts. This year, we are doing something different, which we call the Hamamatsu Vision Suite, in addition to our regular booth. In my mind, it will be something like the Chicago World's Fair, with big new concepts in science and industry on show. We will employ storytelling and seek to inspire visitors.

We are presenting new ideas in photonics like the massive photomultiplier tubes used in neutrino detection. And we will present our mini spectrometers, which are used in the following applications: photometry, cameras, optical components and analysis systems; environmental measurement; color measurement; and quality control in production lines.

SD: So what are differences between the regular booth and the Vision Suite?

SF: For our regular booth at Photonics West, all our products from solid-state sensors to spectrometers, to spatial light modulators and light sources, and cameras are on display. Visitors can also learn about the positron emission tomography (PET) systems used in assessing the biochemistry of living organ tissues. They have been employed in medical settings in Hamamatsu City, and there have been quite a few cases of early detection of disease.

At the Vision Suite we will be showcasing medical instruments, lidar, quantum computing, telescopes, microscopes and other devices used in outer space and to explore the mind and brain. In all, the Vision Suite will have the following sections: Space; Earth; Life; Health/Mind/Brain; and Quantum.

Visitors will see devices from quantum computing to helping people with everyday general living. People don't know all the ways that Hamamatsu is working to help people as they live out their lives. We will focus on the future and the ways that photonics can unlock new possibilities.

SD: What kinds of professionals and other visitors will be most interested in the Vision Suite?

SF: Many different types, but certainly engineers. We work with engineers in product development, and they will be able to use these new ideas to do their research or to build new instruments.

SD: What new developments does Hamamatsu anticipate for 2024?

SF: Part of the philosophy behind Hamamatsu is seen in our motto: "Photon is our business." We have developed a new CMOS sensor from the ground up that can resolve single photons. It is able to detect the photos and make data out of low light conditions. It's one thing to see a photon, it's quite another to measure it."

Hamamatsu's qCMOS (Quantitative CMOS) is a CMOS image sensor that can detect and identify the number of both single and multiple photons. ORCA-Quest is said to be the world's first camera to incorporate the qCMOS image sensor and to be able to resolve the number of photons using its dedicated technology — even when a sample can only deliver a few photons.

SD: What does Hamamatsu see as trends ahead in the photonics marketplace or in technology in general?

SF: It will be different for each application, of course. But to be very general, the trends may include quantitation in biomedicine, and greater speed of devices with the same low noise characteristics, along with improved quality of data. In the imaging world, we see a push toward 3D data and improvements in data management.

SD: What will be the possible impacts on business of changing global economic conditions and geopolitics?

SF: That is a big question. We have to be aware of relationships between United States and China, of course. We will be monitoring that. And given that we buy products from Japan in yen, we will be monitoring that as well.

SD: Are research and other academic inputs central to Hamamatsu?

SF: Yes, absolutely so in basic research. Hamamatsu has close ties to the institutions doing that research. In my case, I have a bias, with strong interests in cameras, in developing light sheet technologies (a microscopy technique that illuminates an entire 2D focal plane). That would let an app go faster than a point scanner, while it eliminates out-of-focus light. We expect work on getting optical slices with multiple cameras, working with living tissue, like embryos, tracking neuron activity in the brain and impacts on tissue samples, and seeing how it all fits together. It is all astoundingly beautiful.

SD: How does Hamamatsu encourage students and new employees?

Hamamatsu's ORCA-Quest qCMOS camera. Credit: Hamamatsu.

SF: We have many connections with academia, and we often hire new talent right out of school and do our own extensive training in our products and also other technology and apps. The newcomers may specialize but also receive broad training.

SD: Is the company widely involved with optics and related associations, such as SPIE?

SF: Yes. And SPIE is so prevalent in optics, it is our primary connection. But we have close associations with many others related to various applications. For example, the Society for Neuroscience in Washington, D.C., which works with basic scientists and physicians around the world. We also work with quantum think tanks and digital pathology associations, all at different levels.

SD: What has been the company's experience of Photonics West, over the years, and what does the event mean to a very large company like Hamamatsu?

SF: Photonics West is absolutely our most important and inspirational show. It's where we can interface with existing customers, hear about their latest projects and learn where various fields are going. We understand that there will be more than 100 visitors from Japan at Photonics West this year. It is a pivotal experience.

FORD BURKHART

Hamamatsu's CEO and President Tadashi Maruno took office in 2022. He is pictured here with the Hamamatsu engineering team that developed the company's latest release in imaging technology: the ORCA Quest. Credit: Hamamatsu.

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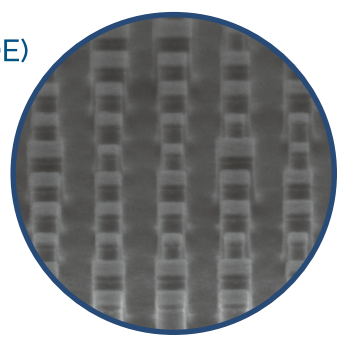

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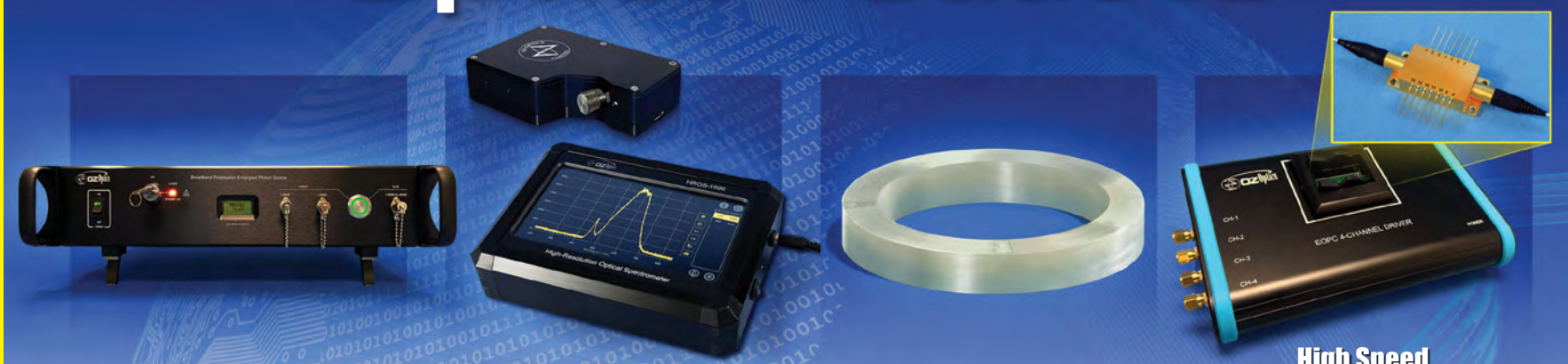

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