

PHOTONICS FOCUS

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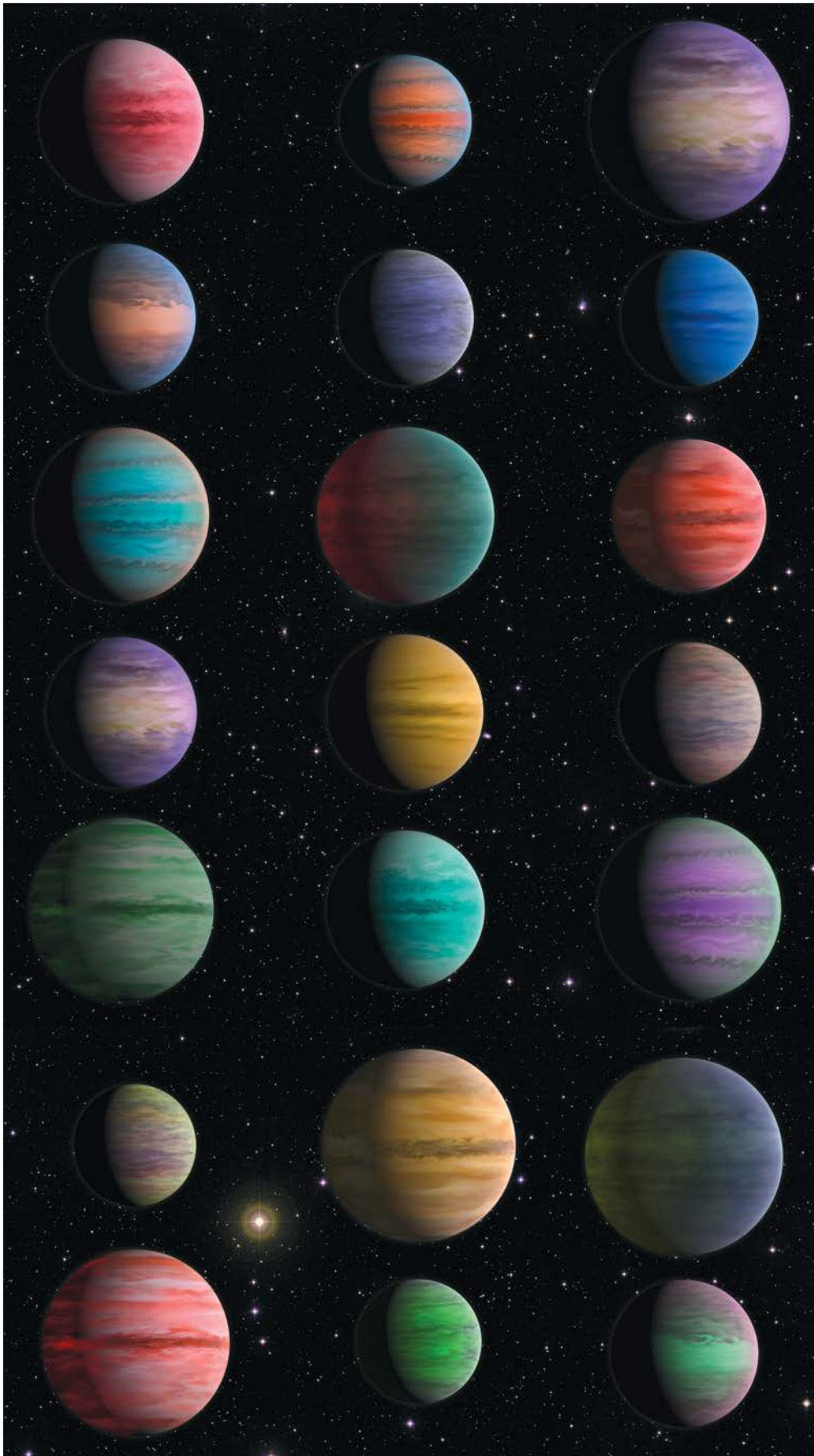
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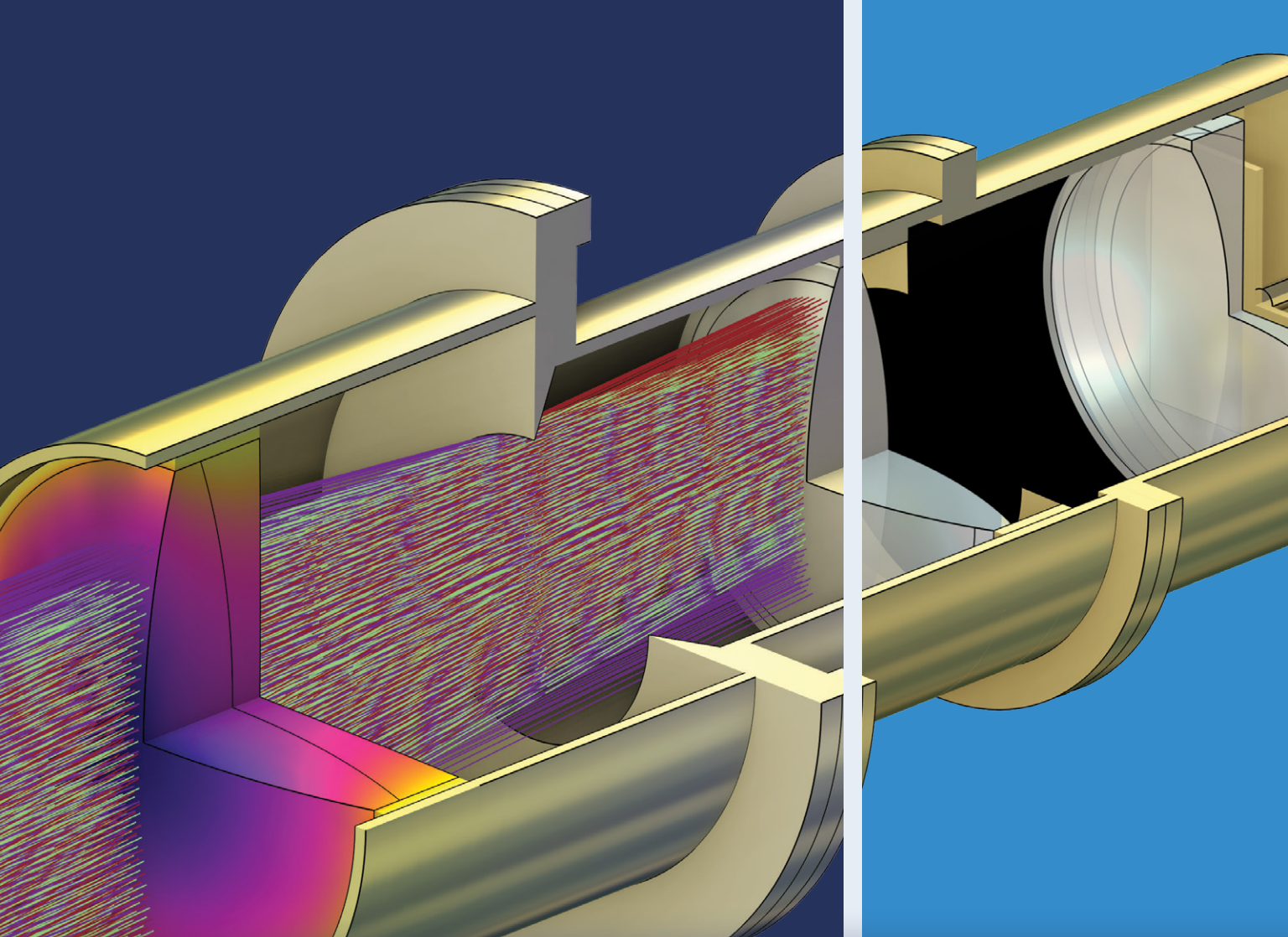
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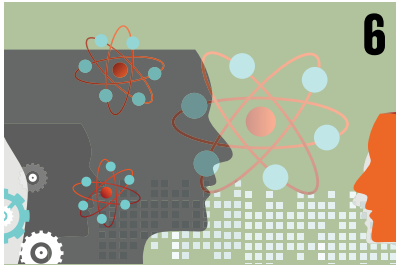
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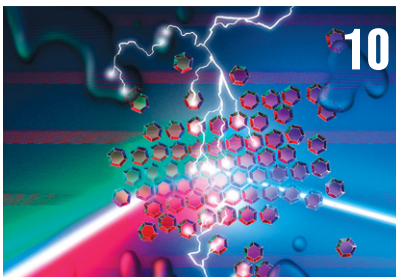
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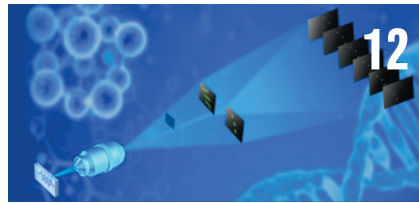
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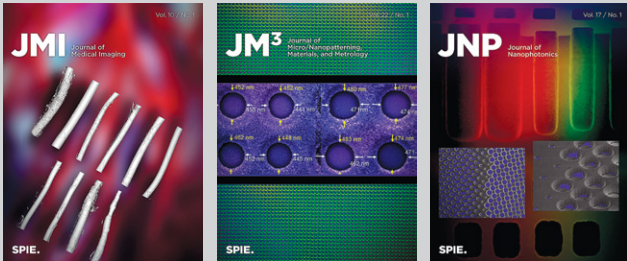
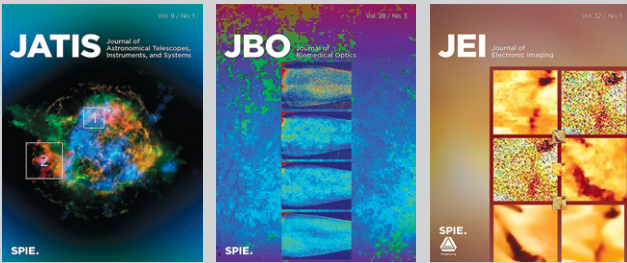


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I Go to Extremes

MOAB, UTAH, HAS LONG BEEN A MECCA FOR EXTREME SPORT ENTHUSIASTS. A combination of dramatic red rock cliffs and canyons, and an absence of the type of legislation designed to protect people from themselves, has made Moab the destination for people who recreationally like to defy death, including extreme ATV-ing, BASE jumping from cliffs, and slacklining across canyons.

The popularity of these sports (and Moab as a destination) has dramatically increased in the past 10 years due to exposure on YouTube, TikTok, and Instagram, which has the US Department of the Interior Bureau of Land Management concerned. Deserts are fragile environments that can take decades to recover from impact, and desert animals have nowhere to hide from the humans who are invading their space. New legislation proposes to ban recreational roped aerial activities—which includes sports like slacklining, rappelling, BASE jumping, and rope swinging on giant sandstone arches—in certain popular canyons near Moab. The extreme sports crowd is outraged. Where else can a person run a slackline across 300 feet of open space and take in the view?

The meticulous maintenance of world records (fastest mile run, longest hair, oldest cat) speaks to the human interest in extremes: We want to go faster, farther, bigger, smaller, higher, and lower than ever before. And that interest in the outer reaches includes scientists.

The extremes of outer space, ultracold temperatures, and the deepest ocean depths may hold secrets to the greatest scientific discoveries yet to be made. This issue of *Photonics Focus* explores those extremes, including ultrafast imaging being done by the Extreme Light Group at the University of Glasgow, which is harnessing light to solve practical problems, like seeing moving objects behind obstacles, and also to answer fundamental physics questions. Astronomical instrumentation engineers are working to develop the next generation of coronagraphs, which will help astronomical telescopes to directly image exoplanets, a feat that will require suppressing light from central stars by a factor of 10 billion. For reference, James Webb's state-of-the-art coronagraph achieved light suppression of 10^{-5} , so there's a ways to go.

But not all extreme science is without extreme consequence. Quantum gravity sensors are new tools in the kit of geophysical surveyors that significantly extend their ability to detect underground features at unprecedented depths. These sensors could have life-saving applications, such as early detection of earthquakes, but oil and mineral exploration companies will be their primary customers. Destruction of habitat and environmental pollution are inevitable consequences. The adrenaline junkies who flock to Moab argue that their environmental impact on the high desert ecosystem is negligible compared to nearby oil and gas development, and they're probably right.

Humans push extremes in order to discover our fundamental limits. Can a human run a mile faster than 3 minutes and 43.13 seconds (Hicham El Guerrouj, 1999)? Can a human hold their breath longer than 24 minutes, 37 seconds (Budimir Šobat, 2021)? And can we see, not just detect, an exoplanet, if we can figure out how to suppress enough starlight? The outer edge of these limits is where exploration and science meet.



GWEN WEERTS, EDITOR-IN-CHIEF



Every issue of *Photonics Focus* includes a section dedicated to our community. This section, formerly called SPIE Community News, is being rebranded as Member Lens to reflect the focus on our Members, the foundation of our Society.

Why Quantum Education?

WHETHER IT BE WATCHING THE WORLD CUP on a Samsung *Quantum* OLED TV, venturing into the *Quantum* Realm with Ant-Man, or cleaning dishes with Finish *Quantum* Detergent, “quantum” has become a household term. However, in the history of science, quantum physics is fairly recent; Erwin Schrödinger introduced his landmark Schrödinger equation, a major milestone at the origin of the field, only about 100 years ago. Thus, it should come as no surprise that corporations and the media preface their products and ideas with the term quantum to evoke thoughts of complicated science, futurism, and technological advancement.

Even within academic circles, quantum is often regarded as a complicated and counterintuitive topic. Niels Bohr, a founder of the field, stated that “anyone who is not shocked by quantum theory has not understood a single word.” Despite its pervasiveness in almost all modern areas of STEM—including biology, chemistry, mathematics, and electrical engineering—quantum mechanics is not usually a curriculum focus for most majors of study. Generally, only university physics students undergo a multi-course quantum series. These courses typically promote a calculation-based approach to quantum mechanics that discourages students from questioning the theory. This is unsurprising, given that leading scientific researchers and philosophers have yet to reach a consensus on all aspects of quantum theory. Despite these challenges in understanding, learning, and teaching quantum, there has been a large push in recent years to make quantum education more accessible to the public, at the K-12 level, for early university students, and for members of the workforce.

From a societal perspective, the motives for quantum education are clear. Today, quantum technologies, such

as semiconductor electronics, lasers, magnetic resonance imaging (MRI), and global positioning systems (GPS), to name a few, are used more than ever before. In 2018, the US government passed the National Quantum Initiative Act, authorizing \$1.2 billion in spending to support and accelerate the development of novel quantum technologies.

Of special interest are quantum computers, which have the potential to break modern cybersecurity and advance quantum simulation, promoting discoveries in domains such as pharmaceuticals, agriculture, and climate change. Major companies, such as Google and IBM, have also invested heavily in quantum computing divisions, and several startups have emerged in the area, creating a booming quantum job market. In the years to come, we will need a trained, talented, and diverse quantum workforce to support this growing quantum economy. Furthermore, as quantum technologies become more prevalent, it is critical for the public to acquire a basic understanding of these technologies, facilitating their adoption and promoting wider use. An informed public can also help ensure that these technologies are developed and utilized in an ethical and responsible manner.

While these are all important reasons, it was not the need for a quantum workforce or public awareness of quantum technologies that led me, personally, to quantum education. Rather, I fundamentally believe that quantum education can enhance general STEM education, especially if done well and at the right time in a student’s academic career.

To elaborate, quantum computation and information is a beautiful theory—at the intersection of mathematics, computer science, electrical engineering, and physics—which directly applies fundamental STEM ideas, such as complex numbers, linear algebra, probability theory, and Fourier analysis. These concepts comprise a core skill set that any

ANYONE WHO IS NOT
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QUANTUM THEORY
HAS NOT UNDERSTOOD
A SINGLE WORD.”



successful STEM student, whether a chemist or aerospace engineer, needs to master at some point in their academic career. Most young students will not immediately recognize the immense importance and power of ideas such as complex numbers or linear algebra when introduced in a standard math class. However, when these math concepts are instead introduced as tools to understand the wacky nature of quantum superpositions, students become excited to learn the math and immediately get practice applying it. Therefore, I see quantum computing education as a unique way to motivate students to “eat their academic vegetables.”

In 2019, this view of quantum education led me to propose the crazy idea of teaching a high school-level quantum computing course to Kiera Peltz, CEO of The Coding School, a tech education nonprofit. At the time, there existed few approachable, introductory resources to quantum computation and virtually no K-12 quantum education. However, Peltz appreciated the vision and together we launched the Qubit \times Qubit (Q \times Q) initiative. During the Covid-19 pandemic there was a dire need for virtual STEM education, to which Q \times Q responded with a year-long “Introduction to Quantum Computing” course, offered to 10,000-plus high schoolers, university students, and members of the workforce, in more than 125 countries. We found students to be exceptionally engaged and excited. The course retained more than 80 percent of students, among which 55 percent came from traditionally underrepresented backgrounds and 85 percent indicated that the course increased their interest in STEM.

As a course instructor, I found this incredibly fulfilling. Irrespective of whether these students end up in quantum-related fields, the knowledge acquired through Q \times Q will serve them in any STEM career. Furthermore, given Q \times Q’s large emphasis on diversity, I believe we gave high school students the confidence and background necessary to excel in first-year college courses. Interestingly, acknowledging that even experts find quantum hard and do not have all the answers did not discourage but, rather,

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empowered students by eliminating their fear of asking questions and getting wrong answers.

In the years since, Q \times Q has continued to offer and improve this course, as well as introduce more programming, such as workshops, conferences, and research opportunities. I am incredibly proud of and excited by how far the organization has come and continues to grow. As of 2023, Q \times Q is a global leader in quantum education, especially at the K-12 level. Beyond training a diverse future quantum workforce, Q \times Q has used quantum education to prepare and excite tens of thousands of students for advanced STEM degrees. Although we may not “understand” quantum mechanics, as Nobel Laureate Richard Feynman once said, we surely can learn from it.

FRANCISCA VASCONCELOS is the founding academic director of Qubit \times Qubit and an NSF graduate research fellow at the University of California, Berkeley, Department of Electrical Engineering and Computer Science. To learn more about Qubit \times Qubit, visit the program webpage qubitbyqubit.org or contact quantum@the-cs.org



Steering Towards the Age of Quantum

PHOTONICS TECHNOLOGIES underpin a new world of quantum developments. But besides the challenge of making these solutions market-ready, quantum champions need also to prepare potential users and society at large for the new ways of working.

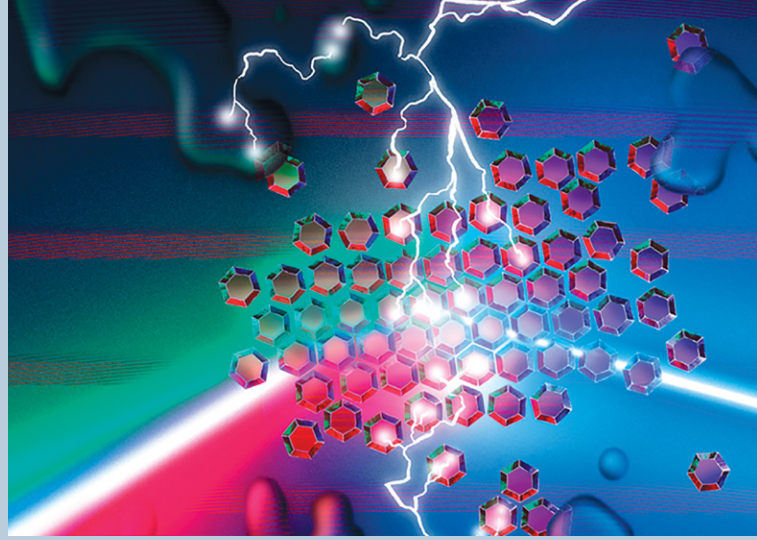
“Quantum innovation and quantum markets are emerging worldwide,” said Celia Merzbacher, executive director of the Quantum Economic Development Consortium (QED-C). She was speaking at Quantum West 2023, part of SPIE Photonics West. The occasion was to announce foundation of the International Council of Quantum Industry Associations.

The new council comprises quantum associations from around the world, including Quantum Industry Canada, Quantum Strategic Industry Alliance for Revolution (Q-STAR), and the European Quantum Industry Consortium (QuIC). Merzbacher added, “The formation of this council creates lines of communication and collaboration that will help our members to develop supply chains, open markets, exchange talent, and support policies that benefit the emerging industry and society.”

At the same launch, Thierry Botter, executive director of QuIC, said, “We are at the beginning of a global technological revolution. Forming this council and working together promotes equity and reciprocity in the advancement of the international quantum ecosystem. It will allow our communities to discuss areas of common interests, such as international standards, intellectual property, and access to funding.”

In February, Australia’s Chief Scientist Cathy Foley gave a “quantum in action” speech at Quantum Australia 2023. She declared, “Quantum is now on the radar of governments, investors, and forward-thinking businesses, who understand how transformative it will be in so many areas. Quantum technologies are already impacting medicine through better imaging. They’re changing our ability to see through barriers, into geological formations, as well as into cells. Quantum optimization is already making a difference in freight and logistics.”

A range of Australian-headquartered companies are manufacturing quantum technologies and selling them worldwide. For example, Quantum Brilliance is developing diamond-based room-temperature quantum computing, and working with the Pawsey supercomputer in Western Australia to host the world’s first diamond quantum accelerator. QuintessenceLabs is selling quantum-based cybersecurity solutions to customers globally. It develops quantum random number generators that produce cryptographic keys for cybersecurity. Another company, Q-Ctrl, provides firmware for quantum error correction that improves performance of quantum computing and quantum sensing hardware.



QUANTUM INITIATIVES ANNOUNCED over the past few years in North America and Europe have committed billions of dollars and euros for quantum research and innovation as well as industrial development of novel applications. New markets are as diverse as physics itself: quantum computing, *in vivo* biomedical imaging, ultra-secure optical communications, underground mapping through the Earth, and gravity wave detection, to name a few. All of these challenges-turned-markets have one feature in common: the interdependence of quantum and photonics technologies.

For this wave of global quantum initiatives, the first country out of the blocks was the UK, which set up the National Quantum Technologies Programme (UKNQTP) in 2013. Its mission is “to translate academic work on quantum mechanics, and the effects of quantum superposition and quantum entanglement into new products and services.” Over the past decade, the UKNQTP has brought together UK physicists and engineers with companies and entrepreneurs who are working to commercialize the technology.

Notable efforts include those of Najwa Sidqi, of Innovate UK Knowledge Transfer Network. Her mission there is to raise awareness about quantum sciences and their applications to end user sectors.

Sidqi tells *Photonics Focus*, “Worldwide there is a big, competitive quantum race going on. I think a lot of countries have learned important lessons from the UKNQTP program. This was followed by other countries launching similar programs, and by about two years ago almost every major nation plus the EU had established a significant quantum development program.”

Sidqi emphasizes the importance of photonics to the quantum sector: “The photonics industry is a key enabler, from providing laser alignment to optical filters, for example. Everything that touches applications like quantum imaging, quantum computing, and quantum sensing involves the photonics industry. There are many single-photon generation and detection technologies—critical to quantum systems—that also rely on photonics. So, the photonics industry is a vital driver of the quantum sector.”



EVERYTHING THAT TOUCHES APPLICATIONS LIKE
**QUANTUM IMAGING,
QUANTUM COMPUTING,
AND QUANTUM SENSING**
INVOLVES THE PHOTONICS INDUSTRY.



People who are already working in areas connected to quantum and photonics should be familiar with the concepts and potential of such integrated solutions to yield greater results in diverse applications. But surely the wider industrial sector is still mystified about the terminology, never mind its potential.

Sidqi says, “We are still at a very low level of awareness from the broader end user sector about quantum and how it can be useful. I think there’s only a very small minority of top businesses out there that can afford to have that understanding and knowledge about how quantum can be useful to them, enough to invest in some piece of quantum technology or collaborate with research in the universities.”

“I think we need a broader awareness about quantum,” Sidqi continues. “There is still a lot of work to be done so my role is to raise awareness about what is quantum and what it can do. My personal commitment is towards pushing for adoption of quantum technologies by industry and also by society. So I envisage more collaborations happening towards accelerating the adoption of quantum. Adoption is a term that’s a bit neglected; we often talk about commercialization, but I think we should push for adopting quantum.”

Raising awareness of the capabilities of quantum solutions while also making them acceptable to industry and wider society are key to transitioning relatively painlessly to the age of quantum, Foley said in a Quantum West 2023 plenary talk entitled “How can quantum technology save the world? An Australian perspective.”

She told the audience at Photonics West: “One step that’s going to be important for the quantum community is consumer engagement with the design of products. For example, at Apple, Steve Jobs designed his own fonts for the products, which was part of his goal to make the technology more acceptable to consumers. This will also be the case with quantum developments: for quantum solutions to become ubiquitous, they will need to be easy to use. Consumers won’t be so much interested in how the technology works as in the applications.”

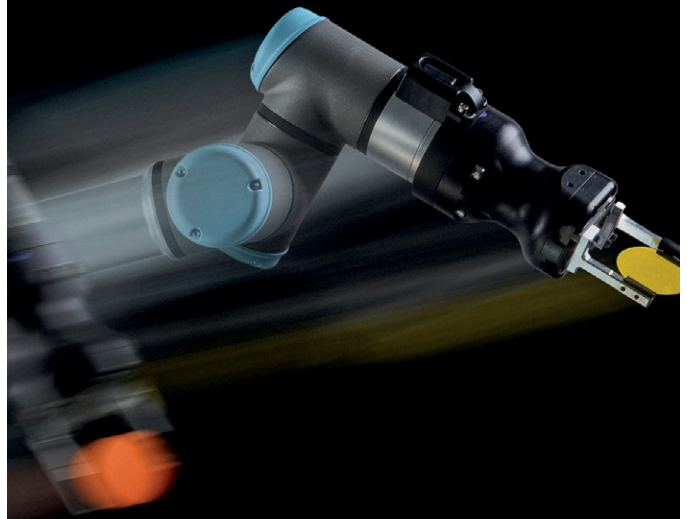
Foley also tackled the importance of applying clear regulation and standards to quantum developments: “There are important safety and ethics considerations with quantum, as there are with any other developments that have significant social impact. So, we need to consider and discuss quantum issues in the same way—to actively engage with the people who will become the consumers of future quantum technologies.”

MATTHEW PEACH is *Editor-in-Chief* of *optics.org*



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Noble Gases and the Shock of War:

Laser and semiconductor manufacturers adjust to price increases while securing supply chains

FEBRUARY 24 MARKED THE ONE-YEAR ANNIVERSARY of Russia's unjustifiable invasion of Ukraine. During this period, the laser and semiconductor industries have endured a number of supply chain disruptions. One often overlooked commodity used in these industries is the high-purity gases needed to manufacture gas lasers and to operate semiconductor manufacturing equipment. Gases such as neon (Ne), krypton (Kr), argon (Ar), and xenon (Xe) are widely used in both applications, and gas supply disruptions have had a significant impact on cost and supply chain complexity.

Before the invasion, Ukraine accounted for 50 to 70 percent of global neon gas production and 40 and 30 percent, respectively, of global krypton and xenon gas production. Companies like Cryoin, Ingas, and Iceblick had major operations in Mariupol, Odessa, and elsewhere in Ukraine. Before the war, Ingas was producing 15,000 to 20,000 cubic meters of neon gas per month. Cryoin Business Development Director Larissa Bondarenko has said that the company produced about 10,000 to 15,000 cubic meters of neon gas per month in Odessa.

Production of these gases in Ukraine halted suddenly at the start of the war. Russia is also a major producer of

high-quality gases. Disruption to the gas supply worsened in mid-2022 when the Russian Ministry of Industry and Trade announced that it would restrict exports of these high-quality gases.

Both Intel and Applied Materials have said that the supply of these specialty gases would be constrained well into 2023. Demand is expected to increase by 30 percent over just the next four years.

The market for rare gases is not transparent and prices are not published. Specialty gas suppliers mainly engage in confidential, long-term contracts. It has been reported that neon prices in China and krypton prices in Japan quadrupled in the first two months of 2022. Since Russia started the invasion, neon prices in China increased tenfold in March 2022, while xenon and krypton prices rose by about 50 percent. In Japan, the price of krypton has risen from as little as \$1.72 per liter to \$8.60 per liter by the end of January.

These noble gas price increases are similar to those experienced after Russia annexed Crimea in 2014. Following that invasion, neon prices increased by 60 percent. Manufacturers responded by diversifying their supplies. In 2016, one of the largest industrial gas suppliers, Linde, invested US \$250 million in a neon production facility in La Porte, Texas. It was designed to produce annually 40 million liters of neon. This year, in Brazil, Karoon Energy doubled down by drilling a second well after it discovered a neon-rich area 210 km off its coast.



THE WAR IN UKRAINE

IS STILL IMPACTING BOTH

LASER AND SEMICONDUCTOR

MANUFACTURING IN UNEXPECTED WAYS.

Gas lasers based on noble gases have been around for more than 50 years. One could easily assume these types of lasers have been replaced with newer laser-diode technologies. This is largely correct except for a few critical applications. Argon-ion and helium-neon gas lasers are still widely used in the semiconductor field. Helium-neon lasers are often used as a wavelength reference for equipment calibration (i.e., spectrometers) or for particle detection systems used in pharmaceutical manufacturing.

High-purity gases are also used for excimer lasers that provide the deep ultraviolet light source for semiconductor lithography. Excimer lasers use a gas mixture that combines argon, krypton, xenon, neon, and halogen to produce light at 193 nm. Neon makes up approximately 96 to 97.5 percent of the mixture and, as a carrier gas, is essential to the laser's operation. These gases are regularly changed out during use, which further drives the demand for a solid supply chain.

The overall supply of high-purity gases is dominated by France's Air Liquide, Japan's Dayo Nippon Acid, and in the US, Linde and American Air Chemical. Together, they account for 80 percent of the total market supply for specialty gases. Each has made significant changes to improve the supply situation and to alleviate pricing concerns.

To secure their supply chain, semiconductor companies have made adjustments, too. One example is TSMC (Taiwan Semiconductor Manufacturing Company), which announced plans to bring some of its neon production to Taiwan. Excimer laser manufacturers have reduced neon consumption by 25 to 70 percent by adjusting software and optimizing processes. They have improved gas collection during the laser recharging procedure as well as improved processes for removing impurities from the gases, ultimately injecting them back into the laser.

Although it's been more than a year, the war in Ukraine is still impacting both laser and semiconductor manufacturing in unexpected ways. The market for specialty gases will eventually rebalance and prices, hopefully, will return to normal. Until then, manufacturers will be spending more time and money to secure their supply chain.

WILLIAM BURGESS is Co-CEO of *Power Technology, Inc.* The company was founded in 1969 to manufacture power supplies for helium-neon gas lasers and is currently one of the top manufacturers supplying customers worldwide. Learn more at www.powertechnology.com.

Industry Updates

M&A

- » **Meridian Bioscience Inc.** was acquired by **SD Biosensor Inc.** for \$1.53B effective February 1.
- » **MCT Worldwide LLC** was acquired by **Cohu Inc.** for an undisclosed amount effective January 20.
- » **ASELTA Nanographics** was acquired by **Applied Materials Inc.** for an undisclosed amount effective January 23.
- » **Phoseon Technology Inc.** was acquired by **Excelitas Technologies Corp.** for an undisclosed amount effective February 16.
- » **Advanced Circuits** was acquired by **APCT** for an undisclosed amount effective February 14.
- » **Herley Industries Inc.** was acquired by **CAES** for an undisclosed amount effective March 3.
- » **IsoPlexis Corp.** was acquired by **Berkeley Lights Inc.** for \$57.8M in stock effective March 21. The combined company has been rebranded as **PhenomeX Inc.**
- » **Fastlite** was acquired in March by **Amplitude Laser Group** for an undisclosed amount.
- » **Gilat Satellite Networks Ltd.** to acquire **DataPath Inc.** for an undisclosed amount. The transaction is expected to close in Q3.
- » **Infineon Technologies AG** to acquire **GaN Systems Inc.** for an undisclosed amount. Closing date TBA.
- » **Waters Corp.** to acquire **Wyatt Technology Corp.** for \$1.36B. The transaction is expected to close in Q2.
- » **Aim Lab Automation Technologies Pty Ltd.** was acquired by **Brooks Automation Inc.** for an undisclosed amount, effective March 1, 2023.
- » **Immucor Inc.** was acquired by **Werfen** for \$2B, effective March 15, 2023.
- » **MACOM** to acquire **OMMIC** for €38.5M. The transaction is expected to close in Q2 2023.
- » **indie Semiconductor** acquired **GEO Semiconductor Inc.** for \$180M in February.
- » **FISBA** to acquire **Gray Optics** for an undisclosed amount.

Executive Updates

- » **Doug Wright** was appointed CEO of **Indicor LLC** effective April 1.
- » **Dirk Bontridder** was appointed CEO of **PerkinElmer US LLC - Analytical and Enterprise Solutions.**
- » **Steve Klinsky** was appointed CEO of **New Mountain Capital LLC.**

Faster Can Also Mean Better

YOU CAN DO IT RIGHT OR YOU CAN DO IT FAST. That's been the case with various super-resolution microscopy techniques meant to overcome spatial resolution restrictions due to optical diffraction. The techniques typically acquire super-resolution at the expense of imaging speed, such that detection of fast dynamics with fine structures has remained a great challenge.

Now, a research team in China reports having resolved the contradiction between spatial resolution and imaging speed. They achieved high-speed super-resolution by developing a method called temporal compressive super-resolution microscopy (TCSR). TCSR merges enhanced temporal compressive microscopy with deep-learning-based super-resolution image reconstruction. Enhanced temporal compressive microscopy improves the imaging speed by reconstructing multiple images from one compressed image, and the deep-learning-based image reconstruction achieves the super-resolution effect without reduction in imaging speed. Their iterative image reconstruction algorithm contains motion estimation, merging estimation, scene correction, and super-resolution processing to extract the super-resolution image sequence from compressed and reference measurements.

The team's studies verified the high-speed super-resolution imaging ability of TCSR in theory and experiment. To demonstrate the imaging capability of TCSR, they imaged flowing fluorescent beads in a microchannel, achieving a 1,200 frames-per-second rate and spatial resolution of 100 nm. They say their method provides a powerful tool for observing the high-speed dynamics of fine structures, particularly in hydromechanics and biomedical applications like microflow velocity measurement, organelle interactions, intracellular transports, and neural dynamics. The framework of TCSR can also offer guidance for achieving higher imaging speed and spatial resolution in holography, coherent diffraction imaging, and fringe projection profilometry.

(He et al., *Adv. Photon.*, 2023, doi:10.1117/1.AP.5.2.026003)

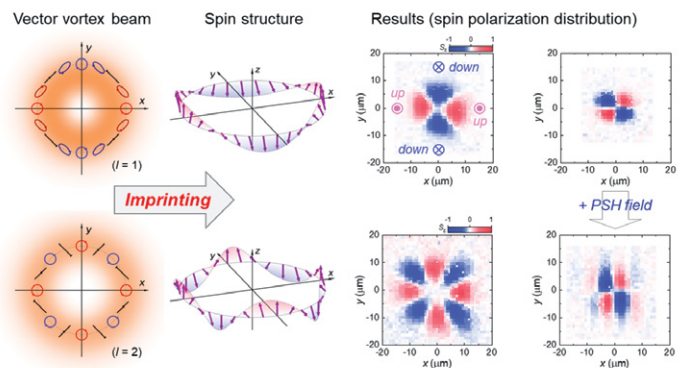
More Types of Spin, More Storage

IF YOU ENJOY SPINNING, adding variation to the work-out could help boost your performance. The same appears to be true of information storage by way of electron spin. Spin can be controlled using polarized light to store information. A polarized light beam interacts with electron spins within a semiconductor to generate spin-polarized electrons. So far, only light with a spatially uniform polarization has been exploited to control electron spins.

Now, researchers in Japan report that if the polarization has an additional spatial structure, or variation, it can produce spatially structured electron spins, opening new ways to store information. The research team generated a vector optical vortex beam with an orbital angular momentum (OAM) from a basic Gaussian beam.

Next, they used this beam to excite the electron spins confined within a semiconductor quantum well. The spins, in turn, formed a helical spatial structure in a circle. While the beam with an OAM number equal to one produced a helix with two spin periods—spin up and spin down—around the circle, an OAM number of two resulted in a helix with four such alterations. The results indicate that the spatial polarization structure of the optical vortex was transferred to the electron spins inside the semiconductor. What's more, increasing the OAM number appears to enable higher information storage capacity, characterized by higher spin repetition rate around the circle. Various spin states with spatial structures could also be produced via the effective magnetic fields alongside structured light beams.

(Ishihara et al., *Phys. Rev. Lett.* 2023, doi: 10.1103/PhysRevLett.130.126701)

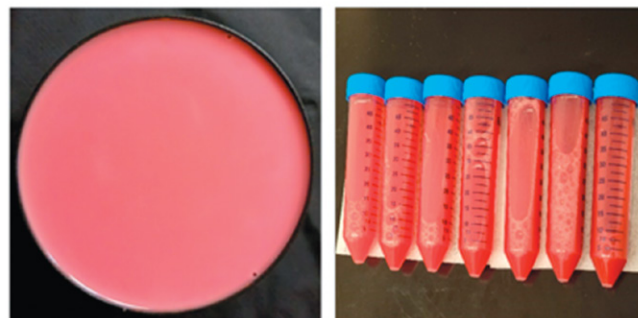
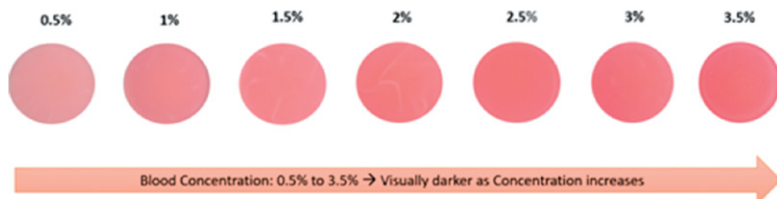


Getting Cherenkov Right

CHERENKOV IMAGING is a valuable cancer treatment tool that should allow accurate detection of the radiation dose delivered to tissue. It works by detecting Cherenkov radiation emitted by tissues when they are exposed to high-energy radiation, such as X-rays or electron beams. In an ideal scenario, where no Cherenkov is absorbed or scattered by the tissue, the emitted light is directly proportional to the radiation dose. However, tissue attenuation does reduce the intensity of emitted Cherenkov radiation such that the proportional relationship does not always hold true.

But all is not lost. In a new study, researchers examined how the intensity of Cherenkov emission changes with variations in biological tissue absorption features such as blood concentration within tissue and melanin concentration in the skin. They exposed prepared tissue and blood phantoms with varying melanin layers and blood volume levels to high-energy X-rays and analyzed the resulting Cherenkov radiation emitted.

A specially designed camera was used to detect the signal in red, green, and blue wavelength bands. The team found that all colors exhibited a similar reduction in intensity with increasing melanin levels. However, in blood



phantoms with increasing blood concentration, they observed the red channel attenuated to a lesser extent than the blue and green channels, due to the absorption of blue and green colors by hemoglobin. They concluded that because the color changes are different, they could calibrate for differences in attenuation based upon either skin color or blood volume in the tissue.

(Wickramasinghe et al., J. Biomed. Opt. 2023, doi: 10.1117/1.JBO.28.3.036005)

The Light Within Oceans

THE RIGHT LIGHTING CAN MAKE OR BREAK AN ENVIRONMENT. But messing with the light in the oceans can have potentially disastrous consequences. Ecologists say that microplastics—tiny plastic particles less than 5 mm—have already negatively affected marine ecosystems by hindering light transmission there. The pollutants have disrupted the functioning of photosynthetic organisms, such as phytoplankton and algae, which can have a cascading effect along the entire food chain.

To dive deeper, researchers in China and Singapore set out to determine just how microplastics might be altering sunlight in ocean water. They looked to assess the radiative properties of microplastics to determine the extent of disruption they cause to light propagation. They were able to determine the absorption coefficient and reflectivity of polyamide-12 (PA12), a common marine microplastic pollutant used in the clothing, cosmetic, and packing industries.

The researchers focused on measuring the absorption coefficient, which indicates the amount of light absorbed, and the extinction coefficient, which accounts for the light attenuated (absorbed and scattered) by the particles. The analysis revealed a scattering albedo of 0.7 for the PA12 suspension, implying that most of the light passing through it was scattered. What's more, the PA12 particles were found to absorb the incident radiation at specific wavelengths corresponding to the vibrational absorption of methylene and amide groups. This suggests that the radiative properties of PA12 can be used to monitor, and perhaps prevent, the flow of microplastics into oceans and aquatic and terrestrial food chains.

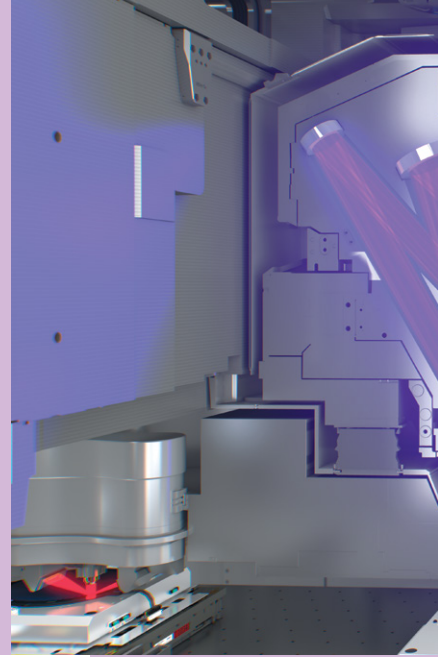
(Wen et al., Opt. Eng. 2023, doi: 10.1117/1.OE.62.3.034102)



HIROO KINOSHITA

Lighting the Way for Extreme Ultraviolet Lithography

By **Jeff Hecht**



THE IDEA OF EXTREME ULTRAVIOLET LITHOGRAPHY (EUVL) came to Hiroo Kinoshita while he worked for Nippon Telegraph and Telephone (NTT) in the mid-1980s—a time when semiconductor lithography still depended on mercury lamps. The semiconductor industry wanted shorter wavelengths for lithography to sustain Moore’s law and continue increasing the number of transistors on a chip that was powering industry growth. Ultraviolet lithography with excimer lasers was already in the pipeline. Kinoshita was looking to much shorter X-ray wavelengths, but kept finding daunting problems, including a lack of lenses or mirrors capable of focusing X-rays for lithography.

Then he came across a paper by Jim Underwood and Troy Barbee, reporting the first multilayer mirrors for wavelengths of 10 to 100 nm that we now call EUV. That was a huge

advance over the glancing-angle reflectors that at the time were the only mirrors available for X-rays at shorter wavelengths. Kinoshita realized that the new mirrors could open the door to lithography at EUV wavelengths. In fact, he tested them and succeeded in demonstrating the first focusing of images in the EUV and reported his achievement at a 1986 meeting of the Japan Society of Applied Physics.

Kinoshita was ahead of his time. “Unfortunately, the audience was highly skeptical of my talk,” he said later in an invited lecture on the emergence of EUV lithography. “However, my belief did not change.” He continued pursuing EUV lithography and is recognized today as its founding luminary. Nonetheless, overcoming the formidable challenges required more than 30 years of effort, billions of dollars in funding, and a cast of thousands of engineers and scientists.

Developing a suitable EUV light source was one of the most obvious and difficult challenges. In the mid-1980s, Obert Wood and Bill Silfvast at Bell Labs tried to develop one based on emission from a laser-produced sodium plasma. They found it easier to study how it would work by using a synchrotron to generate light in the 10 to 100 nm range, then called soft X-rays.

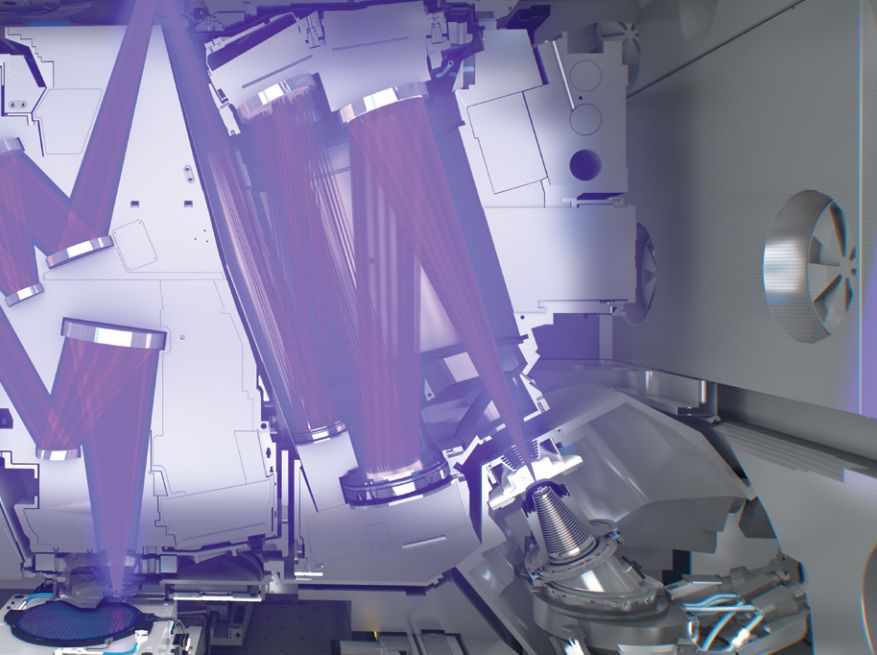
“The synchrotron did not supply much power, but its output could be adjusted to match reflective coatings on the imaging mirrors,” says Wood. Others were skeptical. Then, around 1993, one of their managers, Rick Freeman, recommended a name change for the technology: “extreme ultraviolet lithography, which sounds like deep ultraviolet lithography,” which was already being done with excimer lasers, Wood recalls. “People immediately jumped on that.”

Meanwhile Kinoshita continued his efforts with a group of about five others.

NTT was more interested in other types of lithography, but he credits them with not stopping his research. In 1993, he organized a US-Japan meeting on EUV lithography that attracted about 50 researchers and built a bond between the two countries.

By then, “Moore’s law was in trouble,” says David Attwood of Lawrence Berkeley National Laboratory (Berkeley Lab). The





This illustration shows the full light path from EUV source to silicon wafer. The light is generated in the source (bottom right), sent into the illuminator (mid right) which controls the light beam, reflects off the mask with the chip pattern (top), before being focused in the projection optics (mid left) and exposing the wafer (mid bottom).

193 nm argon-fluoride laser was already in development for photolithography, but that was looking like the end of the road for lithography with deep-UV lasers. Having no way to continue shrinking chip geometry would have been a very big problem for Intel, “which counted on being at the forefront of Moore’s law to sell its products at high prices.” In fact, the whole community was growing very anxious about the future.

Attwood says the turning point came when Intel Research Director John Carruthers took a long hard look at future options and concluded that the only viable course for the company was to place a billion-dollar bet on an industry-wide project to develop a new technology for EUV lithography. When he proposed the option to his bosses, Andy Grove pounded the table in anger, but Gordon Moore didn’t see an alternative and, in the end, Grove went along. Moore further backed Carruthers’ effort to enlist other companies by announcing at an industry meeting, “Intel is here...we are placing our bet and we want you to join us.”

Intel’s call to action succeeded. In 1997, long-time industry competitors, recognizing the severity of the threat, joined together to incorporate Extreme Ultraviolet LLC to develop a new generation of lithography. The consortium contracted with the US Department of Energy to organize research at Berkeley Lab, along with Lawrence Livermore and Sandia National Laboratories. Attwood, who headed Berkeley Lab’s EUV research, recalls the atmosphere as collegial, and counts many EUV LLC colleagues as fast friends. Japan formed a similar group, EUVA, which cooperated with EUV LLC. Wood has fond memories of Kinoshita taking him on a tour of the centuries-old Himeji castle in Japan.

The consortium members’ task was huge. Moving lithography to the EUV required not just new sources, but new optics and optical coatings, photoresists, measurement tools, and nanometer-scale precision. They started with six candidate approaches and gathered every six months to rate them and compare results. Over time, and after several iterations, their research changed their minds, and the laser-produced tin plasma source initially rated last became the top choice.

Optical requirements were especially stringent. A dozen separate mirrors were needed to project the image of the circuit mask onto the silicon surface with the required nanometer resolution. The only option in the EUV was multilayer mirrors, which had quarter-wave layers thinner than 4 nm that had to be kept uniform to daunting accuracy. With maximum EUV reflectivity, after a dozen reflections from a 70 percent reflective mirror, you wind

up with about 1.4 percent of the light left. The 13.5 nm source wavelength used was chosen because it was the peak reflectivity of mirrors made of stacks of molybdenum disilicide and silicon.

By the mid-2000s, researchers had demonstrated tin-plasma sources pumped by carbon dioxide lasers, but their power was limited. Improvements were painfully slow, with output stuck in the watt range for several years. Signs of progress emerged in 2013, when California company Cymer reported pushing EUV power above 10 watts by hitting the tin with a pre-pulse before the main one. That was far short of production requirements, but ASML in The Netherlands, which at the time produced two-thirds of chip production machines, bought Cymer in May of that year, and started pumping money into scaling EUV lithography.

By then, ASML in partnership with Zeiss had spent 20 years developing the complex optics needed for EUV lithography. “It was really a huge amount of work to turn the [patent] concept into a reality,” says Erik Loopstra, who with Vadim Banine, led the partnership’s research team. Freeform optics focuses the EUV light along a 10 m optical path and down to a nanometer-scale spot. “It’s like hitting a golf ball on the moon,” he says. “Measurement is the key to getting it done. Everything you can measure, you can manufacture.”

Today, ASML is the only company selling EUV fab machines, each one slightly smaller than a bus and costing \$150 million. Together with Zeiss, it has 2,500 people building the fabs. The illuminators alone have 15,000 parts, with another 20,000 in the projection optics. Loopstra says it’s more complex than the space shuttle. And they’re already working on the next generation, which will increase numerical aperture from 0.33 to 0.55, allowing focus down to an even smaller spot than today’s capability.

Kinoshita, now a professor at the University of Hyogo in Japan, says EUV lithography “was my dream.” He had expected development to take a long time, and says he is “so happy” today to see it realized.

JEFF HECHT is an SPIE Member and freelancer who writes about science and technology.

CAPTURING

LIGHT IN MOTION

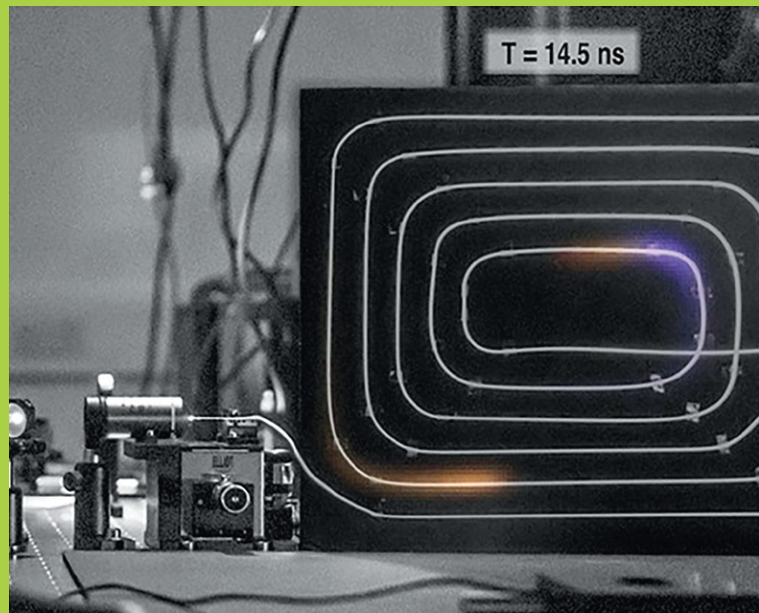
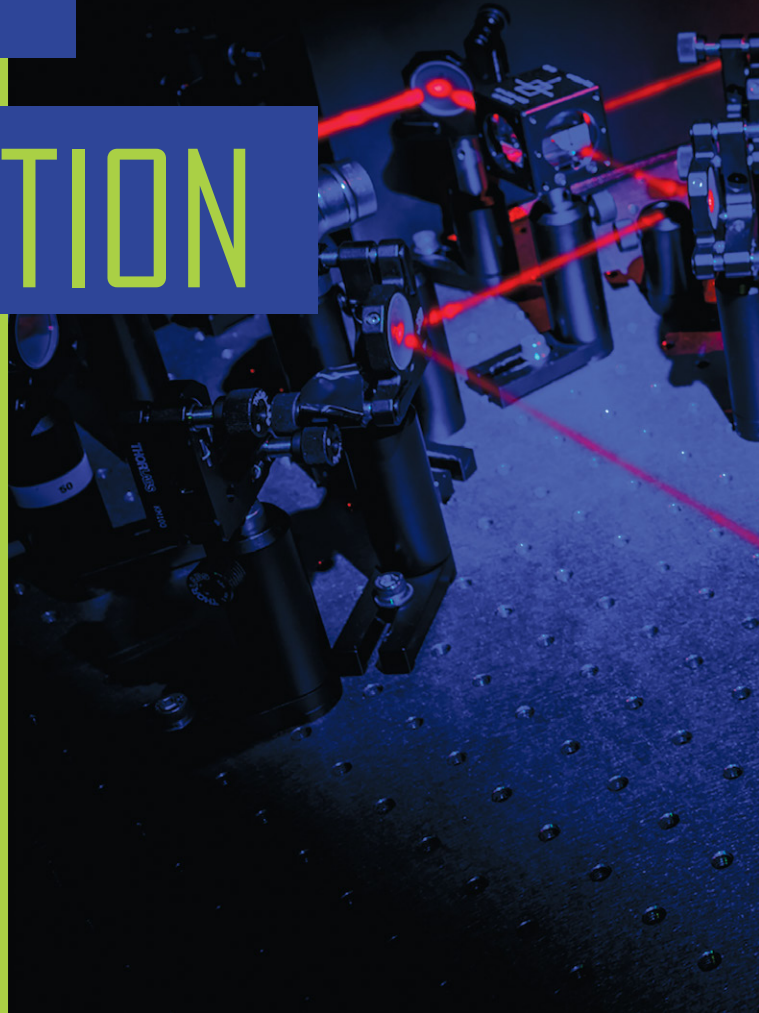
New Frontiers Open for Visualizing the World

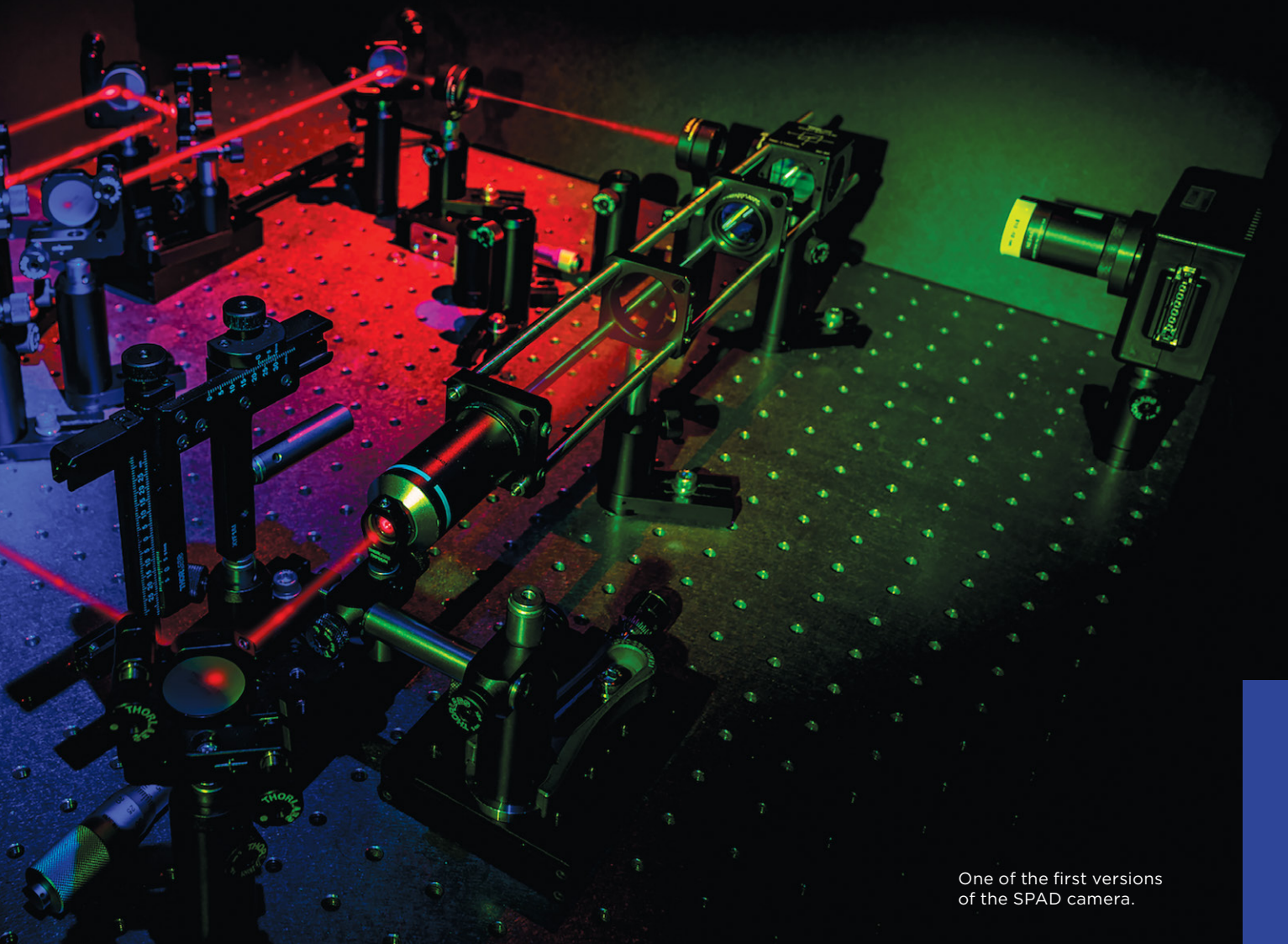
By **Benjamin Skuse**

FREEZING HIGH-SPEED PROCESSES IN MOTION has been a recurring theme in photography since Eadweard Muybridge stunned the world in 1878. His *The Horse in Motion* series of photographs exposed that, in full flight, all four of a horse's hooves are simultaneously off the ground, shattering the illusion of the graceful gallop. The public's imagination was captured again when Harold 'Doc' Edgerton—using a stroboscopic flash that could fire a burst of light lasting microseconds—froze a speeding bullet in motion in 1964's *Bullet through Apple* photograph. Since then, technological developments have seen real-time image-capture at several million frames per second expose many of nature's fastest processes.

But capturing light in motion is a whole different ballgame, requiring a camera that can record scenes on the order of a trillion frames per second. So, when Ramesh Raskar from the Massachusetts Institute of Technology (MIT) Media Lab presented a 20-second video clip of a light pulse travelling in slow motion through a Coke bottle, bouncing off the cap, and reflecting back toward the bottle's bottom during a 2012 TED Talk, it was a sensation. No one had recorded light in flight before. No one had been able to visualize the world at light speed.

For Daniele Faccio, it was also a lightbulb moment. "I was just blown away," he recalls. "I didn't think that was possible." Faccio was at Heriot-Watt University in Edinburgh, UK, at





One of the first versions of the SPAD camera.



the time, and had for several years been working on the idea of using light propagating through optical fibers to mimic black hole processes. These lab-grown black hole analogs can act as a testing ground for black hole theories, without the inconvenience of having to travel to an actual black hole. In 2010, he and his team had managed to create a laboratory proxy for Hawking radiation, a phenomenon by which a black hole should give off a stream of particles from its outer boundary. But whenever he presented the work, the one question Faccio was always asked was: “Can we see it?”

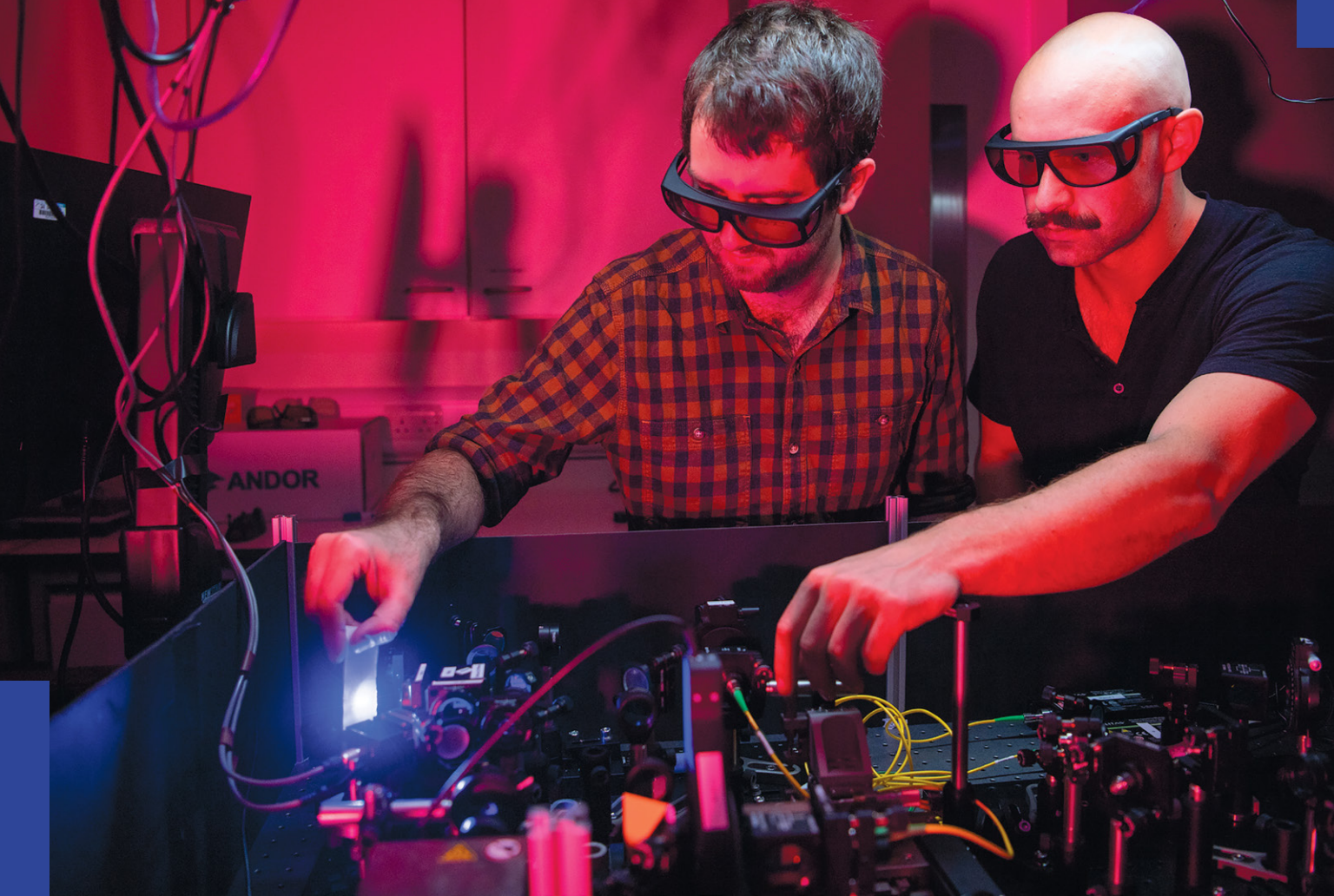
Inspired by Raskar, Faccio was determined to see his Hawking radiation analog moving along a fiber. The technique Raskar used—streak camera imaging, which measures the power of optical pulses over time—was

◀ A light pulse captured moving down a fiber.

“horrendously expensive,” so Faccio looked for alternatives. He found one down the road at the University of Edinburgh. “A group led by Robert Henderson was developing single-photon avalanche diodes (SPADs) to do fluorescence lifetime imaging,” explains Faccio. “They had the same kind of temporal resolution that Raskar was using with his streak camera, which made us think that maybe we could use SPADs for freezing light in motion. That’s when everything started to fall into place.”

SPAD cameras are a type of image sensor in which each pixel possesses an electronic element. Unlike CMOS sensors, where each pixel measures the amount of light that reaches it within a given time frame, in SPAD sensors each photon received by the pixel is converted into an electric charge, with the resulting electrons multiplying to form a single large electric pulse. This enables rapid and clear image capture free from signal noise, and it opens the door to high-precision distance measurements and photon time stamping.

With a prototype SPAD camera in hand, the Heriot-Watt team decided to test out the device, creating the first video of



a laser pulse in motion bouncing off mirrors in free space. Seeing that the technique worked, they then wanted to find out what else it could do. Again, Faccio turned to Raskar for inspiration.

Raskar and his colleagues had already used streak cameras to reconstruct images of 3D objects hidden behind walls. They did so by using a technique known as non-line-of-sight (NLOS) imaging that analyzes light scattered multiple times in a surrounding environment. But generating the final images took several hours of acquisition time and an equal amount for data retrieval, making it impractical for real-world applications in which you need to find a hidden (often moving) object or person, like search-and-rescue or combat.

In 2015, Faccio proved SPAD cameras could perform NLOS imaging in real time, albeit without reconstructing the detailed 3D shape of the object. “We were the first to show two things: that SPAD cameras can be used for NLOS imaging, and that they can detect the position of a hidden moving target in real time,” he explains. “We showed that this technology could go from a very nice and amazing conceptual idea to something that could be done cheaply and at close-to video frame rates.”

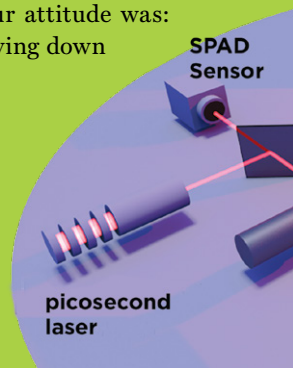
He placed objects behind a wall and then set up a 32×32 pixel SPAD camera and laser pointing at a space on the floor to the side and beyond the wall. The imaging system recorded the time it took for laser light to scatter off

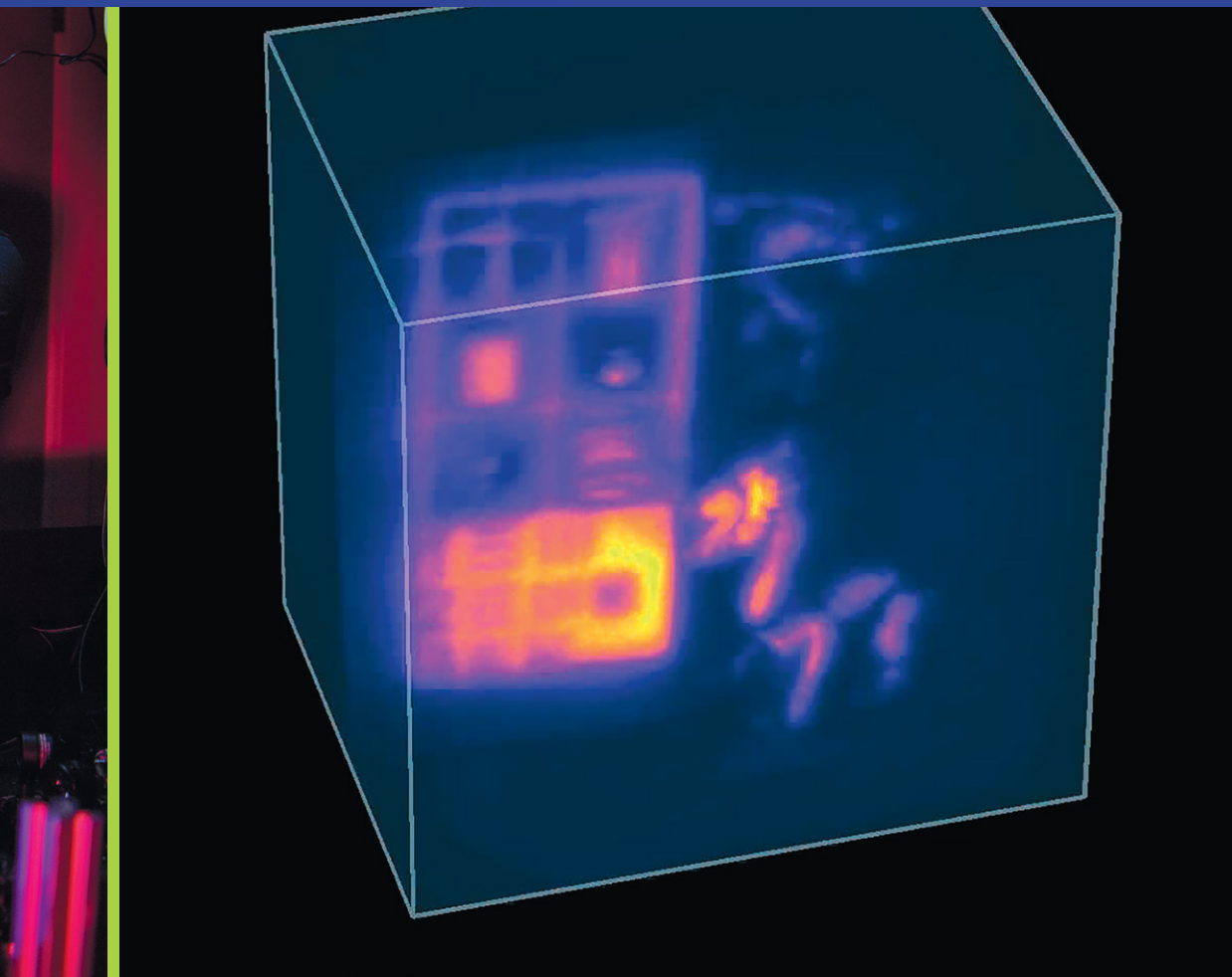
the floor, reflect off the hidden object, and return to the floor, where it was picked up by the SPAD camera. Temporal and spatial information recorded by the SPAD camera then fed an algorithm to retrieve the target’s position and track its speed and position in real time when in motion.

Since then, others have developed the NLOS technique even further. For example, Gordon Wetzstein at Stanford University and colleagues built highly efficient algorithms that process raster-scanned single-photon data on a wall to reconstruct a 3D scene hidden around a corner. More recently, his team pushed SPAD data capture to its limits, in one project reconstructing objects hidden behind a thick slab of polyurethane foam, and in another imaging moving 3D objects through the keyhole of a closed door.

With these and many more experiments proving the ability of SPADs, by the time Faccio had got round to actually recording his Hawking radiation analog moving along a fiber in 2016—the original reason for using SPADs—he realized that the technique was useful for much more than just capturing light in flight. “We had moved on a bit,” he recalls. “Our attitude was: We’ve taken a video of our black holes moving down a fiber—amazing. *Now* what can we do?”

Non line-of-sight imaging of a hidden object using a SPAD camera. ▶





Members of the Extreme Light Group at Univ. of Glasgow (left).

Using a wave migration algorithm, hidden objects are reconstructed (right) by measuring echoes of light with a SPAD camera.

Both Wetzstein and Faccio see a host of applications for SPADs. “Think about a self-driving car that can see around corners and make safer decisions that way,” suggests Wetzstein. “Or the recent earthquake in Turkey and Syria: how helpful would it have been to have had imaging systems that can see inside the structures of collapsed buildings?” Adds Faccio: “It can also be used for bioimaging microscopy or for super-resolution imaging, looking through fog.”

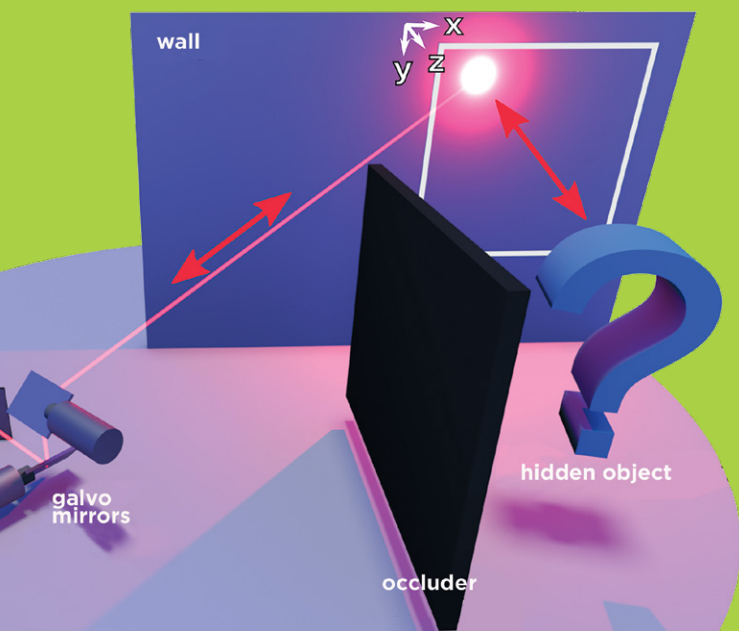
Companies such as Hamamatsu, Sony, Canon, and STMicroelectronics have realized SPADs’ potential, too, bring-

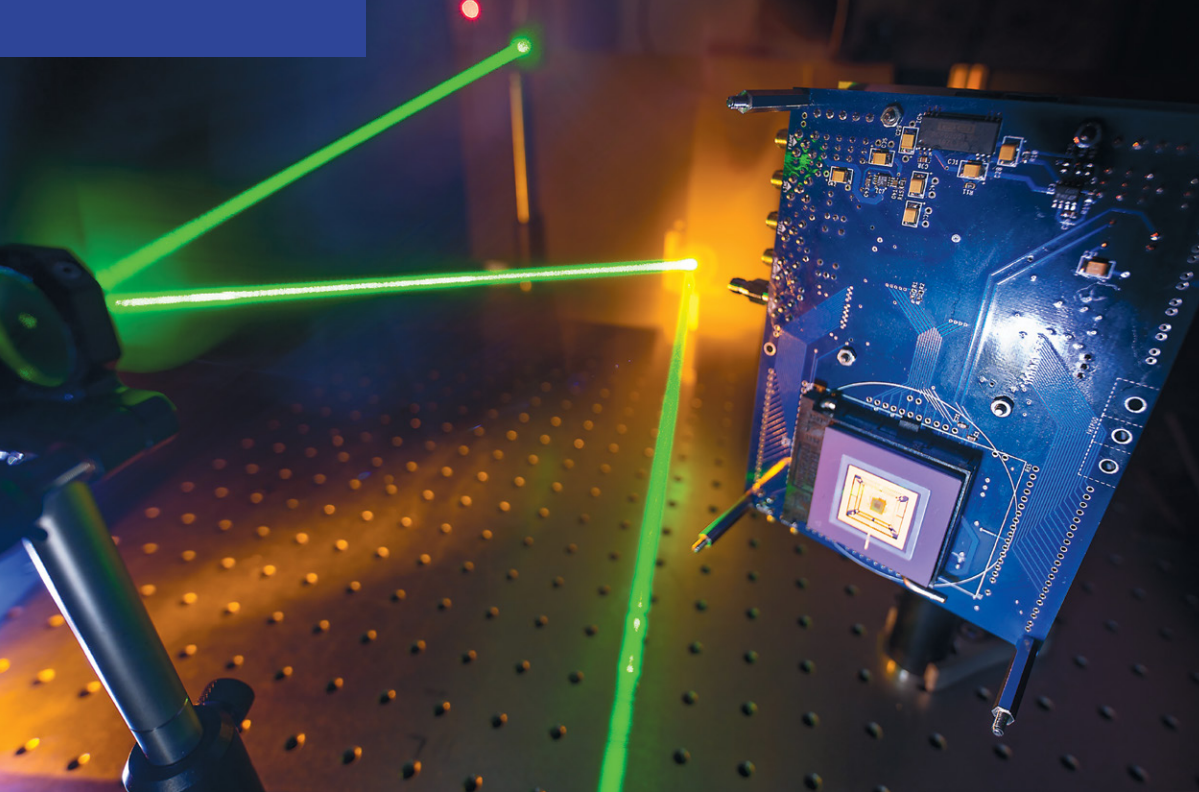
ing significant improvements in SPAD capabilities. “The big companies have reached a very high level of miniaturization and high performance,” explains SPAD engineering expert Federica Villa of the Polytechnic University of Milan, Italy. “They have their in-house technologies that allow them to achieve a very dense array of SPAD sensors, very many pixels, and also a very small form factor.”

These attributes are opening new commercial applications to explore. For example, Hamamatsu and Sony have developed SPAD depth sensors aimed at improving driver-assistance technology and self-driving vehicles. The sensors are intended for automotive lidar systems because they can determine, with high precision, the distance to an object by detecting the time of flight of a signal emitted from a light source until it returns to the image sensor, after being reflected by an object.

The main advantage of SPAD-based lidar is that it can detect single photons, which is the secret to high-precision depth measurement even from a long distance, allowing more accurate determination of the positions and shapes of vehicles and pedestrians.

SPADs could also soon be improving smartphone and security low-light camera performance, driving better medical and scientific imaging instruments, and enhancing augmented-reality experiences. “Hamamatsu is actively developing SPAD arrays with improved characteristics like high photon detection efficiency, lower dark count rate, and





One of the Extreme Light Group's quantum microscopes.

low crosstalk,” says Hamamatsu Applications Engineer Klea Dhimitri. “SPAD arrays are enabling a wide range of applications, from Raman spectroscopy to flow cytometry to lidar and quantum technologies.”

But these applications merely touch the surface of what SPADs could mean to science and society in the future. To fully explore the gamut of possibilities SPADs and other light-based technologies open, Faccio moved to the University of Glasgow in 2017 where his Extreme Light Group—now consisting of around 25 researchers—has since worked on a host of experiments harnessing light to answer fundamental physics questions and develop devices that benefit society.

Topics range from highly practical to extremely speculative, and not all involving SPADs. For example, some members of the team are developing a touch-free diagnostic and monitoring device for cardiovascular disease. The device captures and interrogates images from a high-frame rate CMOS camera of the back-reflected speckle pattern induced by a weak laser beam shone at a patient's neck.

Another project aims to construct a quantum microscope. Working in collaboration with international partners, including Villa who built 24×24 pixel SPAD arrays for the project, Faccio and colleagues harnessed a quantum phenomenon called (HOM) interference to create microscopic images of surfaces. The researchers hope to refine their design to build a practical quantum microscope capable of resolving extremely small features like cell membranes or even strands of DNA.

A more speculative research direction builds on this project. Faccio intends to use the HOM imaging setup to see if acceleration can generate entanglement. “Last year, we demonstrated that theoretically the curved space that you get from acceleration can actually generate entanglement,” explains Faccio. “When we finally do the experiment, it's going to be a very important result because there's an indirect link to gravity.”

All the fundamental forces of the universe are known to follow the laws of quantum mechanics, except one. Gravity is the odd one out, refusing to bend to quantum descriptions and instead demanding its own theory: general relativity. But general relativity and quantum mechanics don't mix when subjected to the most extreme conditions the universe can produce. Therefore, the argument goes, there must be a truer description of gravity—quantum gravity—that we have just not yet found.

Faccio is not claiming positive results from his experiment would provide long-sought evidence for quantum gravity, but it could pave the way for a deeper understanding of gravity's nature. “Could it demonstrate quantum gravity, strictly speaking? No,” he says. “Is it relevant? I think absolutely.”

On first inspection, there appears to be no clear bigger picture or unifying aim to the work in the Extreme Light Group. “We're doing stuff from quantum in curved spacetime, quantum sensing, computational imaging, looking behind corners, looking down microscopes, cancer research,” says Faccio. In fact, he had to split the group into three labs—the Computational Imaging Lab, Quantum Physics Lab, and Human Augmentation Lab—to provide team members structure when they “were getting a bit lost” in the radical cross-disciplinarity and varied research themes they were pursuing.

But zooming out, a picture emerges of a subtle influence pervading all of the Extreme Light Group's work for the past decade: a single TED Talk inspiring a researcher to capture and image light.

BENJAMIN SKUSE *is a science and technology writer with a passion for physics and mathematics whose work has appeared in major popular science outlets.*

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DIGGING THE DARK HOLE



By **William G. Schulz**

NASA's Nancy Grace Roman Space Telescope is scheduled for launch in 2027.

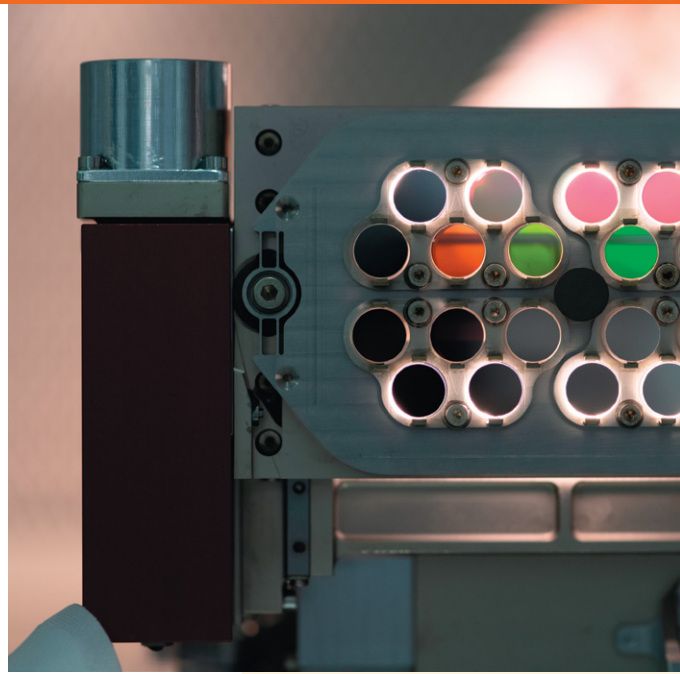
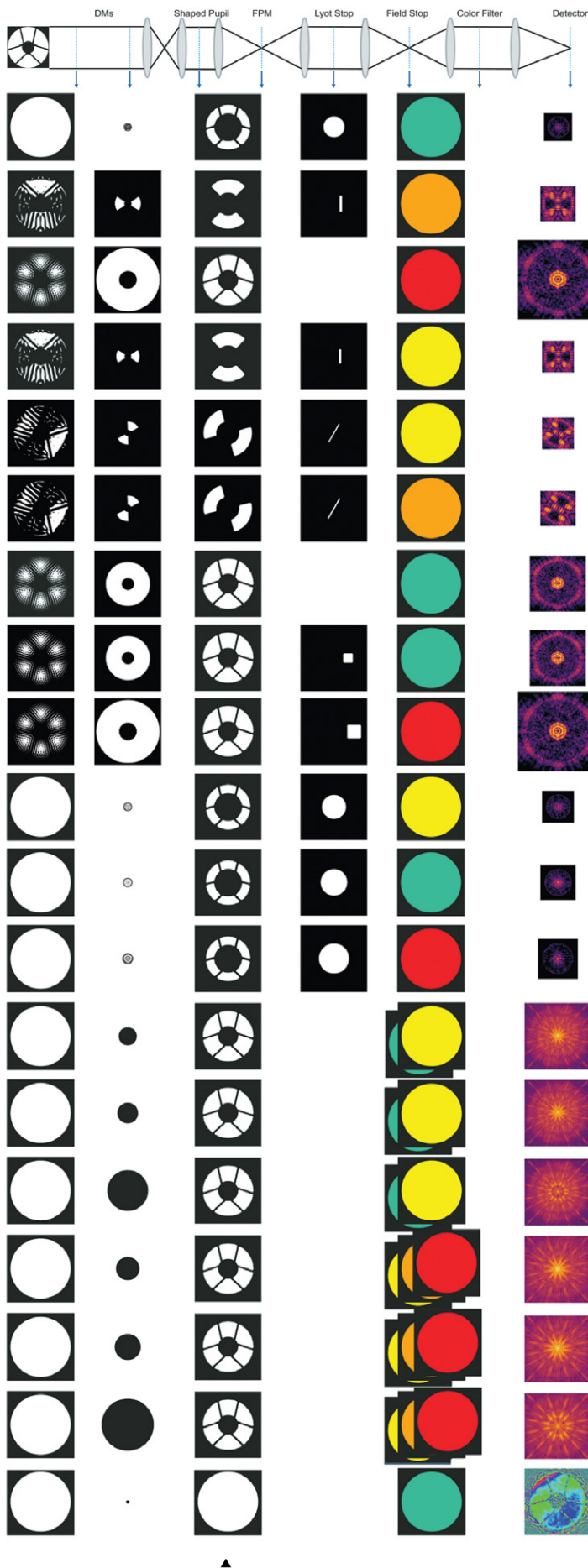
Coronagraphy and the Quest to Find Other Worlds

WHEN FRENCH ASTRONOMER

Bernard Lyot invented the solar coronagraph in 1939, he discovered a simple method for observing the hot, gaseous outer layers of the Sun without having to wait around for a total solar eclipse. By artificially blocking or suppressing most of the sunlight coming into his telescope, he could gather the data of greatest interest for his research.

But decades passed before coronagraphy—valuable as it is—was used to study much more than our nearest star.

Fast forward to today—some three decades after the first discovery of an exoplanet—and a cadre of astronomers and optical engineers are taking the elegant simplicity of Lyot's invention to new and exciting extremes. With advanced versions of the coronagraph—supplemented by adaptive optics, wavefront sensing and control, and powerful computational image processing—they are searching for worlds far beyond our own solar system. Their ultimate goal: Direct imaging of rocky exoplanets in the habitable zones—for life as we know it—around the stars they orbit.



Almost everything about coronagraphy and the search for exoplanets is an extreme, says Julien Girard, an exoplanet researcher at the US Space Telescope Science Institute (STSCI). “It’s extreme in terms of contrast. It’s extreme in terms of the technology. On the ground, we call the adaptive optics extreme adaptive optics because it’s basically adaptive optics on steroids. It’s like the Formula One of astronomy.”

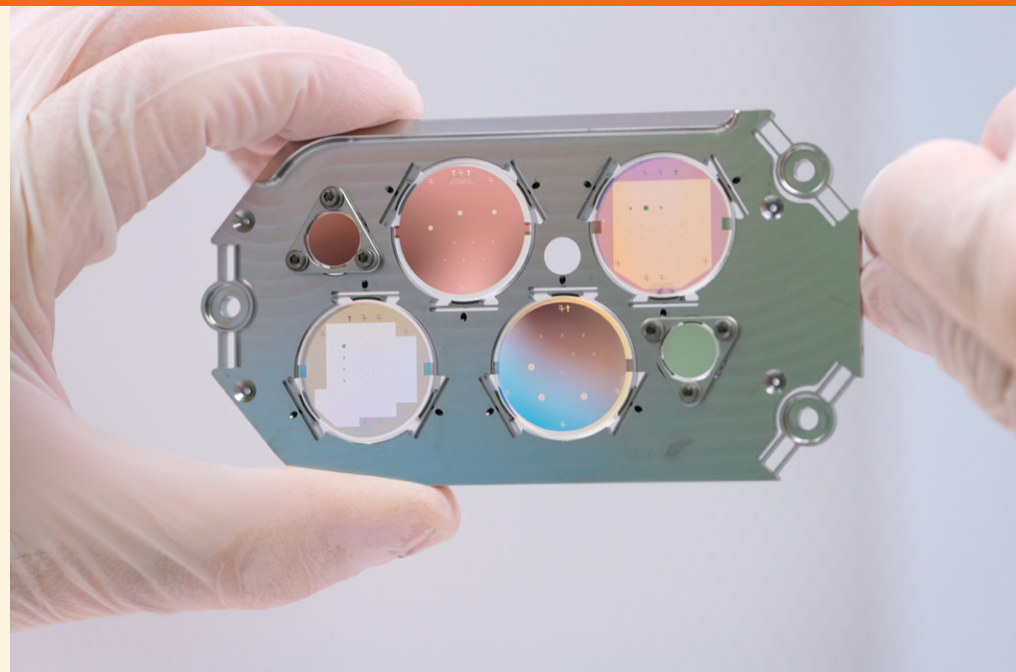
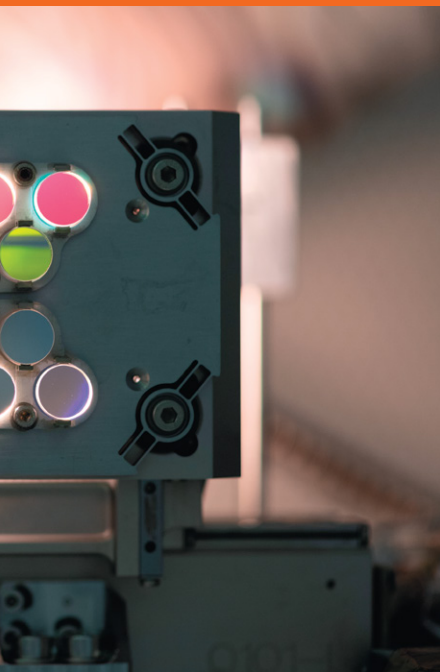
“In the late 1990s, there was really an explosion of papers [on coronagraphy], especially triggered by the first discovery of exoplanets using radial velocities,” says Rémi Soummer, director of the Russell B. Mikidon Optics Laboratory at STSCI. When an exoplanet orbits a star, astronomers discovered, the radial velocity of the star will appear as spectra that are first blue- then red-shifted as the planet makes its rounds, crossing the light paths streaming toward humanity’s eyes in the sky.

Once it was known that exoplanets could be found with methods like radial velocity, “the question became, can we make images of them?” says Soummer, who began his graduate studies in the late ‘90s. Some of his early work centered on how to make coronagraphs better, and he went on to work on coronagraphs for such projects as the European Southern Observatory’s (ESO) Very Large Telescope (VLT) as well as the Gemini Planet Imager, both in the Chilean Andes.

And though coronagraph technology has evolved for newer instruments, the concept remains the same. “The most basic coronagraphs are a physical mask to block starlight, just like you would put your thumb in front of the Sun so as not be blinded,” explains Girard. But the ability to see visible light from exoplanets is still not so easy. With today’s coronagraphs, such as the one onboard James Webb Space Telescope, the achievable on-sky contrast between a planet and the star it orbits is somewhere around 10^{-5} , in rare cases 10^{-7} . Dedicated

The full set of coronagraphic masks for the Roman Space Telescope’s coronagraph instrument.

Credit: Poberezhskiy et al., Proceedings of SPIE (left)



The color filter assembly (left) and focal plane mask (right) that will be part of the coronagraph instrument onboard NASA's Nancy Grace Roman Space Telescope.

future missions to hunt habitable exoplanets will need to supersede that by orders of magnitude.

Today's coronagraphs "have a physical mask that is in the focal plane of the telescope to block the starlight," says Girard. "And then we do what we call a reimaging of the pupil [where light enters the telescope]. And that's where we put another mask, which we call a Lyot stop after Bernard Lyot." That mask is slightly smaller than the pupil (usually the primary mirror), and without it the telescope would still refocus some of the scattered light in the focal plane—that is, there would still be some light contamination from the star. So, at the most basic level, a basic coronagraph has one mask in the focal plane, and a Lyot stop mask in the pupil plane.

Coronagraphs for exoplanet research are part of the optical instrumentation on some of the largest ground-based observatories like the VLT and, in Hawaii, the Keck Observatory telescopes. They will be part of the first, second, or third generation instruments for new ground-based observatories like the ESO's Extremely Large Telescope scheduled to come online within about a decade.

More than 5,000 exoplanets have been discovered so far using a variety of methods, including direct imaging with and without coronagraphy.

And coronagraphy will continue to be important for both ground- and space-based astronomy for many years to come. "Everything we do in high-contrast imaging is done in a tiny field of view," Girard says. "The patch of sky we're looking at [from ground-based instruments] is just the star and a little bit around." Because they are looking so far out in the universe, in

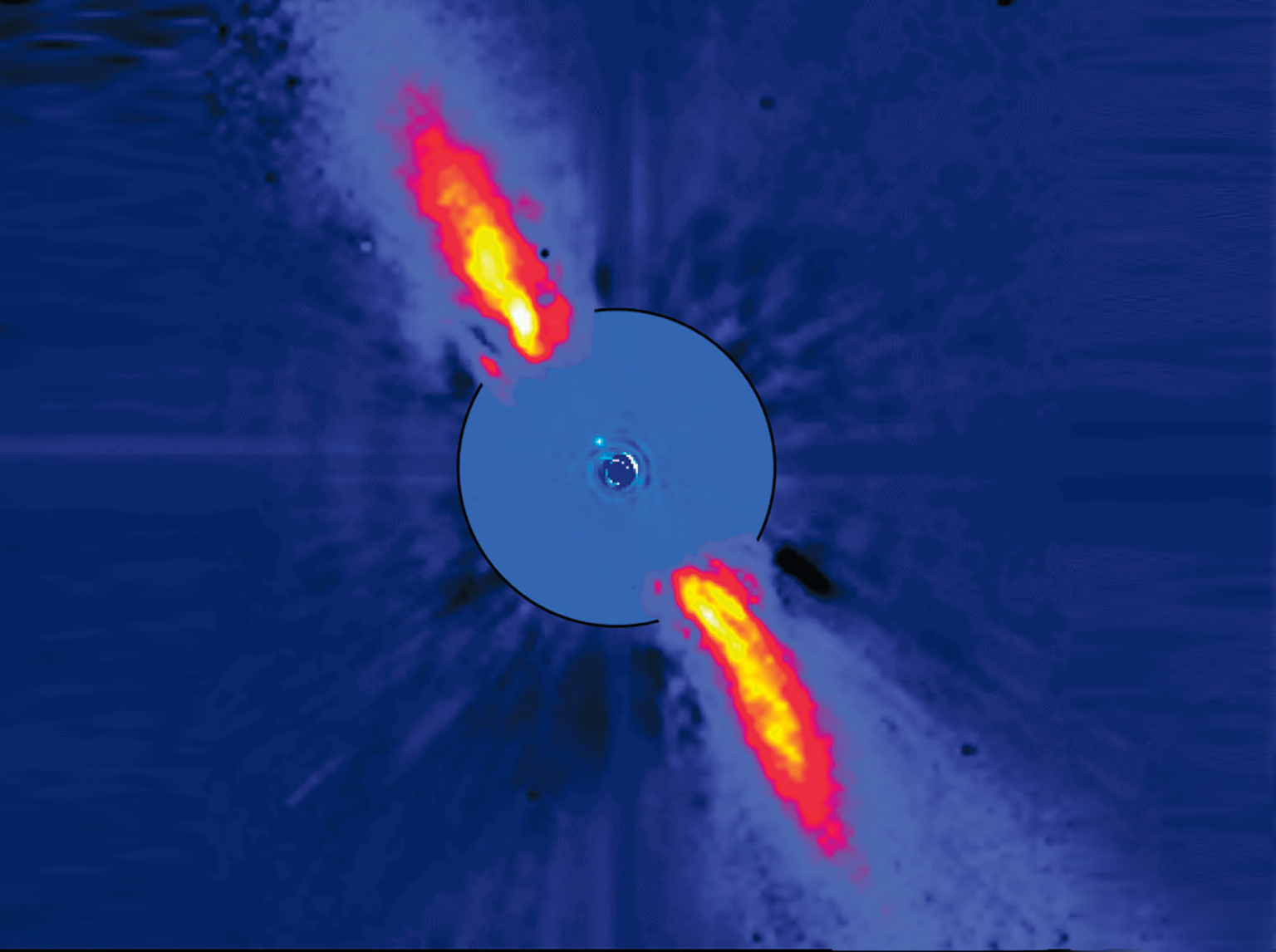
a narrow field, at very specific objects, "We are not so much affected by light pollution or low-Earth orbit satellites, for example."

What's more, he says, "we need ground-based telescopes with 30 to 40 m mirrors [for wider angular resolution], and we are probably not going to launch large-enough telescopes for habitable planet imaging from space for a long time." On the ground, there can be more telescopes for the same amount of money as one space telescope, and "with more and bulkier instruments you can access different techniques simultaneously, which is more difficult to do in space because you usually have to decide everything once, in advance, unless robotic servicing is an option."

But coronagraphy with space telescopes is vital, too, and has a robust future in astronomers' plans even decades from now. Both the Hubble (HST) and JWST have coronagraphs to look for exoplanets, and there will be a coronagraph testbed instrument on the National Aeronautics and Space Administration's (NASA) Nancy Grace Roman Space Telescope scheduled for launch in 2027. Waiting in the wings, in the very early planning stages, is NASA's Habitable Worlds Observatory (HWO), a space telescope that will be dedicated to the search for exoplanets. It will require high-contrast imaging on the order of 10^{-10} between the planet and the star it orbits. That's a power not yet achievable with today's instruments; however, researchers feel confident in the path they are forging.

The coronagraph instrument on the 2.4 m Roman Space Telescope, for example, will aim to do extremely high-contrast imaging of exoplanets in visible light as a demonstration test for the technology to be used on HWO.

"As a technology demonstrator, the Roman coronagraph was designed to reach science goals, and so those will be like 10 to the minus nine contrast rather than 10 to the minus six or seven that JWST, HST, or the ground-based telescopes are currently shooting for," says John Krist, a research scientist on the Roman coronagraph team at NASA's Jet Propulsion Laboratory (JPL) in California.

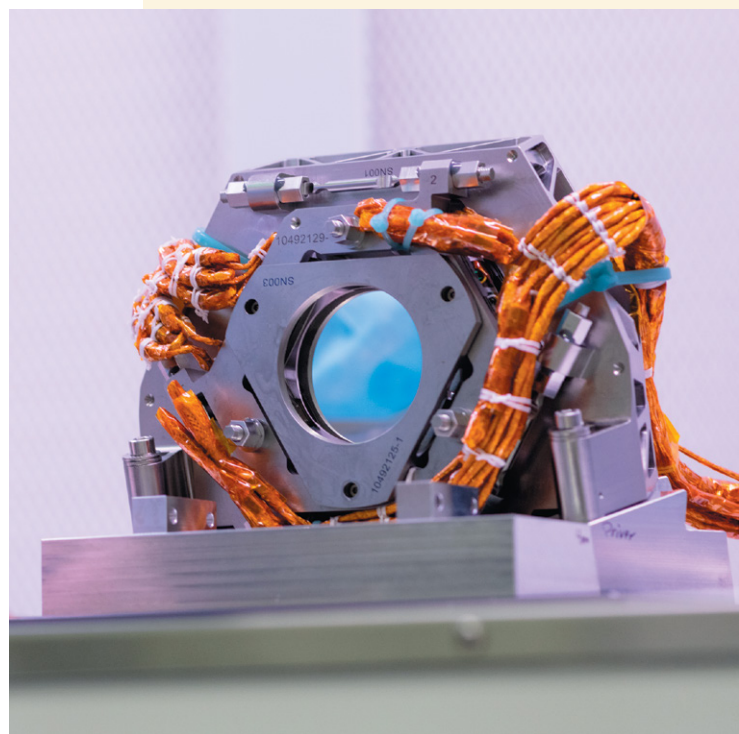


For exoplanet imaging with the coronagraph, “We’re sensitive to wavefront errors on the order of tens of picometers,” Krist says. “By comparison, a hydrogen atom is 100 picometers in diameter, so we have to make corrections [to the mirrors] that are on the order of the diameter of an atom or even less.”

Astronomers sometimes refer to coronagraphy as “digging the dark hole.” Krist explains: “Starting with the light around the star, when you look through any instrument it’s going to have a diffraction pattern, it’s going to have scattered light from polishing errors on the mirror and the optics and all that stuff.” He says another way to think of these distortions is that they are like glare from the Sun through a windshield, “and you’re trying to look for a very faint planet in that sea of light.”

The trick is to create a region around the star where that sea of light is suppressed enough that the planet comes into view. With the coronagraph in place and wavefront control via the deformable mirrors, “You want to create a dark hole around the star. You keep digging ‘dirt’ until you get this dark, dark hole. That’s what we mean by digging the dark hole,” says Krist.

Steering mirror component of the coronagraph instrument. ▶



Stellar coronagraphy began with astronomers looking for dust disks around stars like Beta Pictoris.

Rather than diffracting light everywhere equally around the image of the star, Krist explains, the coronagraph on Roman is set up to diffract the light in certain directions, and by doing so create two dark zones around a star.

On Roman, Krist says, “We first use the hybrid Lyot coronagraph to image the field around the star to find planets, since it can see over a 360-degree annulus around the star.” Once astronomers find a planet, they add a shaped-pupil coronagraph to the mix. It has a smaller field of view, but since they know where the planet is, it can be positioned correctly. The shaped-pupil coronagraph can be used to direct light reflected off the planet through a prism, which separates it into colors. This is where researchers say they will find the signs of biological life, if it exists, on a planet under observation.

Asked if the quest for exoplanet imaging has meant something of a renaissance for coronagraphy, Krist says that for stellar coronagraphy—solar coronagraphy being a separate field—“we started out looking for dust disks around stars, notably Beta Pictoris. And then we started looking for brown dwarfs. We went after the easy targets first, things that you couldn’t see without a coronagraph, faint stuff near bright stars, before getting to planets.”

But the real key for exoplanet imaging with coronagraphy, he says, has been the advent of deformable telescope mirrors for wavefront control.

“It really took until we had deformable mirror technology in the early 2000s, where we could combine a coronagraph and deformable mirrors and get down to the contrast levels that you could see exoplanets.”

The big newsmaker event for future space-based coronagraphy would be detecting signs of biological life in the atmosphere of another planet, says Marie Ygouf, another Roman coronagraph project scientist at JPL. She is both an optical engineer who has worked on building extremely large telescope mirrors and an astronomer.

Finding habitable worlds, she says, will mean placing much larger and very expensive telescopes in space. “You really need to have a dedicated observatory that has been designed with exoplanet imaging in mind,” Ygouf says. Indeed, a telescope like the nascent HWO is a goal of the astronomy community set forth in its most recent decadal survey.

The Roman telescope is not dedicated to exoplanet imaging and was not designed with direct imaging of exoplanets in mind. “That limits a lot of what the Roman coronagraph instrument can do,” Ygouf says. The coronagraph will not be on the lookout for rocky planets in habitable zones. Rather, its goal is to image so-called gas giants, planets more like Jupiter than Earth or Mars.

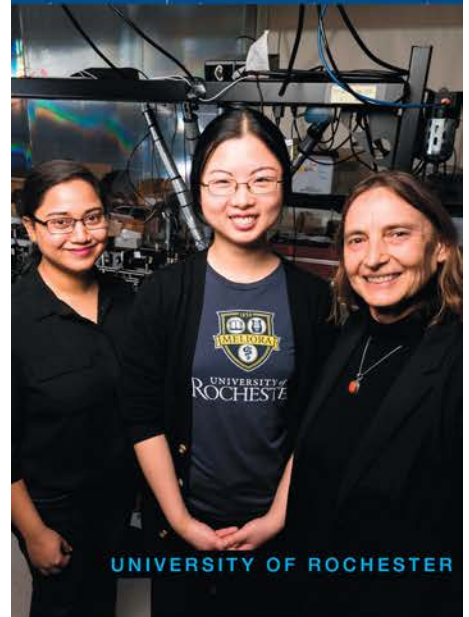
But that’s not to downplay all that astronomers hope to achieve with the Roman coronagraph. “When you have an instrument that is able to take pictures of exoplanets, it would also be able to take pictures of the circumstellar environment. That means we would be able to detect disks around the star that are the components of planet building. We expect with Roman that we might be able to revolutionize the study of circumstellar environments,” Ygouf says.

But “the real reason people want to do coronagraphy is to see another Earth,” says Soummer. “That’s been the real motivation from the beginning. Can we see other Earths around other stars? Can we detect life? Can we find other terrestrial planets like ours?”

WILLIAM G. SCHULZ
is Managing Editor of
Photonics Focus.

The Institute of Optics HOME

Duration	Full Time - One Year Part Time - Two Years
Time Commitment	Full Time - 40 Hours/week Part Time - 10-30 Hours/week
Degree	Master’s of Science in Optics
Platform	Mostly Online
Topics	Optics and Optical Engineering

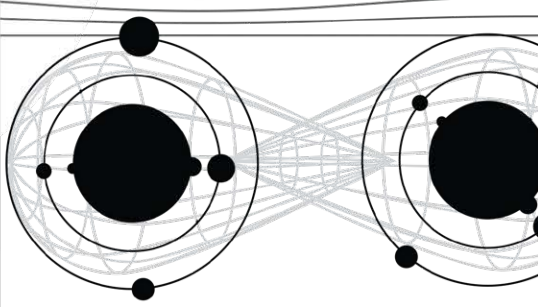
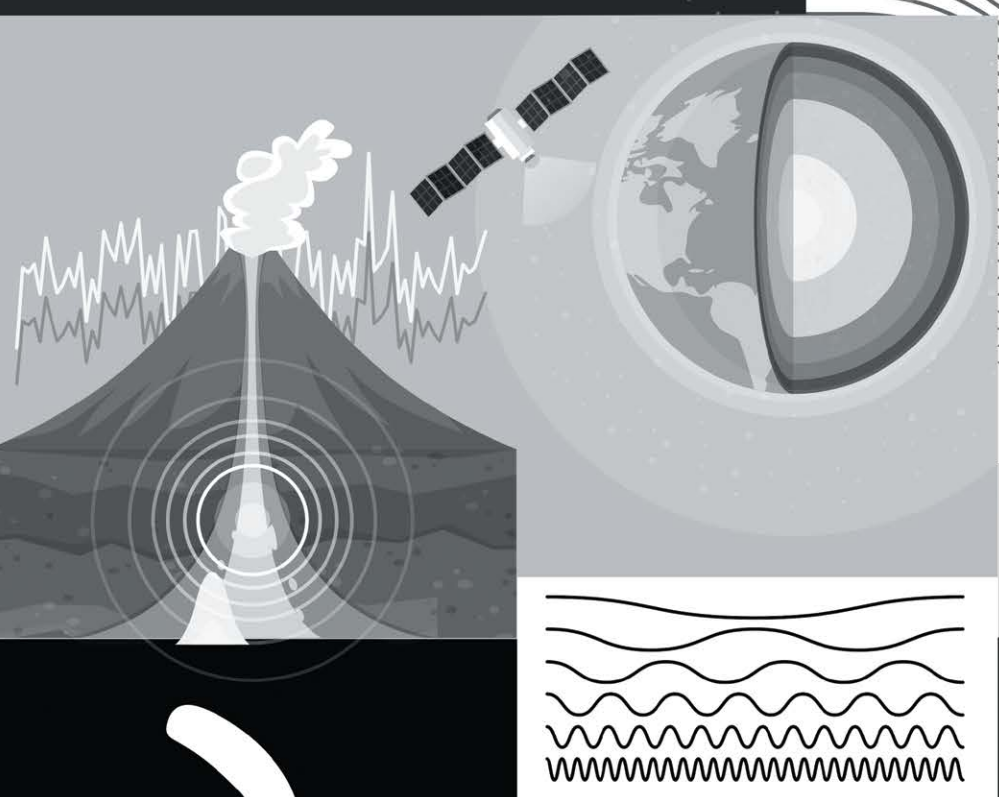
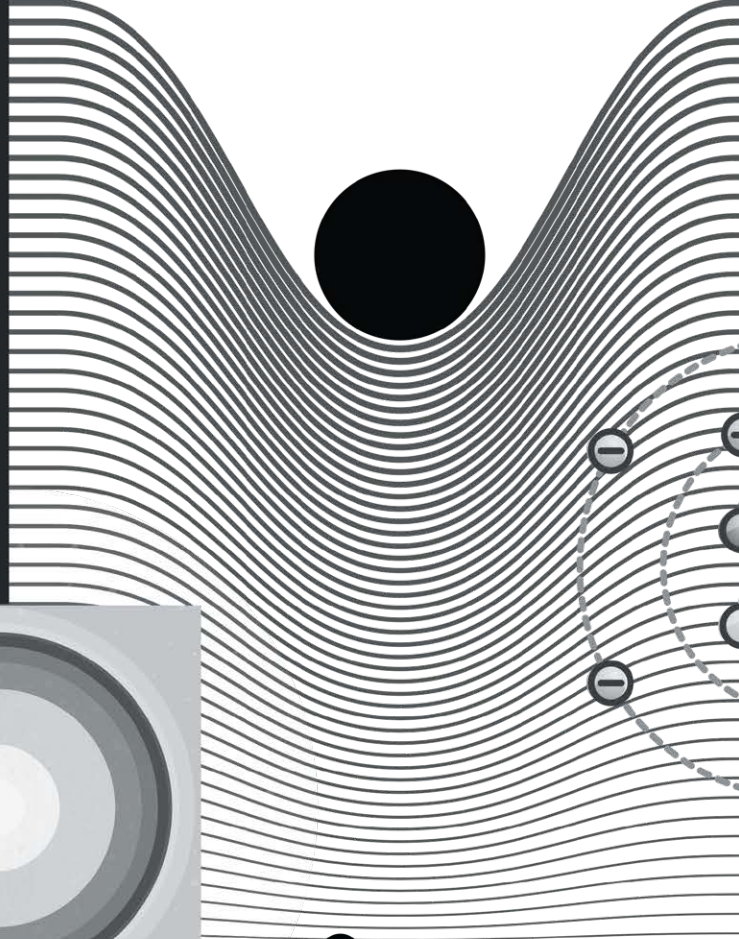
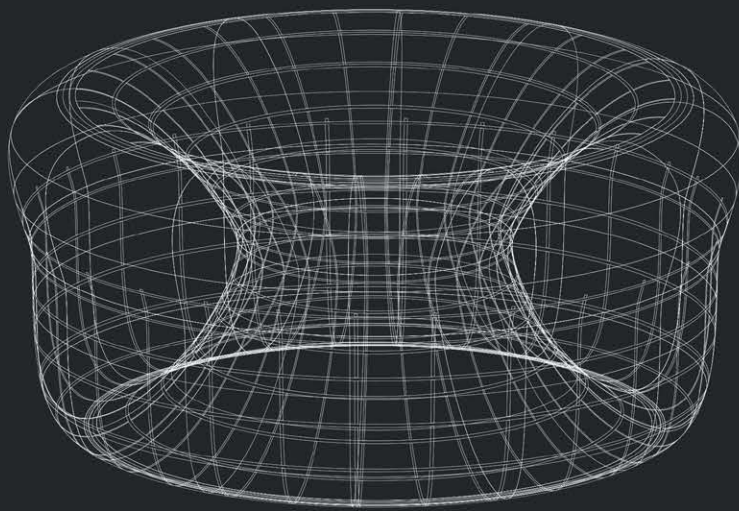


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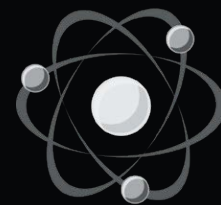
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$$i\hbar \frac{\partial}{\partial t} |\psi_n(t)\rangle = \hat{H} |\psi_n(t)\rangle$$



Probing the Quantum Earth

By **Mark Wolverton**

At first thought, quantum physics and geophysics would seem to have nothing at all in common. The quantum world is all about the very small, the realm of the subatomic, the mysterious and paradoxical phenomena of spins, entanglement, and cats alive and dead at the same time. Geophysics, on the other hand, is about as tangible and large-scale as it gets: the planet we're standing on and the immensity of its many moods, including earthquakes, volcanoes, and tsunamis. How can the two disciplines possibly be linked? Yet there's a strong connection between the extremes of the quantum microworld and the planetary macroworld, one that researchers are using to study the inaccessible depths of the Earth.

One of the links between the quantum world and the macroworld involves gravity. Although it's not noticeable in our everyday lives, the force of gravity is not exactly the same everywhere on Earth. It varies from one place to another depending on local conditions such as the types and density of rock and other forms of mass. Geologists use these tiny variations to find water, minerals, and other materials, and to study volcanoes and fault lines and various other geological phenomena. Devices for measuring gravity, known as gravimeters, have been around for almost a century, but the traditional variety, generally based on a mass suspended on a spring, have some serious limitations.

"They're prone to drift as the spring stretches over time and have differences between instruments due to manufacturing tolerances and so on, which means that different instruments have slight differences in their response," explains Daniel Boddice, a civil engineer at the UK's University of Birmingham. "Springs are also very sensitive to vibration in the ground, so-called microseismic noise, which can be from various sources such as wind, traffic and people movement, ocean waves, etc."

Boddice is part of a research group at Birmingham that is taking a different approach to gravimetry, using a technique called cold-atom interferometry. This exploits the quantum physics principle of wave-particle duality, in which atoms and subatomic particles can behave both as particles and waves of light or other electromagnetic radiation. Atoms of a particular type are cooled by lasers to within a fraction of absolute zero and then placed into the strange quantum state known as superposition, in which they briefly exist in two states at the same time—much like the famous example of Schrödinger’s unfortunate cat, locked in a box and simultaneously alive and dead. The fleeting quantum states of the atoms are measured, and the slight differences in measurements mathematically combined to create an interference pattern from which information—in this case, gravimetric data—can be obtained. The idea of using supercooled atoms to measure gravitational fields by interferometry can be traced back about 30 years to the groundbreaking work of Nobel Prize-winning physicist and former US Energy Secretary Steven Chu.

Previous work in cold-atom interferometry was extremely promising, but essentially confined to the laboratory because of the bulky and sensitive equipment required. Although the technique avoids the problems of the traditional spring-based instruments, the extreme fragility and transience of the quantum phenomena involved in cold-atom interferometry has made practical application a huge challenge.

“QUANTUM GRAVITY SENSORS HAVE THE CAPABILITY TO REVOLUTIONIZE OUR UNDERSTANDING OF UNDERGROUND SPACE.”

Boddice and his colleagues are changing all that by perfecting an instrument that’s portable, robust, and small enough to take out into the field. Their quantum technology (QT) gravity gradiometer, described in a 2022 *Nature* paper, is a cylindrical instrument a little less than two meters high, mounted on a wheeled cart, with its controlling electronics also on wheels and tied to it by cable. Arranged in an hour-glass configuration inside the instrument are two counter-oriented single-beam magneto-optical traps (MOTs), one aimed upward and the other downward. Clouds of supercooled rubidium atoms are dropped through the device, vertically separated by a meter, and measured simultaneously as they fall. Using two clouds of atoms as test masses not only adds valuable redundancy, but allows more sensitive measurements of the gravity gradient, the subtle differences between the two.

“There are several advantages of a QT gravity gradiometer based on cold-atom interferometry,” Boddice explains. The two atom clouds used in the instrument have what’s called a uniform test mass—that is, they weigh exactly the same today or in a year. “That makes the measurements extremely accurate and highly repeatable, even between different instruments,” says Boddice. The lack of mechanical parts also means less wear on the system and the functional drift during a survey is much lower. Using a single laser on atom clouds at two different heights “locks” the two clouds of atoms, suppressing microseismic vibrational noise, simplifying the measurements, and allowing more survey points to be collected in a shorter amount of time. “Taking a gradient is also less sensitive to the instrument being tilted, which relaxes the need to level the instrument as accurately in the field, which is especially challenging in certain ground conditions,” Boddice adds. And unlike other instruments, which can only take readings when stationary, the cold-atom technique can potentially take measurements even on a moving platform.

The *Nature* paper describes a successful field test of the Birmingham team’s instrument in which they detected a 2 × 2 m utility tunnel buried half-a-meter deep beneath the ground between two buildings. Their equipment accurately located it solely via the subtle gravitational effects the tunnel created, despite the possibly complicating interference, both gravitational and vibrational, from the nearby buildings, other structures, and passing vehicles. The test both validated the team’s previous computer models of how the QT gradiometer might operate, and it opened the door toward the development of a truly practical and wholly portable field instrument for a wide range of applications.

“We’re working towards other applications such as aquifer monitoring and planning application-specific field trials,” says Boddice, “especially for moving platforms such as railways, as well as how to integrate the instruments with other sensors.” For example, it might be possible to take a hybrid approach and combine highly accurate quantum sensors and cheaper, more ubiquitous MEMS devices.

Although the Birmingham team’s instrument will still need further refinement and development before it’s convenient and mobile enough for a surveyor’s toolkit, Boddice is enthusiastic about the promise of quantum technology gravimetry. “I would love to see quantum gravity sensors being used more widely and think they have the capability to revolutionize our understanding of underground space, enabling us to make better planning decisions. Gravity surveys have potentially the best resolution with depth of any geophysical technique,” he says.

While the technology has obvious applications for construction and civil engineering companies looking for hidden tunnels, pipelines, abandoned mineshafts, and other subterranean hazards, that’s only one possibility. QT gravity sensors could also find underground mineral and water deposits,

A quantum phase transition called spin crossover can be used to visualize deep-Earth processes like subducting tectonic plates.

help archaeologists locate buried artifacts without digging, and even be used by the military for underwater navigation.

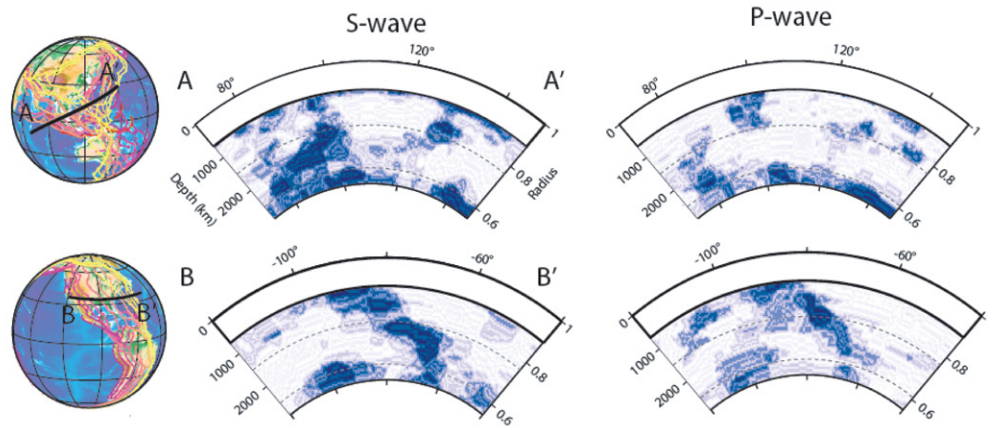
“I’d like to see QT gravity gradiometers used more proactively than reactively to manage the underground and do preventative maintenance on infrastructure,” Boddice notes. “I hope that by making gravity a faster and more reliable method for underground mapping, there will be a more widespread adoption and more opportunities to use the sensors to solve challenges for societal good.”

While some investigators are using quantum physics to build instruments to directly measure and map the larger world, others are finding ways to use quantum phenomena to study the unseen depths of the planet. Renata Wentzcovitch, a condensed matter physicist at Columbia University, is using a particular quantum phenomenon found in certain minerals to help geophysicists understand and describe what’s happening deep in Earth, a thousand miles or more underneath our feet.

In 2003, a group of researchers found that iron in ferropericlase, a magnesium-iron oxide mineral that comprises the second largest component of the Earth’s lower mantle, displays a type of quantum phase transition called a spin crossover at certain extreme pressures and temperatures—the same conditions that exist in that region. Wentzcovitch specializes in ab initio materials simulations and began investigating the spin crossover in ferropericlase, in particular, how it worked and how it might be detected in the depths of Earth.

Without direct access to the realm thousands of miles inside our planet, geologists have to use indirect means to visualize those regions, mostly based on constructing tomographic and other images using seismological data, much as a CT exam provides pictures of the interior of the human body. Wentzcovitch’s calculations showed that the spin crossover in ferropericlase would affect the characteristics of lower mantle rocks in detectable ways, such as its compressibility. “Wherever the material exists, the compressibility of that region is affected,” Wentzcovitch explains. “It’s a unique fingerprint.”

Wentzcovitch’s work provided a firm theoretical basis for that fingerprint, showing that the spin crossover would affect the Fe-O bond length in ferropericlase and thus its particular properties, especially elasticity and compressibility. Those changes would consequently affect how P- and S-waves, the main types of seismological waves studied by geophysicists, propagate through the mineral in the inner Earth in ways that are directly related to earthquake and volcanic behavior, convection in the mantle, and tectonic plate motion. “In collaboration with my group, I developed



a theory for the elastic properties, and we were able to predict the changes in compressive and shear wave speeds of ferropericlase at lower mantle conditions,” she says.

But theoretical predictions can be fiendishly difficult to isolate and detect, especially when dealing with something as delicate as quantum phenomena. Wentzcovitch started her investigations of the ferropericlase spin crossover in 2005, calculating every possible permutation of the phenomenon and how it might be detected. But it wasn’t until 2021 that she and her geophysicist collaborators could announce the actual detection of the ferropericlase spin crossover in the lower mantle. “The prediction of the velocity changes in lower mantle rocks is very, very subtle,” Wentzcovitch notes. She worked with seismologists and geodynamicists to search for these patterns of velocity changes in the lower mantle and identify them specifically in seismological data.

The identification of an exotic quantum phenomenon deep within our own planet is important not only in the understanding of Earth but also has implications reaching back to the origins of the solar system. An important open question in geophysics is related to the amount of ferropericlase in the lower mantle, says Wentzcovitch. If the composition of the lower mantle is the same as the upper mantle, “then the Earth’s composition is different from the solar composition and that of primitive meteorites that formed the Earth.” New mineralogical/thermal models of the mantle based on tomographic images can show the amount and extent of ferropericlase in the lower mantle. “The answer to this question will shed light on the planetary formation process that produced Earth from the solar nebula,” Wentzcovitch says.

From the origins of Earth, to its present-day and future moods and behaviors; from the infinitesimal realm of the quantum, to the scale of our entire planet, the work of these and other scientists is tying together the extremes of small and large, deep within Earth. Although quantum effects are rarely immediately obvious at the scale of our human perceptions, they still govern our world. One way or another, as Wentzcovitch points out, in the final analysis, everything is quantum.

MARK WOLVERTON is a freelance science writer and author based in Philadelphia.

2023 | SPIE and the Organic Growth Circle



SPIE, LIKE MANY SCIENTIFIC SOCIETIES, thrives as an organic community with sustained growth through the involvement, dedication, and efforts of its Members. Accessing and benefitting from the many services SPIE offers is the main goal for many Members as they advance their work and careers, either through in-person events or other offerings such as publishing or reading scientific literature in the SPIE Digital Library.

The Society's ever-growing membership speaks to the quality and breadth of the services it provides. One may attend a conference to listen to presentations or present a paper, converse with poster authors, stroll through the exhibition hall or browse to find new potential partners, listen to a panel session, keynote, or plenary talk, or mingle with colleagues and friends at the various networking sessions, receptions, awards dinners, and other social events at SPIE Conferences.

However, getting involved in the Society can also provide a great leveraging effect: It will not only further your professional development but your personal development, too. Your service will help the Society grow, which in turn bolsters the services it provides back to the community. This is the mechanism behind the organic growth circle.

Getting involved in the Society and being a community champion is rewarding and can be initiated at various levels: Participating or presiding in a student chapter, engaging in a technical committee, helping chair sessions and conferences, being a journal reviewer, stepping in to participate in a panel session, or acting as a member of a standing committee are some of them. These activities provide opportunities to further personal growth and develop precious communication and management skills that can help leverage your technical skills to further your career in industry or academia. It will also provide a great sense of satisfaction.

Recognizing and honoring the value that individuals provide to the Society and the larger optics and photonics community is important for all Members to take part in. Nominating colleagues for Senior and Fellow Members or for one of the 20-plus Society Awards to those who are volunteering and excelling in services to the community is a token of appreciation and provides an official recognition of the quality of their engagement. Being honored in this way can bolster a Member's confidence and help secure a continuation of such services for future generations.

I encourage you not only to actively engage in some of the exciting activities the Society offers, but also to help identify and reward community heroes. Self-nomination is also an option, and all awardee processes are done blindly by committee.

One of the great honors of being SPIE President is having the opportunity to meet and congratulate the year's awardees. It always gives me great joy to see the pride on their faces as they accept an award from their peers. By nominating them, you can bring joy to a colleague and show your appreciation and admiration for their work. I invite you all to take the time to make a nomination and help SPIE honor our community's best.

A handwritten signature in black ink that reads "Bernard Kress". The signature is fluid and cursive, with a long horizontal stroke underneath.

BERNARD KRESS
2023 SPIE PRESIDENT

SPIE

Deadlines and Events

May

- 3: Abstracts due for SPIE Laser Damage
- 3: Abstracts due for SPIE Optifab
- 15-18: Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023, Florida, USA
- 16: International Day of Light
- 16: SPIE International Day of Light Photo Contest opens
- 17: Abstracts due for SPIE Photomask Technology + EUV Lithography
- 17: Manuscripts due for SPIE/RIT Photonics for Quantum
- 17: Abstracts due for SPIE/COS Photonics Asia
- 26: Applications due for SPIE-BACUS Scholarship

June

- 5-8: SPIE/RIT Photonics for Quantum, Rochester, New York, USA
- 16: Abstracts due for SPIE Photonex
- 22: Voting opens for the SPIE 2023 Election
- 25-29: European Conferences on Biomedical Optics, Munich, Germany
- 26-29: SPIE Digital Optical Technologies, Munich, Germany
- 26-29: SPIE Optical Metrology, Munich, Germany

July

- 1: Nominations due for SPIE Society Awards
- 19: Abstracts due for SPIE AR | VR | MR 2024
- 19: Abstracts due for SPIE Photonics West 2024

August

- 2: Manuscripts due for SPIE Optics + Photonics
- 4: Voting closes for the SPIE 2023 Election
- 9: Abstracts due for SPIE Medical Imaging 2024
- 16: Abstracts due for SPIE High-Power Laser Ablation 2024
- 16: Manuscripts due for SPIE Sensors + Imaging
- 20-24: SPIE Optics + Photonics, San Diego, California, USA
- 22-23: SPIE-CLP Conference on Advanced Photonics, San Diego, California, USA

SPIE. PHOTONICS INDUSTRY SUMMIT

27 September 2023

Washington, DC, United States

Gather with government decision makers in Washington, DC

Help position the optics and photonics industry as the essential enabler of emerging technology. Discuss US federal policy and funding opportunities with industry executives and leaders from government agencies. Learn of investment plans that may help your company grow.

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2023

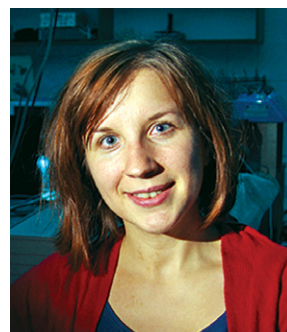
SPIE Society Awards

EACH YEAR SPIE HONORS INDIVIDUALS WITH SIGNIFICANT technical achievements and contributions to the Society through its 23 annual Awards. Recipients are selected by the Awards Committee from community nominations. We encourage Members to nominate people who deserve recognition, especially those from historically marginalized groups. Each issue of *Photonics Focus* highlights a selection of this year's recipients. See the entire list of 2023 Award Recipients at spie.org/2023awards.

Diversity Outreach Award

DANUTA SAMPSON, a research fellow at the University of Western Australia, is the recipient of the Diversity Outreach Award for her outstanding achievements in international educational outreach and leadership of activities promoting public engagement and diversity in science. Her outreach activities include events aimed at encouraging female students to enter STEM fields; serving as a mentor to female high-school and university students; initiating optics student chapters across the globe; and promoting professional development and scientific outreach to young and upcoming members of the optics and photonics community in Poland, Australia, and the UK.

The SPIE Diversity Outreach Award recognizes outstanding contributions to promoting diversity in the education, training, and participation of women and/or minorities in optics, photonics, electro-optics, or imaging technologies or applications.



Danuta Sampson

Rudolf and Hilda Kingslake Award in Optical Design

WILHELM ULRICH is the recipient of the Rudolf and Hilda Kingslake Award in Optical Design for his decades of transformative design solutions across a broad range of optical products, especially including lithographic optical systems and optical designs for photographic lenses, microscopy objectives, medical-imaging instrumentation, laser optics, metrology systems, and infrared optics. Ulrich recently retired from Zeiss Optics where he was head of optics research and design focused on microscopy and medical instrumentation.

The SPIE Rudolf and Hilda Kingslake Award in Optical Design recognizes significant achievement in the field of optical design, including the theoretical or experimental aspects of optical engineering.



Wilhelm Ulrich

Maiman Laser Award

SPIE FELLOW BO GU, founder, president, and CTO of BOS Photonics, is the recipient of the Maiman Laser Award for his critical innovations in industrial laser technology and for laser-industry leadership. Throughout his 30-plus year career, Gu has been a key player in the development and commercialization of fiber laser technology, particularly fiber laser marking and high-power fiber laser cutting, welding, cladding, and additive manufacturing.

The Maiman Laser Award recognizes sustained contributions to laser source science and technology at the highest levels.



Bo Gu

See the entire list of SPIE Award winners at spie.org/2023awards

Five Tips for Corporate Cybersecurity

IN TODAY'S DIGITAL AGE, CYBERSECURITY is an essential aspect of any organization. At SPIE, by securing the data and activities that support our efforts for the global photonics community we have gained insights on effective approaches and are working to share benefits with the community. Here are five effective ways to improve your company's cybersecurity and ensure a safe digital environment.

EDUCATE YOUR TEAM

Over 90% of all data breaches are the result of phishing attacks, according to a report from Cisco. By running internal phishing exercises and educating your staff with Ninjio you can reduce that risk. SPIE has been using Ninjio (www.ninjio.com) as a security awareness training platform for many years. It uses engaging, micro-learning videos to teach employees about various cyber threats. Now, SPIE Corporate Members qualify for a 20% discount from Ninjio. Reach out to corporatemembership@spie.org to learn about this benefit.

IMPLEMENT THE NIST FRAMEWORK

The US National Institute of Standards and Technology (NIST) Cybersecurity Framework is a comprehensive guide to managing and reducing cybersecurity risk. It provides a set of best practices, guidelines, and standards that can help organizations establish a strong cybersecurity foundation. By implementing the NIST Framework, your company can improve its security posture and enhance resilience against cyber threats (www.nist.gov/cyberframework).

INVEST IN A SECURE NETWORK INFRASTRUCTURE

A secure network infrastructure is the backbone of any organization's cybersecurity strategy. Invest in advanced security solutions, such as firewalls, intrusion prevention systems, and endpoint protection software. Additionally, adopt a zero-trust model and implement multi-factor authentication to ensure only authorized users have access to sensitive data and systems.

CONDUCT REGULAR CYBERSECURITY AUDITS

Regular cybersecurity audits can help identify vulnerabilities and gaps in your organization's security posture. By evaluating your company's compliance with industry standards, cybersecurity policies, and best practices, these audits can provide valuable insights and recommendations for improvement. Make sure to address identified weaknesses promptly and continuously update your cybersecurity strategy to stay ahead of evolving threats.

ESTABLISH EXECUTIVE SUPPORT FOR CYBERSECURITY

In the end, creating a culture of security starts at the top. To strengthen your organization's cybersecurity, gain the support and commitment of top-level executives. They should understand the importance of cybersecurity and its potential impact on the company's operations and reputation. By allocating sufficient resources, setting clear expectations, and encouraging open communication, executives will create an atmosphere where employees feel empowered to take cybersecurity seriously.

Improving your company's cybersecurity requires a comprehensive approach that involves executive support, adherence to best practices, staff education, investment in secure infrastructure, and regular audits. By implementing these five tips, you can create a more secure environment and safeguard your organization's valuable assets.

**SPIE CORPORATE MEMBERS SAVE
20 PERCENT OFF NINJIO,
A USEFUL CYBERSECURITY TOOL.**



SPIE Fellow wins Gordon E. Sawyer Award from the Motion Picture Academy

CINE LENS DESIGNER AND SPIE FELLOW IAIN NEIL received the Gordon E. Sawyer Award—and accompanying Oscar statuette—from the Academy of Motion Pictures Arts and Sciences. The award recognizes his lifetime of creative achievement as an optics designer for film.

As noted by the Academy, Neil has contributed “substantial, extensive, and innovative lens designs which have had lasting impact in motion picture cinematography.”

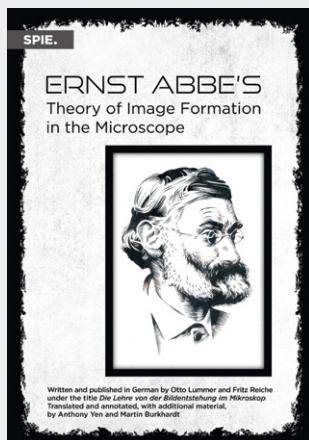
For camera-maker Panavision, he led the development of such innovative lenses as the Primo Macro Zoom lens that unlocked

new creative possibilities in cinematography for directors like Steven Spielberg in his science-fiction classic *Minority Report*.

“Because I come from a baker’s family, I won’t give this award a number,” Neil said at his acceptance speech on 24 February. “We just called it a baker’s dozen.”

With 13 Academy Awards, Neil now holds more than any other living person. The late Walt Disney holds the all-time record with 26 Academy Awards.

Read more at spie.org/NeilAcademyAward



SPIE Publishes English Translation of Abbe's *Theory of Image Formation in the Microscope*

ONE HUNDRED AND THIRTEEN YEARS AFTER its original publication, *Ernst Abbe's Theory of Image Formation in the Microscope* reappears as a newly published book, in English, from the SPIE Press. Anthony Yen and Martin Burkhardt provided translation, along with annotations and other new material. The book is available free online in the SPIE Digital Library. Print copies are available for purchase.

The book is an expanded version of lectures Abbe gave in 1887. It is based on notes taken by Otto Lummer, a professor

of physics at University of Breslau, who attended the lectures along with his assistant Fritz Reiche.

Yen and Burkhardt say the book is of more than historical value. They note that while today's lithographic systems used to fabricate advanced semiconductors can resolve close to 20 nm in pitch, the physics of image formation, as described by Abbe in the late 19th century, still apply.

The book discusses some of the innovative topics of Abbe's time. For example, it states that, for incoherent imaging, the resulting intensity is obtained by summing the intensities generated by individual luminous points. Today, one of the popular methods for calculating aerial image in microlithography is done in exactly this manner, and it is called Abbe's method.

As the lithography community continues its efforts to extend the resolution limit in patterning, one nanometer at a time, more innovative ideas are likely to emerge. Abbe's book may give some needed inspiration.

See the new book at spie.org/ErnstAbbe

SPIE Awards Nominations Due 1 July

YOU CAN HONOR A COLLEAGUE who has made outstanding contributions to optics and photonics by nominating them for an SPIE Award.

Since 1959, the Society's awards have recognized technical accomplishments and service to SPIE by honoring transformative advancements in a variety of professional areas such as medicine, astronomy, lithography, optical metrology, optical design, and community leadership.

Nominations of people in historically marginalized groups are especially encouraged. The SPIE Awards committee utilizes a blind review process, ensuring the elimination of bias when selecting award recipients. Both self-nominations, and nominations by others are accepted.

Nominations are due 1 July and recommendation letters are due no later than 15 July. Learn more at: spie.org/NominateAwards

SPIE to partner on EDI program at World of Photonics Congress 2023

JOIN US FOR AN IMPACTFUL diversity, equity, and inclusion program at the World of Photonics Congress, 26-29 June, in Munich, Germany. The program will feature events each day and include a range of activities from workshops and networking events to panel discussions and keynote presentations, including one from Nobel Laureate Donna Strickland.

Topics to be covered include:

- The importance of diversity, equity, and inclusion in the photonics industry
- Support for early-stage researchers
- DiversiWiki session
- Workshop exploring the concept of privilege.

The program will be open to all attendees of World of Photonics Congress and Laser World of Photonics and is organized in collaboration between the European Optical Society (EOS), the European Physical Society (EPS), Wissenschaftliche Gesellschaft Lasertechnik und Photonik e.V. (WLT), Optica, and SPIE.

All are welcome as we raise awareness of the importance of diversity and inclusivity within the photonics community and provide attendees with the tools and strategies they need to create a more welcoming and inclusive industry for all. Program details available spie.org/PhotonicsCongressEDI

In Memoriam: SPIE Fellow Jim Schwiegerling of the University of Arizona

JIM SCHWIEGERLING, an SPIE member for more than 18 years, passed away on 5 April.

Schwiegerling authored several papers in the SPIE Digital Library on subjects such as instrumentation for ophthalmology and optometry, and remote measurement of spectacle lenses. He also published two books, *Optical Specification, Fabrication, and Testing* and *Field Guide to Visual and Ophthalmic Optics* with SPIE Press.

A holder of nine patents, Schwiegerling received international recognition in 2020 when he designed implantable cataract replacement lenses for the eye that allow for distance, mid-range, and near vision, possibly eliminating the need for glasses or contacts for some.

“One of the complaints about bifocal lenses is that you can drive a car and read, but everything in between was kind of fuzzy and with all the screens (we use today), people wanted that extra intermediate distance,” Schwiegerling said in a *University of Arizona News* article.

The family has requested that those wishing to make donations in memory of Schwiegerling direct their gifts to the ARVO Foundation for Eye Research. Read more at spie.org/SchwiegerlingObit



IDL Photo Credit: Alexis Acosta

International Day of Light 2023

AS A GLOBAL INITIATIVE, the International Day of Light (IDL) each year provides a focal point for the continued appreciation of light. The celebration aims to raise awareness of the critical role light-based technologies play in our lives, elevating science, technology, art, and culture. What is more, IDL efforts aim to inform the public about careers in optics and photonics, an industry sector experiencing labor shortages. In the US, there is a particular need for graduates of two-year technical degree programs.

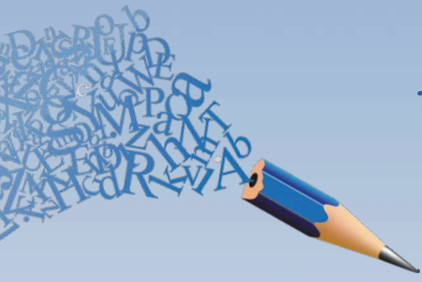
The 2023 celebration will once again include the SPIE IDL Photo Contest, open 16 May through 16 September. The contest aims to raise awareness about IDL and light-based technologies impact cultural, economic, and political aspects of our

world. Amateur and professional photographers alike are encouraged to submit photos for a chance to win cash prizes:

- First Prize: US \$2,500
- Second Prize: US \$1,000
- Third Prize: US \$500
- Technology and Science Prizes: US \$750
- Youth Prizes: Surprise gift box of SPIE merchandise

SPIE has again partnered with Optica and the Institute of Electrical and Electronics Engineers (IEEE) Photonics Society on a Day of Light campaign to foster awareness of light sciences, technology, and career opportunities in the field.

Download resources and find out more at spie.org/idl and www.dayofflight.org



WORD JUMBLE

Unjumble these words.

Then, solve the bonus clue at the bottom by unjumbling the circled letters. Snap a photo of your completed word jumble and send to photonicsfocus@spie.org. One winner, drawn at random, will receive a gift!

Congratulations to Esteban Carbajal, winner of the January/February *Photonics Focus* word jumble!

P	N	K	Y	T	O	R						
O	S	R	T	N	Y	C	O	R	N	H		
U	D	I	S	M	O	M	A	S	P	L	A	
A	P	S	D	M	I	I	N	A	G	G		
T	L	N	E	T	M	E	G	N	E	N	A	
N	O	E	X	N								
H	P	R	A	O	O	C	R	G	N	A		

BONUS: Unscramble the letters to solve the final puzzle. This word goes the distance:

Entries must be received by June 30.

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See the Light



The aurora borealis, or “northern lights,” and its cousin STEVE (strong thermal emission velocity enhancement) paid a colorful visit to the northern midlatitudes on 23 March, as shown in this photo taken just outside of Bozeman, Montana, by Joseph Shaw. STEVE, which was first identified as an optical phenomenon separate from the aurora borealis in 2016, has a broader-bandwidth optical emission spectrum. In contrast, the aurora borealis (seen on the left-hand side and on the bottom of the STEVE arc in this photo) contains largely green and red atomic emission lines of oxygen and nitrogen excited by energetic particles from the Sun. STEVE often appears at lower latitudes than the aurora borealis, so watch carefully!

Photo by: Joseph Shaw

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