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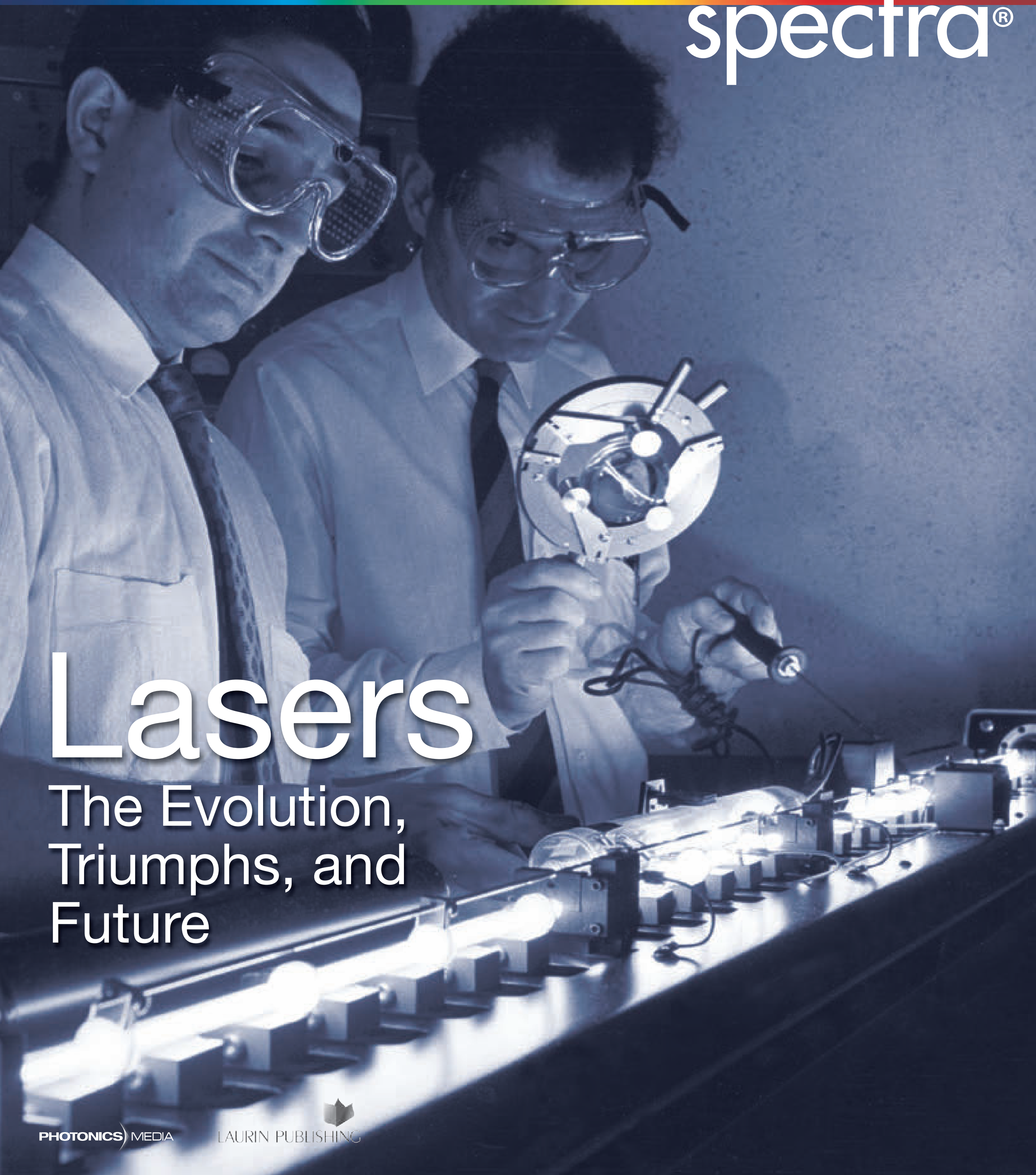

Lasers

The Evolution, Triumphs, and Future

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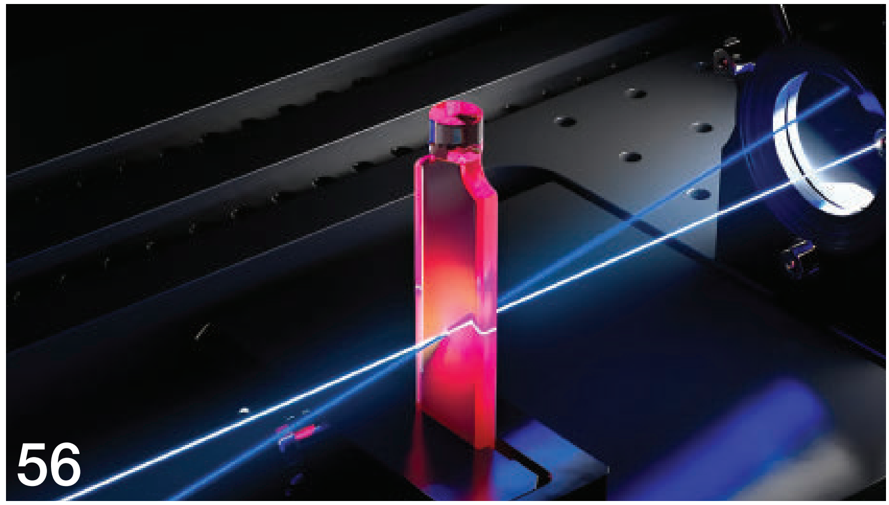

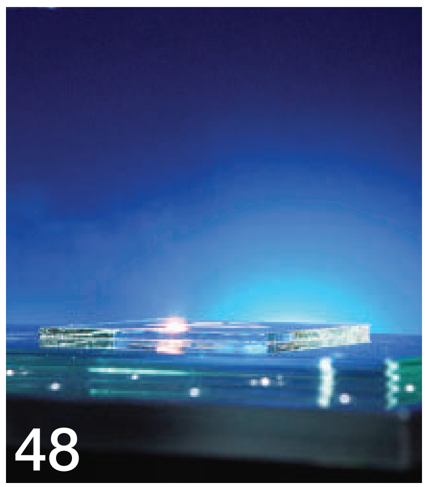

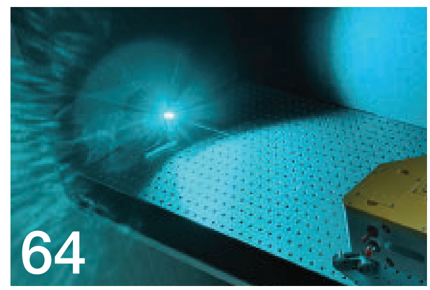

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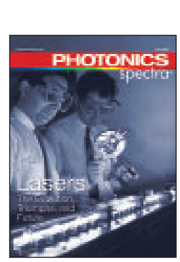
Columns

PHOTONICS: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing.



The Cover

Physicists and engineers have advanced laser system architectures for 65 years. Today, high-efficiency systems and sophisticated applications characterize the technology space. Both are rooted in fundamental research and testing performed early in the technology's history. Cover design by Senior Art Director Lisa N. Comstock.

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Editorial Offices

100 West Street, PO Box 4949
Pittsfield, MA 01202-4949
+1 413-499-0514; fax: +1 413-442-3180
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Advertising Offices

Main Office 100 West Street, PO Box 4949
Pittsfield, MA 01202-4949
+1 413-499-0514
Fax: +1 413-443-0472
advertising@photonics.com

Japan Sakae Shibasaki
The Optronics Co. Ltd.
Sanken Bldg., 5-5 Shin Ogawamachi
Shinjuku-ku, Tokyo 162-0814, Japan
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Editor's Note

Another chance to take the industry's temperature

A look at the news headlines that ran in the lead-up to LASER World of PHOTONICS 2023 provides convincing evidence that the events of the past portend the future. During spring 2023, bank failures in the U.S. triggered a flurry of action from the Federal Deposit Insurance Corporation — an institution that instills confidence in consumers largely by staying out of news cycles. Armed conflicts raged on three continents without indications of slowing. And the U.S. and European powers expanded export controls on Russia. The measures raised the public's anxiety about the prospect of tit-for-tat restrictions on and from world powers and, more broadly, an increasingly disconnected global commerce.

Photonics Spectra's June 2023 editorial captured the uncertain atmosphere of the season. As it turns out, the column also provided a remarkably apropos bit of foreshadowing.

This year, the backdrop of uncertainty against which LASER World of PHOTONICS 2025 (LASER Munich) will kick off may resemble that of 2023, but there is no question we are in different times. Global alliances are altering. Supply chains are on the verge of shifting. Science and research budgets face cuts that inhibit the types of breakthroughs that catalyze and sustain iterative advancements and culminate in Nobel Prizes.

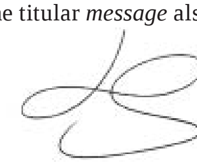
Much is apt to change during two years. In the current state of the world, however, conditions are ripe for upheavals seemingly every day. As a highly connected industry, photonics is susceptible to the effects of such turmoil.

For this reason, the industry's convergence in Munich cannot come soon enough. Though the year is not yet half over, previous gatherings, such as Photonics West in January, OFC in March, and, most recently, CLEO and SID Display Week in May, feel like distant memories. In the roughly two-month spans between each of those events, uncertainty has not only intensified — it has eclipsed all contenders to prevail as the dominant theme of the year-to-date.

How, exactly, the more than 1300 anticipated exhibitors at LASER Munich expect this reality to play out is the question that we endeavor to answer.

Though one never knows what an exhibitor has in store, a possible clue exists in the aforementioned June 2023 column. "Uncertainty" was the topic, and "How uncertainty can drive innovation," was the title.

It is already apparent that the *topic* of the article has resurfaced. Now, let's hope that the titular *message* also comes to pass.



jake.saltzman@photonics.com

Contributors

Greta Bučytė
Greta Bučytė is product manager for spectroscopy systems at Light Conversion. Page 56.

John T.C. Lee
John T.C. Lee has served as president and CEO of MKS since January 2020. He holds an M.S.CEP and a Ph.D. from MIT, both in Chemical Engineering. Page 84.

Gabrielė Stankūnaitė
Gabrielė Stankūnaitė is head of marketing and communications at Light Conversion. Page 56.

Antonio Castelo
Antonio Castelo is technology manager for Biomedical and Lasers at the European Photonics Industry Consortium (EPIC). Page 90.

Philip Makotyn
Philip Makotyn is president of Vexlum US, a subsidiary of Vexlum Ltd. He has more than 15 years of experience in quantum technologies and earned a Ph.D. in Physics from the University of Colorado. Page 64.

Bogusz Stępak
Bogusz Stępak, Ph.D., is the R&D director of laser microprocessing at Fluence's Ultrafast Laser Application Laboratory. Page 48.

Marie Freebody
Contributing editor Marie Freebody is a freelance science and technology journalist with a master's degree in physics from the University of Surrey in England. Page 76.

Kimon Moratis
Before joining Tematys as a photonics market analyst, Moratis collaborated on multiple R&D projects for the elaboration of novel photonic and semiconductor devices with applications in renewables, communications, and quantum computing. Page 10.

Andreas Thoss
Andreas Thoss, Ph.D., is a laser physicist, founder of THOSS Media, and contributing editor to *Photonics Spectra*. He has been writing and editing technical texts, with a focus on the field of photonics, for two decades. Pages 70 and 87.

Mircea Guina
Mircea Guina is chairman, chief science officer, and cofounder of Vexlum Ltd. He is also a professor of semiconductor technology at Tampere University, where he leads the Optoelectronics Research Centre. Page 64.

Jussi-Pekka Penttinen
Jussi-Pekka Penttinen is the CEO, CTO, and cofounder of Vexlum Ltd. He has more than 15 years of experience in optically pumped vertical-external-cavity surface-emitting lasers and is a leader in the field. Page 64.

Mikas Vengris
Mikas Vengris is a professor at the Laser Research Center, Faculty of Physics, Vilnius University, and an R&D engineer at Light Conversion. His research focuses on ultrafast laser applications for investigating dynamic processes in various materials. Page 56.

Jeff Hecht
Jeff Hecht is a veteran science and technology writer with a specialty in optics and an Optica fellow. He is the author of *Understanding Lasers*, *Understanding Fiber Optics*, *City of Light: The Story of Fiber Optics*, and *Beam: The Race to Make the Laser*. Page 42.

Thierry Robin
Thierry Robin is a cofounder of Tematys with more than 20 years of experience in both technology innovation and marketing in the optics and photonics industry. He oversees many projects with prominent players in defense and security, biomedical optics, and industry. Page 10.

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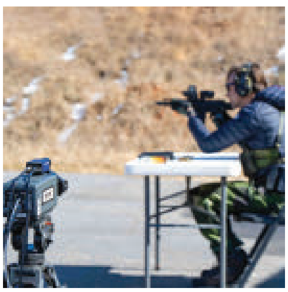
FLIR MIX — A Breakthrough in Infrared and Visible Imaging



Until now, researchers have had to choose between thermal and visible imaging. Recording both and trying to align them manually — or harder, synchronizing them temporally — can be inconsistent and time-consuming. The resulting data is close but never quite complete. The new FLIR MIX is a game changer, capturing and synchronizing high-speed thermal and visible imagery at up to 1000 fps. Visible and high-performance infrared cameras with FLIR Research Studio software work together to deliver one data set with perfect spatial and temporal alignment. This mitigates missed details and second guessing, providing a complete picture of fast-moving events. Presented by Teledyne FLIR.
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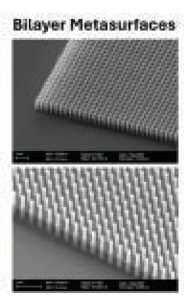
Multifunctional Metaoptics: From Science into Your Smartphones



Metasurfaces provide an almost unlimited toolbox to design the wavefront of light in search of new phenomena and applications. Using matrix Fourier optics aided in the design of spatial distribution of Jones matrices to achieve polarization-sensitive imaging, polarization metaoptics has led to an error-free biometric authentication system for smartphones. Federico Capasso will present recent developments in large-area metalenses for astrophysics as well as high-efficiency broadband metalenses. He will conclude with recent work on bilayer freestanding metasurfaces and the new functionalities that they enable. Sponsored by Pixelligent.
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Amid Global Uncertainty, Industrial Drivers Continue to Shape the Global Laser Market

BY KIMON MORATIS AND
THIERRY ROBIN, TEMATYS

The Global Lasers Market 2025 report, published this year by Tematys and Yole, provides a detailed market analysis of the different technologies for each laser application segment. The report considers revenues and units sold, isolating individual applications and sources. It also includes an analysis of future trends and a market forecast for more than 50 segments for the period spanning 2025 to 2029.

Tematys' analysts have distilled key messages from the report into this article. The report methodology is shared below and the full report is available for order.

Laser market trends

After showing excellent performance during the three-year period between 2015 and 2017, the global laser market faced rising uncertainty in the years preceding the COVID-19 pandemic. Following its cyclical pattern, industrial production began to decline globally, and the 2018 trade war between the U.S. and China put additional strains on the supply chain. Though markets were preparing for a slowdown in early 2020, the pandemic disrupted most expectations and planning — in a most unpredictable way.

Electronic devices for both commercial and personal applications were unquestionably an integral part of everyday life before 2019. However, the conditions that arose out of the pandemic markedly accelerated sales. One indicator, the market for PCs, experienced year-over-year (YoY) growth of >10% in 2020.

This level of demand drove laser sales for semiconductor materials processing and components manufacturing, both of which are essential for the manufacture and performance of electronic devices. In parallel, the storage and distribution requirements of increasingly large volumes of data triggered the rapid expansion of data centers. This had a positive effect on the VCSEL and diode laser market, particularly due to the increased sales of optical modules for telecommunications and data communications.

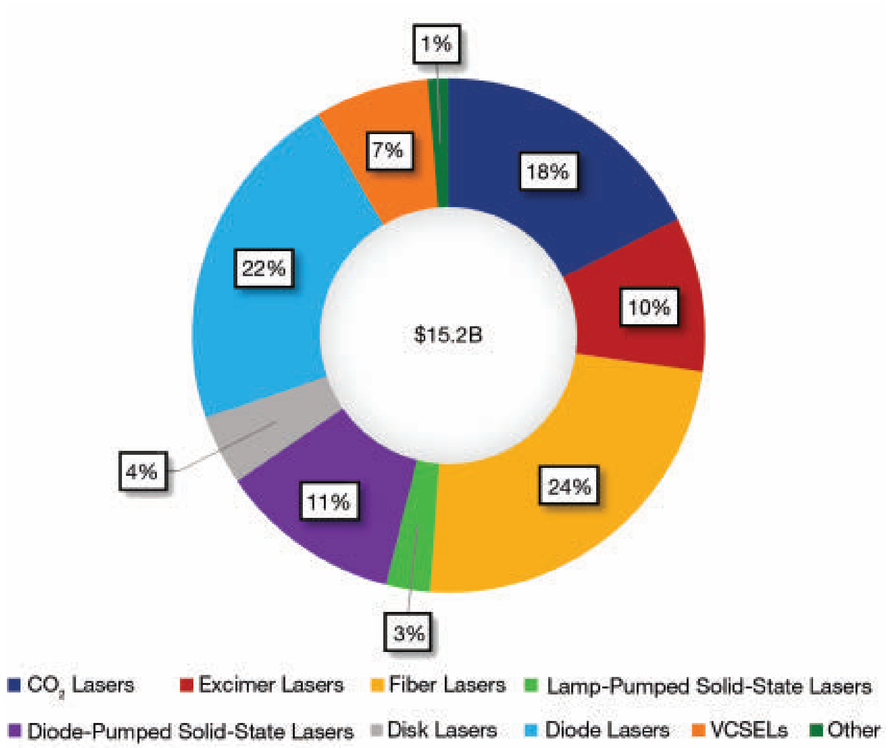


Figure 1. The global market of laser sources in 2023, segmented by the most common technologies.

Following the pandemic, multiple industrial sectors faced challenges in 2023 and early 2024. There were multiple causes, including seasonal variations on the demands of goods, ongoing global conflicts, and, more generally, the escalation of tensions between East and West.

This slowdown, however, did not show a strong effect on the laser market, which grew globally by almost 7% between 2022 and 2023, reaching almost $15.2 billion (Figure 1).

Industrial laser applications for materials processing and manufacturing hold the largest share of the global laser market. The strong performance of these segments is attributed predominantly to post-COVID-19 momentum and expectations for further growth, particularly in the automotive and semiconductor industries.

Despite the 2023 growth, the global laser market for 2024 reflects the effects of the sluggish performance of industrial production. It is expected to achieve YoY growth of $<1\%$.

Lasers for industry

Segmented by application, kilowatt and sub-kilowatt materials processing, marking and engraving, and photolithography have a combined share of 54% of the 2023 global laser market (Figure 2). In each of these four applications, and their sub-applications, discernible trends are evident in the evolution of laser technologies used by the market as well as the adoption of new materials and other requirements.

Kilowatt materials processing includes all applications that require output powers in the order of 1 kW and higher. As the standard tool used for thick metal cutting, drilling, welding, brazing, surface treatment, and high-power additive manufacturing, continuous-wave fiber lasers maintain the largest market share for this segment.

At the same time, the beam quality and output powers achieved by direct-diode lasers have improved significantly in recent years. In combination with their comparatively lower price point, these sources are becoming an attractive alternative for applications such as metal hardening, drying, and cladding. Disk lasers compete with fiber lasers for precision cutting and welding of metals due to their high-quality beam. One of their limitations, however, is their lower maximum powers; current commercial solutions do not exceed 24 kW. CO_2 lasers maintain a small market share for mechanical components, deep welding, and steel processing.

In sub-kilowatt materials processing, lasers are used in the manufacturing of polymer, ceramic, glass, semiconductor, and thin metal-based components. Excimer lasers formerly dominated in this segment, and their large market share owes to their utility in annealing amorphous silicon to polysilicon. The process is a vital step for OLED displays manufacturing. Looking ahead, however, excimer technology will face strong competition from energetic pulsed diode-pumped solid-state lasers (DPSSLs), emitting in the UV, due to the lower maintenance and operation costs associated with these sources compared with excimers.

Additionally, ultrafast DPSSLs and fiber lasers can provide solutions to other industrial applications. These range from precision micromachining and fine metal and glass processing to printed circuit boards and displays cutting.

Following a YoY decline of almost 10% in 2023, the global semiconductors market showed impressive growth of 13% in 2024. Strong demand for lasers used in the manufacturing of electronic devices balanced the negative performance of

Common Technologies and Their Applications Segments of Laser Sources

Applications	CO_2	Excimer	Fiber	LPSSLs	DPSSLs	Disk	VCSELs	Diode	Other
Kilowatt materials processing	✔		✔			✔		✔	✔
Sub-kilowatt materials processing	✔	✔	✔	✔	✔	✔	✔	✔	
Marking and engraving	✔		✔		✔			✔	
Photolithography	✔	✔						✔	
Communications			✔				✔	✔	
Sensing and instrumentation	✔	✔	✔	✔	✔	✔	✔	✔	✔
Optical pumping								✔	
Medicine and cosmetics	✔	✔	✔	✔	✔	✔		✔	
Mobile and consumer						✔	✔	✔	
Aerospace and defense			✔	✔	✔			✔	✔
R&D	✔		✔	✔	✔	✔		✔	✔

DPSSLs: Diode-pumped solid-state lasers
LPSSLs: Lamp-pumped solid-state lasers

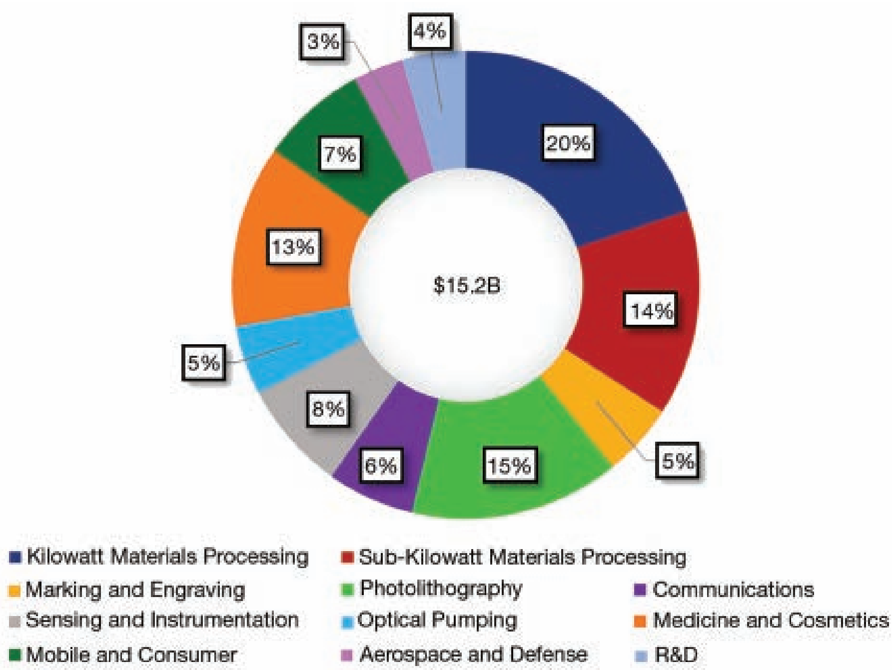


Figure 2. The global market of laser sources in 2023, segmented by applications.

lasers for heavy industrial applications. The latter is attributed to the sluggish performance of the auto industry during the first half of 2024 and the massive adoption of high-power fiber lasers from Chinese manufacturers. Western laser companies face strong competition from Chinese manufacturers because products with similar characteristics and quality standards sell at a third of the price.

In marking and engraving, CO_2, DPSSLs, fiber, and, less frequently, diode lasers are each used for textile, food, and packaging marking. This market has growth potential in the future; the decrease of ultrafast laser prices has made these sources attractive for high-precision jewel, microchip, and leather marking.

Photolithography, which is performed at industrial scale using deep-ultraviolet (DUV) and/or extreme-ultraviolet (EUV) systems, is an essential step in the fabrication of semiconductor devices. For this application, the DUV and EUV sources are equipped with excimer and CO_2 lasers, respectively. This segment currently has a share of >14% over the total laser market, and, between 2022 and 2023, the number of DUV and EUV systems sold grew by 30% and 32%, respectively. Yet the disappointing performance of the semiconductor industry in 2023 shrank the sales of these systems by 10% in 2024.

Medicine and cosmetics

Lasers for use in medicine and cosmetics have a share of ~13% over the total market. The major applications that comprise this segment are in surgery, ophthalmology, and dentistry, as well as dermatology and cosmetic operations. Given the number of applications that require precision, numerous laser types have application in this segment.

For example, CO_2 lasers are used in surgical operations because the generated heat aids in sterilization and bleeding reduction. In LASIK operations, a femtosecond laser is used to make the corneal cut and an excimer laser to vaporize the cornea, which modifies the focusing ability of the eye. In dentistry, Q-switched lasers have in some cases replaced drills for tooth operation and lesion removal.

The dermatology and cosmetics subsegment holds a share of 40% over the total medical segment, enveloping applications such as epilation, skin rejuvenation, and skin lesions treatment — each of which is typically performed with diode lasers. Solid-state lasers are also used to treat spider veins and skin discoloration, as well as to remove tattoos.

Mobile and consumer applications

With a share of >75%, VCSELs are the most common laser sources for mobile and consumer applications. Here, the main application of these lasers is for 3D sensing in mobile phones, wearables, and novel smart devices. Time-of-flight sensors based on VCSELs are used in smartphones for facial recognition, camera adjustments, and augmented reality applications.

VCSELs are also essential for many advanced driver-assistance and autonomous driving systems, and for driver and cabin interior monitoring. This market is expected to grow as countries continue to impose safety regulations.

Diode lasers are found in projectors, printers, light shows, and optical storage systems. This market has a segment share of <2%, and it is not expected to change significantly in upcoming years.

Sensing, instrumentation, optical pumping

The sensing and instrumentation segment grew by 2.5% between 2022 and 2023. Due to its versatility across applications, it is the most resilient segment in the face of macroeconomic uncertainty right now.

Additional Report Methodology

The data and figures presented in the Global Lasers Market 2025 report are based on internal knowledge of Tematys and Yole and databases built by publicly available financial reports and presentations. The validation of these assessments, as well as the collection of information regarding technological and applications trends, is accomplished through interviews with industry specialists and representatives of laser companies. Both Tematys and Yole are regularly expanding their networks via participation in international conferences and exhibitions related to photonics technologies.

In the life sciences subsegment, the most common laser technology used is solid-state lasers. DPSSLs, for example, are the sources that are typically used in flow cytometry systems, which enable multiparametric cell analysis. Optically pumped semiconductor lasers are found in DNA sequencing systems for medical diagnosis and virus studies. And ultrafast lasers are used for studying opaque biological samples via multiphoton imaging.

Lidar is another core application covered in this segment. This technique uses wavelengths from the UV to near-infrared, and the most common sources in these systems are diode lasers, DPSSLs, and fiber lasers.

A notable trend in industry is the use of frequency-quadrupled DPSSLs to replace excimer lasers for semiconductor wafer inspection. This trend is ongoing and intensifying. An additional set of use cases for diode lasers are in machine vision and gas sensing systems.

Diode lasers are also the preferred light sources for optical pumping of solid-state lasers, and the segment follows the trends of these laser sources. Its market size for 2023 is almost $730 million, and

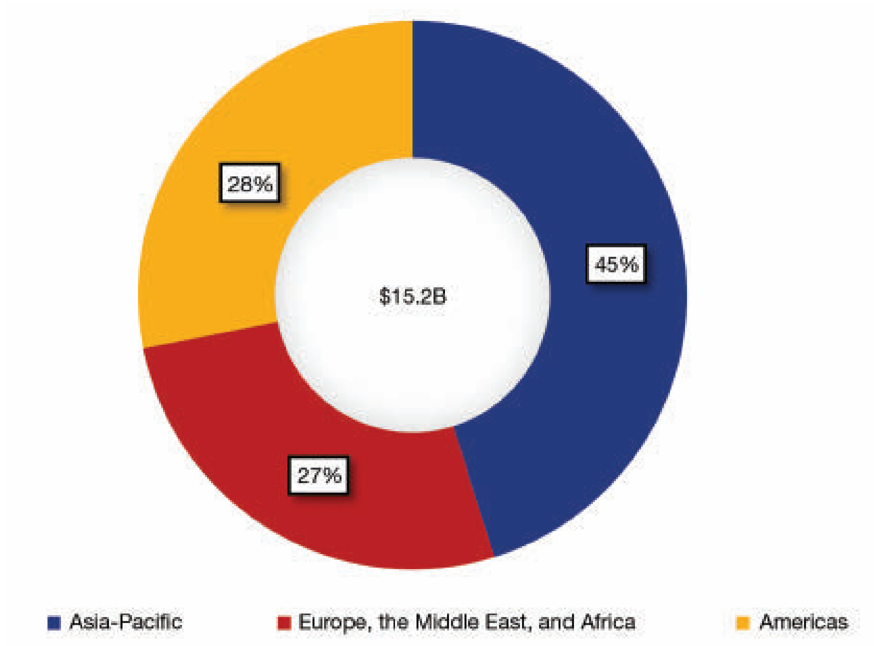


Figure 3. The global sales of laser sources in 2023 by geographical region.

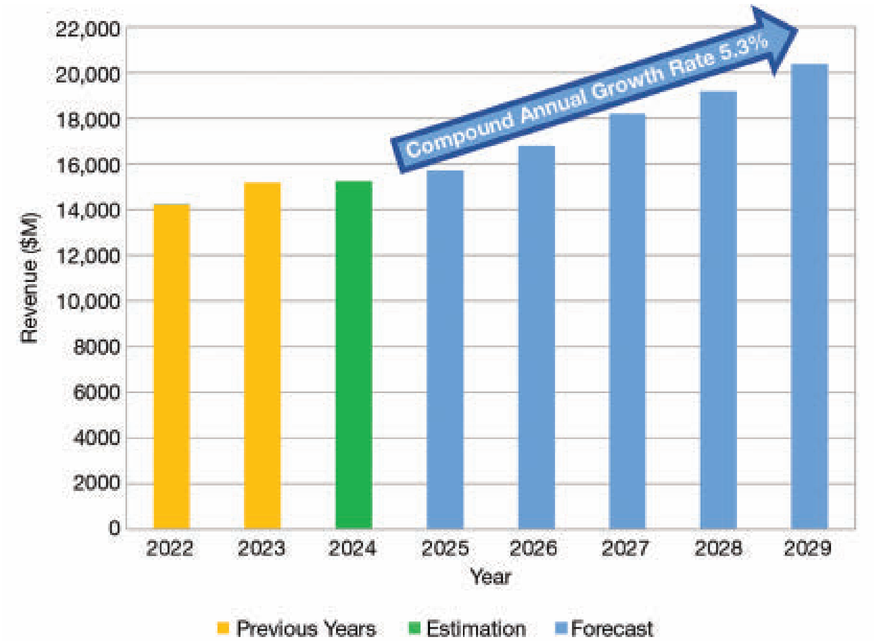


Figure 4. The evolution of the global laser market between 2022 and 2029.

its weak growth (<2% in 2024) is in line with broader trends occuring in industrial production.

Communications

In detailing the laser market for communications, the Tematys-Yole report does not consider the global transceivers market. Only the chip laser source inside the transceiver is accounted for in the market analysis of this segment, which spans both telecommunications and data communications.

Together, they have contributed significantly to the growth of the laser market, largely through the sales of diode lasers and VCSELs for optical transceivers. In telecommunications, optical transceivers are most often equipped with electro-absorption-modulated distributed-feedback lasers. Due to their design, they maintain a stable wavelength and low chromatic dispersion, making them well suited for high-speed data transmission over long distances of >10 km. In data centers, for node-to-node short-distance data exchange, the transceiver sources are usually based on VCSELs. The laser sources for applications requiring high data transmission speeds for distances up to several kilometers are directly modulated distributed feedback lasers.

In recent years, data communications experienced massive growth due to the ongoing expansion of data centers addressing the computational needs of AI and AI applications. It is expected to continue to trend in forthcoming years, driving diode laser and VCSEL sales.

Aerospace and defense

Lasers are used both for sensing-related applications and directly as weapons. DPSSLs are used for telemetry, range finding, and target designation, and pulsed fiber lasers are used for aircraft trajectory correction during landing and as illuminators and pointers. High-power fiber lasers with multi-kilowatt output powers are used to intercept airborne threats such as drones, cruise missiles, and artillery. And due to their compact size and reliability in demanding environments, diode lasers are fundamental components in missile warning, electro-optical targeting, and imaging systems.

Applications in R&D

Lasers play an important role in both basic and applied R&D. Today's sources enable critical experiments that posed major challenges or were even impossible to implement prior to their invention and availability.

These experiments span laboratory and industrial environments and demand numerous types of laser technologies and laser-enabled systems. For example, ultrafast solid-state lasers are used in multiple spectroscopy and microscopy techniques in science, as well as for probing nonlinear optical effects, such as in high-harmonic generation. High-power Ti:sapphire lasers, emitting pulses of several terawatts up to petawatts, find application in plasma physics, particle accelerators, and nuclear waste management systems. Photonics technologies are promising for the implementation of quantum computing platforms, and external cavity and distributed feedback diode lasers are used for optically pumping quantum emitters based on semiconductor nanostructures.

Distribution of laser sales and new trends

As a consequence of the dynamics of the Chinese market, Asian nations had the highest demand for laser sources in 2023 (Figure 3). The increased sales in the Asia-Pacific region were driven mostly by the needs of industry for high- and medium-power lasers for kilowatt and sub-kilowatt materials processing. The three major applications in this context are high-power metal cutting and welding, battery manufacturing for the automotive industry, and materials processing for the manufacturing of electronic devices.

The high-power laser industry in China is highly competitive: >90% of domestic manufacturers' sales addressed the needs of the Chinese market. Alongside the increased sales of lasers for manufacturing purposes, the high demand of light vehicles in China also drove sales of lidar-based driver-assistance modules.

In late 2024, global industrial production began to rebound, and these positive trends continued into early 2025. Barring unforeseen disruptions, the global laser market is estimated to continue growing at a compound annual growth rate of 5.3% through 2029 (Figure 4).

Aside from industrial applications, the demand of lasers is also expected to grow for medical and diagnostic equipment. Health care systems around the world will face new challenges, particularly due to environmental and demographic factors. Climate change is another consideration. As it pertains to the laser market, the demand for energy transition is the key driver. The production of essential goods, such as food and medicines, could also show improvement. Novel devices based on lasers will ensure product quality, production efficiency, and smart infrastructure to respond quickly to new market needs.

It is anticipated that ongoing global tensions will force many countries to enlarge and modernize their arsenals of weapons systems and defense technologies. This upcoming wave of intense militarization will broadly contribute to the growth of laser sales for military sensing and weapons systems.

kmoratis@tematys.com
trobin@tematys.com

Maxwell Labs, Sandia collaborate to test laser-based cooling tech

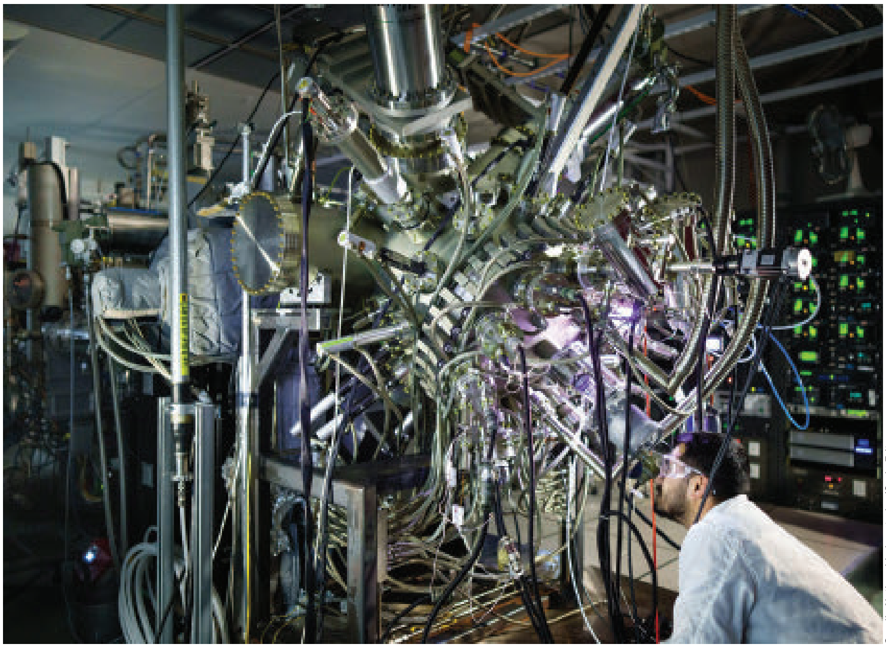
A Minnesota-based startup, Maxwell Labs, entered into a cooperative R&D partnership with Sandia National Laboratories and the University of New Mexico to demonstrate laser-based photonic cooling for computer chips. The company's technology, currently under development, aims to increase the efficiency of conventional air- and water-based systems for cooling and regulating the temperature of chips.

"About 30% to 40% of the energy data centers use is spent on cooling," said Raktim Sarma, the lead Sandia physicist on the project. Further, the amount of water needed for cooling can strain local resources in certain communities, Sarma said.

Laser cooling occurs when a particular light frequency is matched with an extremely small, pure target of a specific element. In certain quantum computers, for example, lasers help hold individual atoms at super-cold temperatures.

Though a laser system is not suitable to cool an entire house or any bulk materials, it could be effective for computer chips such as GPUs if the cooling light can be focused on small, localized hot spots. "We really only have to cool down spots that are on the order of hundreds of microns," Sarma said.

Maxwell's technology uses a photonic cold plate to either replace or complement water- and air-based cooling systems, which also allows for the resulting heat, which is extracted in the form of light, to be recycled and turned back into electricity. In some current systems, cold water flows through microscopic channels in copper cold plates laid over a chip to soak up heat. The Maxwell cold plate would be a light-based variation, designed with materials and microscopic features that channel cooling laser light to localized hot spots.


Sandia National Laboratories/Craig Fritz

Sadhvikas Addamane, a materials scientist at Sandia National Laboratories, looks into a viewport of a molecular beam epitaxy reactor, a system that Sandia will use to build experimental photonic cooling plates, designed at a startup, Maxwell Labs, for testing.

According to Maxwell CEO Jacob Balma, the company's models indicate that a laser-based cooling system can keep chips colder than water-based systems. If these models prove to be accurate, the cooling method could enable chips to operate harder without overheating, improving their overall performance and power efficiency simultaneously.

"The unique capability of light to target and control localized heating spatially and at optical timescales for these devices unlocks thermal design constraints that are so fundamental to chip design that it is hard to speculate what chip architects will do with it — but I trust that it will fundamentally change the types of problems we can solve with computers," Balma said.

Sandia brings specialized expertise working with gallium arsenide, which composes most of Maxwell's cold plate design. Because laser light will heat up impurities, erasing any cooling effect, the cold plate needs to have extremely pure, thin layers of crystalline gallium arsenide, also known as epitaxial layers, to work.

Through the agreement, Maxwell Labs will generate the technical designs, Sandia will build the devices, and the University of New Mexico will analyze their thermal performance.

$14.9B

— estimated value of the global fiber optics market by 2030, according to Grand View Research

nEye Systems secures $58M for optical switch tech

nEye Systems, an optical switch startup spun out of the University of California, Berkeley (UC Berkeley), completed a $58 million series B round. The funding, led by Alphabet's independent growth fund CapitalG, with participation from Microsoft's venture fund M12, Micron Ventures, NVIDIA, and Socratic Partners, brings the company's total funding to $72.5 million.

Formed in 2020, nEye developed a high radix silicon photonic switch with ultralow power consumption, leveraging more than a decade of research from professor Ming Wu's lab at UC Berkeley. Compared with existing optical switch solutions, the technology is 100× smaller and has 1000× lower power consumption, while boasting 10,000× greater speeds at 10× lower cost, the company said.

The technology is poised to improve AI infrastructure by addressing data center communication bottlenecks that have hindered high-performance computing, AI, and machine learning systems. According to nEye, its wafer-scale optical circuit switch uses direct optical connections that offer virtually unlimited bandwidth to provide a more efficient and cost-effective solution.

nEye previously secured an unannounced series A round led by TEDA Holding with support from InnoLight Technology USA, and additional seed funds.

CamGraPhIC secures $27M in series A funding

CamGraPhIC, a provider of high-bandwidth optical interconnect technology and a subsidiary of 2D Photonics, completed a €25 million (approximately $27 million) series A equity funding round raised through 2D Photonics. The funds will be used to support CamGraPhIC's continued development of graphene photonics transceivers for AI and cellular data transmission applications.

The company plans to enhance its R&D capabilities at its site in Pisa, Italy,

This month in history

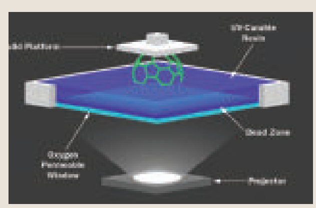
What were you working on five, 10, 20, or even 30 years ago? *Photonics Spectra* editors have perused past June issues and unearthed the following:

1995

A group of researchers from the University of St. Andrews reported that it had induced a lens in a gas medium by using an electromagnetically induced transparency arrangement. This was accomplished by focusing two Ti:sapphire lasers into opposite ends of a 10-cm cell containing rubidium gas.

2005

Scientists at the University of California, Berkeley, realized a resolution of 60 nm using a film of silver as a superlens. Instead of imaging the propagating light from an object, the technique imaged the evanescent fields coming from the object.

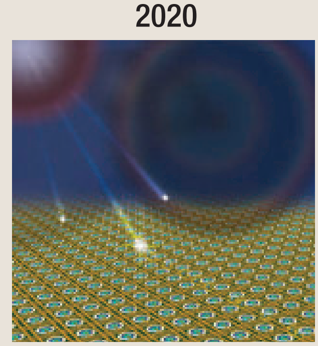


2015

Investigators from the University of North Carolina at Chapel Hill and Carbon3D Inc. developed a 3D-printing approach that used photopolymerization to create objects such as stents in minutes. The method, called continuous liquid interface production, or CLIPS, worked by projecting UV light through an oxygen-permeable window into a liquid resin.

2020

Researchers at École Polytechnique Fédérale de Lausanne developed a megapixel camera based on time-gated, single-photon avalanche diode image sensors. The camera could detect single photons and convert them into electrical signals at a rate of ~150 million times/s. It also had a rate of 24,000 fps and a 3.8-ns time gating.



and establish a pilot manufacturing line in Milan. The company said that it is also in discussion with the Ministry of Enterprises and Made in Italy regarding measures to support its new activities via the National CHIPS Fund. The planned facility in Milan will demonstrate a scalable mass-production process that is compatible with commercial semiconductor and photonics foundries.

According to CamGraPhIC, its graphene-based transceivers provide superior performance in terms of bandwidth density, latency performance, and temperature tolerance, while consuming 80% less energy than traditional pluggable data center optical transceivers. This eliminates the need for complex and costly cooling systems. The technology is particularly effective for transferring large volumes of data between GPUs and high-


2D Photonics

2D Photonics' subsidiary CamGraPhIC will use its recent funding to fuel an expansion of its workforce and manufacturing capabilities in pursuit of commercializing its graphene-based optical interconnect technology.

bandwidth memory, which are fundamental to generative AI and high-performance computing. Due to a simplified device architecture enabled by a unique integration of ultrahigh-quality graphene into the photonic structure, these transceivers are also more cost-effective to manufacture, the company said.

Initially targeting AI GPU to high-bandwidth memory interconnects, 2D Photonics and CamGraPhIC also plan to expand into avionics, automotive advanced driver-assistance systems, and space applications. In these sectors, the companies said, CamGraPhIC's transceivers are poised to offer significant technical and commercial advantages compared with existing technologies.

The funding will additionally be used to build out the senior team and initiate the scale-up of the technology in Milan, focusing on optimizing production for large-scale manufacturing in a semiconductor foundry environment.

Cambridge and Southampton join PIXEurope consortium

The University of Cambridge's Cambridge Graphene Centre and the CORNERSTONE Photonics Innovation Centre at the University of Southampton will partner with members across Europe to host a pilot line. Coordinated by the Institute of Photonic Sciences in Spain, the partnership underscores a project that combines state-of-the-art equipment and expertise from 20 research organizations spanning more than 10 countries.

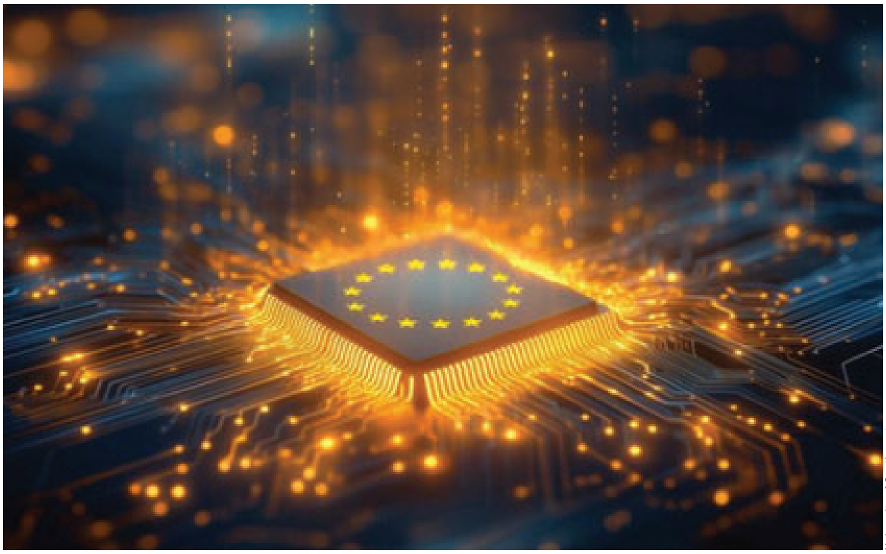
The PIXEurope consortium has been selected by the European Commission and Chips Joint Undertaking, a European initiative aiming to bolster the semiconductor industry by fostering collaboration between member states and the private sector. The consortium is supported by €380 million ($413 million) in total funding.

The U.K. participants specifically will be backed by up to £4.2 million ($5.4 million) in funding from the Department of Science, Innovation and Technology, match-funded by Horizon Europe. The U.K. joined the European Union's Chips Joint Undertaking in March 2024, allowing the country to collaborate more closely with European partners on semiconductor innovation.

Researchers at the Cambridge Graphene Centre will be responsible for the integration of graphene and related materials into photonic circuits for energy-efficient, high-speed communications and quantum devices.

The pilot line aims to encourage the adoption of cutting-edge photonic technologies across more industries to boost their efficiency, and to offer cutting-edge technological platforms, transforming and transferring integrated photonics processes and technologies to accelerate their industrial adoption. The objective is the creation of European-owned and -developed technology in a sector of capital importance for technological sovereignty, and the creation and maintenance of corresponding jobs in the U.K. and across Europe.

The University of Cambridge and the University of Southampton joined the PIXEurope consortium to advance semiconductor technologies for photonic integrated circuits.


University of Southampton

Luminate NY names companies in eighth cohort

Empire State Development named the 10 companies selected to participate in round eight of the Luminate NY accelerator program, investment fund, and competition. Each finalist will receive an initial investment of $100,000 and will have the chance to compete for up to $2 million in follow-on funding upon the completion of the program.

The cohort launched April 22 and will conclude in October.

The selected companies:

amPICQ, a designer and developer of photonic integrated circuits (PICs) for quantum communications, data communications, and telecommunications.

IRIDESENSE, a developer of a 3D-SWIR multispectral perception solution that offers long range and high resolution to optimize resources and reduce the carbon footprint.

LirOptic, a creator of a solid-state, shape-shifting, tunable optical lens technology that facilitates optical zoom in a shorter compact camera module stack.

Metahelios, a designer and developer of metasurface image sensor technology, enabling camera technologies that surpass current technological limitations.

Oblate Optics, a company targeting the design and fabrication of advanced meta-optics for laser and imaging applications.

Pensievision, a creator of 3D-imaging technology for industrial applications and medical devices, including a portable colposcope that can produce high-resolution 3D images to assist in early-stage detection and analysis of precancer cervical lesions.

Pixel Photonics, a developer of an approach to combine superconducting nanowire single-photon detectors with PICs.

SNOChip, a provider of semiconductor nano-optical chip technology with on-chip nanostructures.

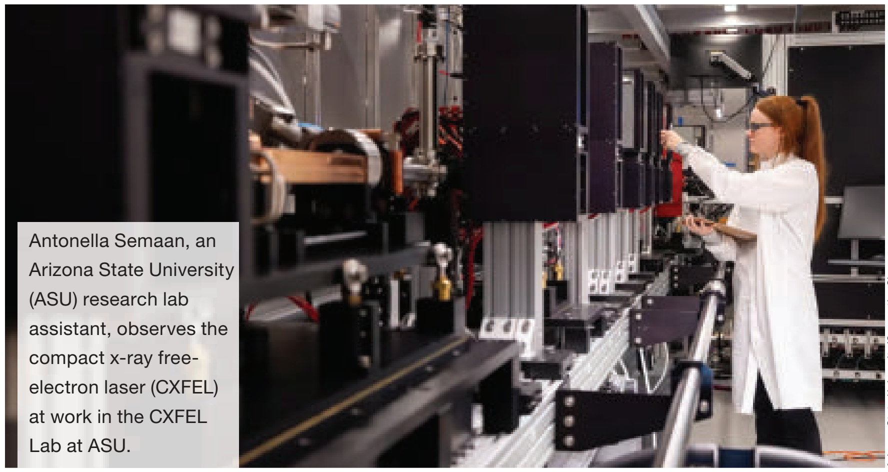
VanaM, a creator of next-generation semiconductor thin films (quantum materials, smart glass) based on innovative deposition source technology and core intellectual property.

Wyse Light, a developer of simple, fast, and affordable optical measurement of reflective surfaces at nanometric precision.

Two companies, **Dottir Labs** and **Ciconia Medical**, were selected to participate outside of the finalist structure as runners up and will be auditing the program to help prepare and advance their businesses. Dottir Labs integrates hundreds of sensors over large distances and provides real-time, high-quality data on dynamic and complex chemical processes. Ciconia Medical is improving women's childbirth experiences and outcomes through the first AI-based medical device for vaginal exams.

The companies were selected from a pool of 197 applications sent from 38 different countries, Luminate said. Since its inception, Luminate has invested $21 million in 73 startups. Funding for the program, which is administered by NextCorps, is provided through the Finger Lakes Forward Upstate Revitalization Initiative.

Arizona State University builds compact x-ray free-electron laser



Antonella Semaan, an Arizona State University (ASU) research lab assistant, observes the compact x-ray free-electron laser (CXFEL) at work in the CXFEL Lab at ASU.

Arizona State University/Samantha Chow

It is well known that x-rays enable medical personnel to view inside the human body and diagnose broken bones and other hidden problems. Recent x-ray advancements are enabling events to be viewed at the scale of atoms and molecules, revealing targets for new medicines and materials. The development of the x-ray free-electron laser (XFEL) allows chemical reactions of the molecules of life to be seen as they unfold in real time. The fundamental insights of this technology hold promise in helping to accelerate the development of cancer treatments, drugs to fight viral pandemics, and powerful quantum computers.

But massive costs inhibit access to this technology. The first XFEL cost around $1 billion to build and requires a giant atom-smashing, kilometer-long particle accelerator facility. Less than 10 XFEL instruments exist worldwide.

Arizona State University (ASU) is working to develop what it expects will be the world's first compact version of an XFEL, a CXFEL. This garage-size instrument will be dramatically smaller and less expensive and promises to expand opportunities for researchers to explore atomic-scale events important for biochemistry, microelectronics, bioenergy applications, drug discovery and development, quantum computing, and more.

"We believe this is the start of a new paradigm that will enable many institutions to follow in our footsteps, providing novel instruments for scientific breakthroughs," said William Graves, who leads the CXFEL project at ASU.

The CXFEL project comprises two light sources, which will enable a national lab-caliber user facility for forefront x-ray science, according to the university. The compact approach accelerates electrons to near light speed, structures them, and collides them with an intense laser beam to produce a highly directed beam of coherent x-rays that can access atomic-scale details invisible to longer wavelengths of light. The CXFEL instrument will fire extremely short x-ray pulses on the scale of a femtosecond. Like the strobe lighting of high-speed photography, these fleeting x-ray pulses can capture the ultrahigh-speed movements of electrons and atoms.

The scientists at ASU are working to finalize the commissioning of the compact x-ray light source, one of the two sources comprising the CXFEL, and to begin using it to record the structure and dynamics of complex biomolecules and quantum materials. This latest milestone indicates that the key power, safety, and operational parameters have already been successfully met, and with its ability to generate a stable electron beam and ultrashort x-rays, the first measurements for ASU and other scientists will begin later this year.

The light sources are expected to advance a broad range of fundamental science applications. "For example, it will be extremely exciting to make a movie of how a virus binds to a cell and then visualize all the processes that allow the virus to enter the cell," said Petra Fromme, ASU director of the Biodesign Center for Applied Structural Discovery and a Regents Professor in the School of Molecular Sciences.

"Another example would be to see how a cancer cell hides from destruction by the immune system," Fromme said. This could usher in a wave of cancer therapies.

Black Semiconductor acquires Applied Nanolayers

Black Semiconductor acquired fellow graphene technology company Applied Nanolayers (ANL). With the acquisition, it plans to accelerate technology development of energy-efficient, high-performance chip technology.

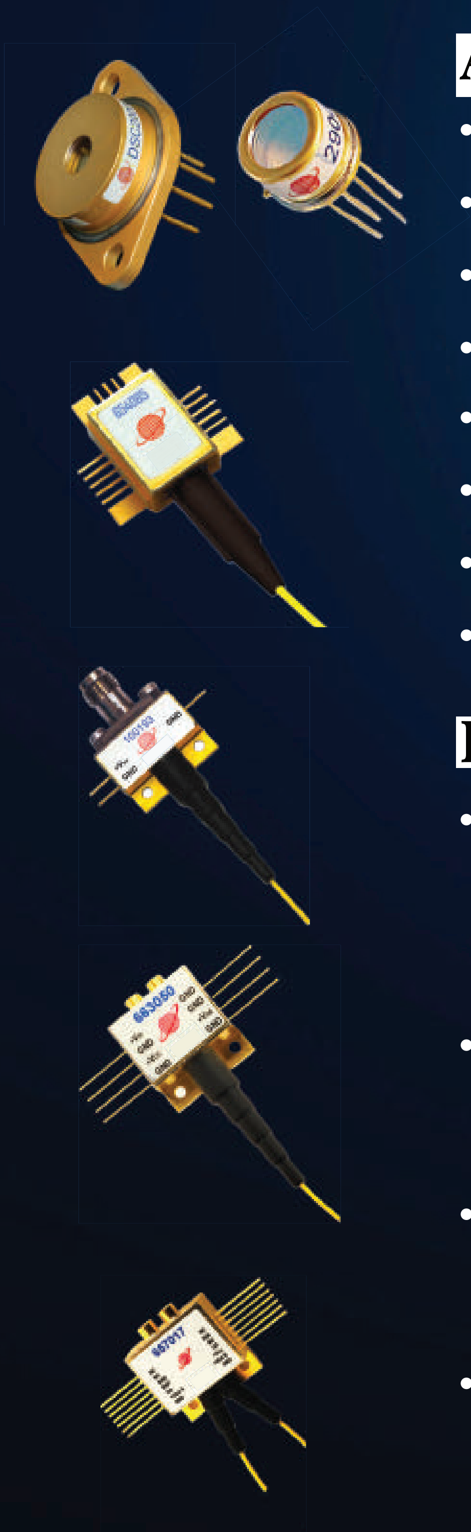
Black Semiconductor anticipates that the acquisition will advance the timeline for technology development by two years.

The acquisition combines Black Semiconductor's expertise in chip architectures and photonic process technology with ANL's specialized knowledge in graphene material production. ANL uses a semiautomated 200-mm process platform capable of producing 10,000 wafers per year, which will be scaled up to a fully automated 300-mm process to reach >1 million wafers per year.

The addition of ANL follows the opening of Black Semiconductor's FabONE headquarters in January, and positions the company to build a 300-mm wafer pilot line later this year for its integrated graphene photonic chips. The company is planning for volume production by 2029.

The business of graphene photonics

Though graphene is a frequent focus of R&D efforts targeting the intersection



of photonics and materials science, the business sector has led to a recent wave of positive momentum in graphene photonics. Most recently, 2D Photonics subsidiary CamGraPhIC raised $27 million to support the company's continued development of graphene photonics transceivers for AI and cellular data applications (see page 17). The financing occurred after the company Akhetonics brought in $6.3 million late last year to fuel the development of its full-stack all-optical general-purpose processor. Akhetonics is part of the European Union-funded Graphene-based All-Optical Technology Platform for Secure Internet of Things (GATEPOST) project, which reported its first photonic integrated chip in May 2024.

In the electronics and quantum technology spaces, Paragraf — which previously achieved mass production of graphene-based devices using standard semiconductor processes — established a partnership with the University of Birmingham in January to further the development of graphene devices for quantum computing. The partners aim to develop cryogenic testing of graphene devices to study their properties at the ultralow temperatures required for many quantum applications.

And earlier this spring, AIXTRON SE became a partner in the GraFunkL (graphene as a functional layer in UVC LEDs) project. The project will study the use of novel UVC LEDs against multiresistant hospital pathogens as well as the application of graphene over wafers up to 150 mm in diameter.

Headwall partners with GRYFN to boost hyperspectral data collection

Headwall Photonics partnered with GRYFN, a developer of multimodal sensing solutions, to streamline hyperspectral data collection and processing. The collaboration seeks to enhance accessibility and precision for industries such as agriculture, natural resources, environmental monitoring, and defense.

Per the partnership, Headwall is to integrate its high-performance hyperspectral imaging systems with GRYFN's advanced software and calibration tech-

People in the News


Walmsley.
Imperial College London

Imperial College London's provost **Ian Walmsley** will step down from his position in September to pursue different opportunities. Walmsley is the cofounder and chairman of ORCA Computing and has held the role of provost at Imperial College London since 2018. He previously chaired the Beirat of the Max Born Institute and served on the Max Planck Institute for Quantum Optics' science advisory board. Walmsley was elected as fellow of the Royal Society in 2012 for his contributions to quantum optics. He is also a fellow of Optica and served as its president in 2018. Walmsley was named a Commander of the Order of the British Empire in 2024 for his services to science and quantum technologies. The college will begin a global search for Walmsley's replacement.

The supervisory board of Jenoptik AG extended the contracts of **Ralf Kuschnereit**, responsible for the former Advanced Photonic Solutions division, and CFO **Prisca Havranek-Kosicek** through December 2030 and February 2031, respectively. Kuschnereit has been responsible for the Semiconductor & Advanced Manufacturing and the Biophotonics strategic business units, created in connection with the Jenoptik Group's new reporting structure that began in January 2025.


Seuret.
LASEA Switzerland

LASEA Switzerland appointed **Christophe Seuret** head of the company. Seuret has 25 years of experience in the sectors of microtechnology, luxury goods, and electronics, having most recently been in charge of commercial and technological development at Pink Engineering SARL.

Optical components and systems company FISBA North America appointed **Daniel Gray** president. Gray is the founder and former president of Gray Optics, which was acquired by FISBA in 2023. He has more than 20 years of experience in the development of precision optical systems for medical, biometric, consumer, and industrial markets.


Yu.
NLM Photonics

NLM Photonics, a developer of hybrid organic electro-optic technology, appointed **Anthony Yu** as a strategic advisor. Yu, former vice president of silicon photonics product management at GlobalFoundries, will help NLM establish an ecosystem of foundries, outsourced semiconductor assembly and test partners, and optical chip designers that will use NLM's technology.


Bonati.
Sill Optics

Laser optics manufacturer Sill Optics appointed **Guido Bonati** CEO, succeeding **Christoph Sieber**. Bonati has spent 30 years in various management positions in the optical industry, most recently as CTO and head of R&D at FISBA AG.

BluGlass Limited, a semiconductor developer, established an industry advisory board led by **Steven DenBaars** and **Richard Craig**. DenBaars is the cofounder of Soraa Laser Diode Inc., where he served as chair and CEO until its acquisition by Kyocera Corporation in January 2021, and is codirector of the Solid State Lighting & Energy Electronics Center at the University of California, Santa Barbara. Craig previously served as president and chief scientist at Oclaro and senior vice president at SDL and JDSU (now Lumentum). He currently serves on the boards of multiple laser companies.


Alexus.
Neonode

Optical sensing technology company Neonode appointed **Daniel Alexus** president and CEO. Alexus served as global head of innovation and founder of Ericsson ONE, an innovation accelerator within Telefonak-


Headwall Photonics

Headwall is partnering with multimodal sensor solutions developer GRYFN.

nologies, providing a complete solution for research-grade remote sensing. The combination aims to simplify data acquisition, processing, and analysis while maintaining accuracy and reliability.

As part of the agreement, Headwall will also offer the GRYFN Processing Tool, a software solution that integrates uncrewed aerial vehicle-based hyperspectral, lidar, and global navigation satellite system data. This tool streamlines job management, automates workflows, and enables efficient multimodal data processing.

tiebolaget LM Ericsson, since 2018. He has held several other senior roles at Ericsson since 2010.

Lightmatter, a photonic supercomputing company, added **Jason Zander** to its board of directors. Zander brings experience leading engineering and sales field organizations and currently serves as leader of Microsoft's strategic missions and technologies division.

Digital infrastructure developer TiniFiber appointed **Chris Pegge** vice president of sales. Pegge has nearly 40 years of technical and sales leadership in the fiber optic industry, having held key roles at KITCO Fiber Optics, Marmon Aerospace & Defense, Stran Technologies, and General Cable.

Natcast, a nonprofit entity designated by the Department of Commerce to operate the National Semiconductor Technology Center established by the CHIPS and Science Act, named **Craig Child** director of the CHIPS for Americas Extreme-Ultraviolet Accelerator, located at NY CREATES' Albany NanoTech Complex. Child joins Natcast from IBM Research and has more than 20 years of experience in semiconductor R&D.

STEMMER IMAGING

(From left) Andreas Holt, Peter Keppler, STEMMER IMAGING CEO Arne Dehn, and Philipp Stein.

Machine vision company STEMMER IMAGING updated its leadership structure. **Peter Keppler** was promoted to chief marketing officer from his previous position as senior director of international sales enablement. **Philipp Stein** was promoted from director of operations and supply chain to COO and will lead digitalization initiatives. **Andreas Holt** is currently serving as interim CFO while the company finalizes the appointment of a permanent CFO. The company also established an extended management team, including **Johannes Hiltner**, who will lead STEMMER's business development. The newly created position will focus on new market opportunities.

European Union invests $16.3M to support photonics companies

The European Commission launched the €15 million ($16.3 million) PhotonHub PHACTORY initiative to support the development of photonic technologies. The initiative is designed to provide companies with expert support and fast-track access to Europe's leading laboratories.

Led by Brussels Photonics (B-PHOT) at Vrije Universiteit Brussel, the initiative builds on the success of PhotonHub Europe. To date, the PhotonHub Europe initiative has helped more than 100 companies deliver more than €750 million in new revenues, create 1000 jobs, and raise €250 million in venture capital in just four years.

"Building on our impact to date and in response to the needs of the market, we are extending PhotonHub's previous offering to also support entrepreneurially minded researchers and startups," said professor Hugo Thienpont, director of Brussels Photonics and coordinator of the PhotonHub program. The program will work to lower the barrier to market entry by offering subsidies that can cover up to 85% of project costs, greatly reducing risks for businesses. It is expected to help companies achieve a wider and faster uptake, integration, and deployment of photonics technologies, boost competitiveness, and foster new business.

With more than 30 European partners, the framework covers the entire value chain from early-stage concept and prototyping to upscaling. It also spans technology platforms, facilitating open access and guided orientation to a broad range of photonics expertise, equipment, and technologies that are available from leading facilities throughout Europe.

Professor Hugo Thienpont, director of Brussels Photonics and coordinator of the PhotonHub program.

PhotonHub

The PhotonHub PHACTORY team is offering tailored support streams for European Union companies, depending on their stage, technology readiness level, and strategic ambitions. These include a launchpad for spinouts and startups, a scaling club for fast-growing ventures, and customized business coaching for established small- to medium-size enterprises and certain large-scale companies aiming for market growth.

The framework, which runs until the end of 2028, targets small- to mid-size firms across all sectors. Tailored support includes expert assessments on technical and commercial viability, access to Europe's researchers and laboratories, and training and coaching across various industries.

Kraken Robotics acquires underwater lidar company 3D at Depth

Marine technology company Kraken Robotics will acquire 3D at Depth Inc., a U.S.-based subsea technology and services company specializing in high-resolution lidar imaging and measurements for underwater applications. The deal carries a cash value of $17 million.

According to Kraken Robotics' president and CEO, Greg Reid, the acquisition builds on Kraken's expertise in subsea optical systems and expands offerings in this area by adding solutions that feature differentiated capabilities. Kraken provides subsea sensors, batteries, and robotic systems that are designed for marine and underwater use cases.

The combined company's platforms will have a strong R&D feedback loop as technologies are deployed, tested, and iterated in Kraken's services business, Kraken said.

3D at Depth's headquarters and production facility are based in Longmont, Colo., with offshore service operations based out of Houston. The company operates two satellite offices in the U.K.

Kraken said that it plans to make the acquisition through a subsidiary and that it already signed a definitive agreement and plan of merger for the indirect acquisition.

$15B

— expected value of the global 3D metrology market by 2029, according to MarketsandMarkets

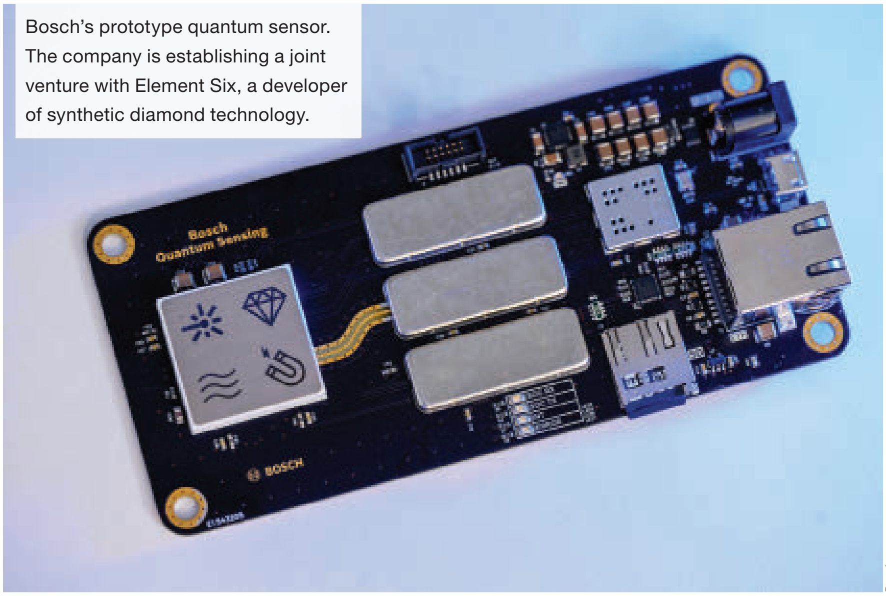
Bosch launches joint venture with diamond developer Element Six

Bosch established a joint venture aimed at commercializing quantum sensing, partnering with synthetic diamond producer Element Six. Called Bosch Quantum Sensing, the company will be based on the in-house startup of the same name, which Bosch set up in 2022.

Element Six, which has been a Bosch partner since 2023, will hold a 25% stake in the new company. Further financial details have not been disclosed, and the establishment of the company remains subject to official approval.

Bosch has conducted research in quantum sensing for more than 10 years and diamonds have been a key element to the company's approach to quantum sensors. According to Bosch, its latest quantum sensor prototype is the most compact of its kind for the level of sensitivity required and is the size of a smartphone. In the area of mobility, it could enable robust navigation in the future, complementary to conventional GPS systems. It could also offer advantages for the exploration of natural resources and, in medical technology, for the measurement of cardiac activity, Bosch said.

Headquartered in Ludwigsburg, Germany, Bosch Quantum Sensing employs 30 associates.



Bosch's prototype quantum sensor. The company is establishing a joint venture with Element Six, a developer of synthetic diamond technology.

Bosch

Optical connectivity startup InfiniLink raises $10M in funding

InfiniLink, an Egypt-based semiconductor startup specializing in advanced optical data connectivity chips for AI-driven data centers, closed a $10 million funding round. Founded in 2022, InfiniLink develops silicon photonics-integrated optical transceiver chiplets (iOTC) technology.

The funds will be used to accelerate the development of optical connectivity solutions, leveraging expertise in analog mixed-signal and photonics to address growing bandwidth and energy efficiency demands of AI-driven data centers. The company's technology aims to enable low-power pluggable transceiver modules and high-bandwidth-density co-packaged optical engines.

InfiniLink's iOTC technology features in the company's iOTC-G1 product, an optical transceiver engine optimized for low-power Ethernet and PCI Express linear pluggable optical modules. The company has additionally developed patent-pending photonics modulator architectures and integrated wavelength division multiplexers and demultiplexers. The technology uses high-density fiber interfaces that are designed to be compatible with external laser sources using a hybrid integration design for a streamlined manufacturing methodology for supply chains.

The seed round was joined by MediaTek, a fabless semiconductor company, and Sukna Ventures, with participation from Egypt Ventures and angel investor M Empire Angels.

Briefs

Semiconductor technology firm **Retym** emerged from stealth with more than $180 million raised across multiple rounds to drive AI infrastructure innovation. The funding will support scaling to production and continued product development advancements as the company charts a product road map to address increasing bandwidth demand driven by AI. Retym specializes in programmable coherent digital signal processing solutions for cloud and AI infrastructure.

Coherent Corp. intends to sell its epitaxial fabrication facility in Champaign, Ill. The 65,000-sq-ft campus comprises four buildings and features five G3 epitaxial systems in 15,000 sq ft of Class 1000 ballroom-style cleanrooms. The fab is designed for up to 10 epitaxial tools and previously produced 2- to 6-in. indium phosphide and gallium arsenide wafers.

Lumai, a developer of optical computing technologies, secured an investment round totaling more than $10 million. The investment will support the startup's next stage of growth by advancing product development, increasing its workforce, and expanding the company's U.S. presence. Lumai's optical processor uses low-cost optical components in a PCI Express form factor to deliver 50× the performance of silicon processors while using 10% of the power. The company is creating optical processor technologies to accelerate large language models and other transformer-based AI.

Aeluma, a semiconductor company specializing in high-performance, scalable technologies for mobile, automotive, AI, aerospace and defense, communications, and quantum computing, received approval to list its common stock on the Nasdaq Capital Market stock exchange under the ticker symbol ALMU. The company also priced an underwritten public offering of its stock, which is expected to yield approximately $12 million in gross proceeds.

Sparrow Quantum, a provider of photonic quantum chips secured €21.5 million ($24 million) in series A funding. Building on a €4.1 million seed round in 2023, the investment will help the company accelerate R&D, expand chip production, and bring its next-generation quantum chips to market. The company's technology platform stems from research conducted by founder Peter Lodahl at the Niels Bohr Institute in Copenhagen, Denmark. The work laid the foundation for the company's flagship product, Sparrow Core — an on-chip deterministic single-photon source designed to help scale photonic quantum computing by generating photons reliably on demand.

VTT Technical Research Centre of Finland invested €3.4 million ($3.7 million) to open a pilot line environment in Finland for medical devices. The investment into the line provides a state-of-the-art cleanroom and manufacturing equipment to help accelerate the market entry of innovative medical technologies. The facility enables the production of small- to middle-size prototype series of advanced electronic, photonic, microelectronic, and microfluidic components, in addition to integration technologies. These technologies enable the development of comfortable, skin-like wearable sensors for continuous monitoring of cardiovascular diseases and microfluidics biochemical sensors for ultrasensitive cancer diagnostics, VTT said.

Alcon, a provider of ophthalmology-focused medical devices, will acquire **LENSAR**, a medical technology company focused on laser solutions for the treatment of cataracts. The acquisition includes ALLY Robotic Cataract Laser Treatment System, LENSAR's proprietary Streamline software technology, and LENSAR legacy laser system, building Alcon's femtosecond laser-assisted cataract surgery offering. The transaction represents a total consideration of up to $430 million and is expected to close this year.

Exaktera acquired **autoVimation**, a manufacturer of high-performance enclosures and mounting solutions for industrial cameras, lighting, and related vision system components. The terms of the transaction were not disclosed. autoVimation will become Exaktera's fifth operating asset. It joins Z-Laser, ProPhotonix, Advanced Illumination, and iiM in the portfolio, which is owned by Union Park Capital. Per the deal, autoVimation founder and managing director, Peter Neuhaus, will continue to lead the business under Exaktera's ownership.

Fusion energy company **Marvel Fusion** extended its series B funding round by €50 million ($54.2 million) to support the company's transition from R&D to industrial deployment. Marvel Fusion is currently working to build a $150 million laser facility in partnership with Colorado State Univer-

EPIC adds board members, issues awards at annual meeting

During its 2025 Annual General Meeting, the European Photonics Industry Consortium (EPIC) appointed Claire Valentin, chief strategy officer at Exosens, and Maria Chiara Carrozza, president of Italy's national research council (CNR), as members of EPIC's board of directors.

Valentin's expertise is expected to strengthen EPIC's connections to high-growth photonics sectors, including defense, space, medical, and industrial applications and help EPIC members to navigate commercialization and business expansion. Carrozza brings experience in optics and photonics applications in health care, AI, and robotics as well as expertise in academia, politics, and industry.


EPIC

Maria Chiara Carrozza, president of Italy's national research council (CNR).


EPIC

Basil Garabet, president of the European Photonics Industry Consortium (EPIC) **(left)**, presents the 2025 EPIC Lifetime Achievement Award to Eric Mottay, founder of Amplitude Laser Group.

sity. Full proof of technology at the facility is expected by 2027. The company is also progressing its industrial partnership with **Siemens Energy** by jointly developing a conceptual design of a fully integrated fusion power plant.

VIGO Photonics entered into a strategic framework agreement with **PCO SA**, a manufacturer of optoelectronic solutions for the military. The contract is for the supply of cooled infrared detector arrays and worth PLN 200 million ($52.4 million). It describes a long-term collaboration aimed at the final development of arrays in line with PCO's demand, followed by their production and sale. The developed solutions will find application in combat platforms as well as in antiaircraft systems in both the Polish army and the European defense industry.

Phlux Technology, an infrared sensor technology developer, secured a £9 million ($11.8 million) series A funding round. According to the company, the funding will accelerate expansion into optical communications and sensing industries, leveraging its antimonide-based semiconductor technology.

Xanadu, a photonic quantum computing company, and **Corning Inc.** entered into a collaboration to develop customized fiber and fiber-array solutions to enable low-loss networking of photonic quantum computing chips. This collaboration unites Xanadu's expertise in developing ultralow-loss photonic chip components using customized fabrication and design techniques and Corning's innovations in low-loss optical fiber and high-precision fiber arrays.

The Annual General Meeting, which took place in Barcelona, Spain, also saw the issuing of EPIC's Lifetime Achievement, CEO, and Sustainability Awards. Eric Mottay, founder of Amplitude Laser Group, received the 2025 Lifetime Achievement Award in recognition of leadership in the field of ultrafast laser technologies and their applications. Founded in 2001, Amplitude has become a global leader in ultrafast lasers, catering to scientific, medical, and industrial applications.

Theodor Nielsen, founder and CEO of NIL Technology, was awarded the 2025 EPIC CEO Award for exceptional technology and business leadership in nanoimprint lithography and metaoptics. NIL Technology was acquired last year by Radiant Opto-Electronics for €300 million ($324 million).

IMM Photonics received the inaugural Sustainability Award for contributions to environmental, social, and economic sustainability. Since 2015, the company has been pursuing a corporate policy of sustainability.

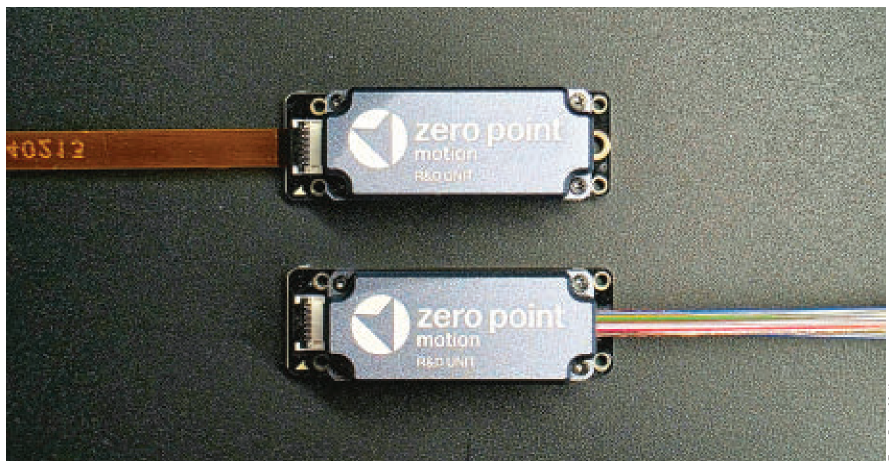
Zero Point Motion emerges from stealth mode

Sensor technology startup Zero Point Motion closed a £4 million ($5.2 million) pre-series A funding round. The investment supports the company's scaleup efforts and the expansion of its team as the company develops a scalable volume-manufacturable process for its next-generation positioning and navigation sensors.

"We are working with two of the world's leading foundries to push [microelectromechanical systems] performance beyond its limits," said Lia Li, founder and CEO of Zero Point Motion. "We've also brought more integration and packaging R&D in-house, cutting iteration times from eight weeks to just one day."

Zero Point Motion's technology fuses silicon photonics and microelectromechanical systems (MEMS), taking inspiration from Nobel Prize-winning gravitational wave detection principles. The approach enables low-cost, low-noise, miniaturized accelerometers and gyroscopes that are 100× more sensitive compared to conventional MEMS sensors. The technology has applications in defense, space exploration, and autonomous systems.

The investment round was supported by SCVC (the official funding arm of Science Creates), Foresight Group, Verve Ventures, and u-blox AG.



Zero Point Motion

Zero Point Motion's technology platform combines silicon photonics and microelectromechanical systems (MEMS) to create high-performance, miniaturized accelerometers and gyroscopes suitable for defense, space, and autonomous systems.

European consortium targets sensor advancements for space imaging

A consortium funded by the European Union (EU) is developing advanced high-resolution image sensing technology that could be used in a variety of space missions, including Earth observation, planetary exploration, and scientific research. The three-year Technology for European iNdependence in Space Image Sensor (TENSIS) project will address the EU-based development of advanced CMOS imaging sensors.

The project will aim to create a strategic, competitive advantage for European prime and equipment manufacturers and reduce the dependence on critical technologies and capabilities from outside the EU.

8.3% — predicted compound annual growth rate of the global terrestrial laser scanning market by 2031, according to Data Bridge Market Research

A goal of the program is to validate a scalable, large-area, high-resolution, radiation-tolerant, customizable, and affordable 180-nm CMOS detector, with the key technical characteristics of a 24k- × 16k-stitched CMOS matrix of 400 MP. A smaller 4k- × 4k-stitched CMOS array will also be designed and manufactured.

The project comprises several industrial partners. Teledyne e2v Semiconductors SAS and Teledyne Innovaciones Microelectronicas SL will oversee the project and design the detectors, while imec will manage the development of the optical stack on top of the CMOS detector, including filters and optical microlenses. Meanwhile, Airbus Defence and Space SAS will lead the development of the test equipment and assess the performance of the detector prototypes. Alter Technology Tüv Nord will validate the smaller 4k × 4k detector for use in the space environment.

The project will run until Dec. 31, 2027. The 24k- × 16k-stitched CMOS array is expected to reach technology readiness level 6, with a prototype sensor tested in a relevant environment. The 4k × 4k CMOS detector is targeted for technology readiness level 7.

Teledyne

The three-year Technology for European iNdependence in Space Image Sensor (TENSIS) project was launched February 11 at an inauguration event in consortium member Teledyne e2v's facilities in Saint-Égrève, France.

DESY achieves laser plasma acceleration milestone

HAMBURG, Germany — Laser plasma acceleration promises to be a disruptive technology, providing a route to build far more compact accelerators and open avenues in fundamental research, industry, and health. Before it reaches that potential, however, certain properties of the plasma-driven electron beam, as it is delivered by current prototype accelerators, must be refined.

To this end, DESY's LUX experiment has made significant progress. Using a novel correction system, a research team significantly improved the quality of electron bunches accelerated by a laser plasma accelerator, thereby bringing the technology a step closer to concrete applications, such as a plasma-based injector for a synchrotron storage ring.

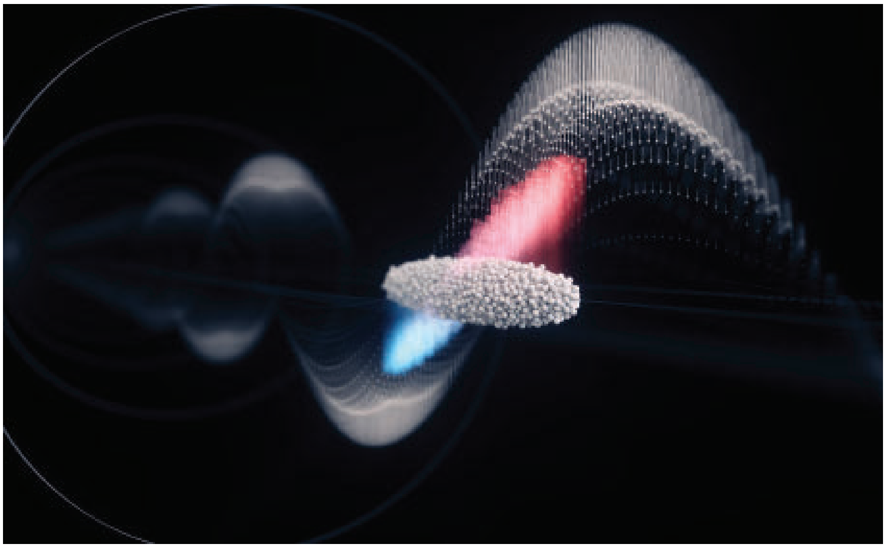
Conventional electron accelerators use radio waves that are directed into so-called resonator cavities. The radio waves transfer energy to the electrons as they fly past, increasing their velocity. To achieve high energies, many resonators must be connected in series, making the machines large and costly.

Laser-plasma acceleration is a novel — and compact — alternative. Short, intense laser pulses are shot into a small hydrogen-filled capillary generating a plasma — an ionized gas. When the laser pulse passes through the plasma, it creates a wake similar to the wake of a high-speed boat traveling though water. This wake can accelerate bunches of electrons to enormous energies within a few millimeters.

To date, the technology has had certain drawbacks.

"The electron bunches produced are not yet uniform enough," said Andreas Maier, lead scientist for plasma acceleration at DESY. "We would like each bunch to look precisely like the next one."

Another challenge concerns the energy distribution within a bunch. Figuratively speaking, some electrons fly faster than others, which is unsuitable for practical applications. In modern accelerators, these problems are solved using machine control systems.


Science Communication Lab for DESY

By improving the quality of electron bunches accelerated by a laser plasma accelerator, DESY researchers have hit a milestone that is poised to bring laser plasma accelerator technology to concrete applications — such as a plasma-based injector for a synchrotron storage ring.

Using a two-stage correction, the DESY team sent electrons accelerated by the LUX plasma accelerator through a chicane consisting of four deflecting magnets. By forcing the particles to take a detour, the pulses are stretched in time and sorted according to their energy. "After the particles have passed the magnetic chicane, the faster, higher-energy electrons are at the front of the pulse," said Paul Winkler, first author of the study. "The slower, relatively low-energy particles are at the back."

The stretched and energy-sorted electron bunch is then sent into a single accelerator module similar to those used in modern radio frequency-based facilities. In this resonator, the electron bunches are slightly decelerated or further accelerated.

"If you time the beam arrival carefully to the radio frequency, the low-energy electrons at the back of the bunch can be accelerated and the high-energy electrons at the front can be decelerated," Winkler said. "This compresses the energy distribution."

The team reduced the energy spread by a factor of 18 and the fluctuation in the central energy by a factor of 72. Both values are smaller than one permille, making them comparable to those of conventional accelerators.

Most of the components used were from existing DESY stocks. The team had to invest a great effort in setting up the correction stage and synchronizing the extremely rapid processes. "But once that was done, things went surprisingly well," Winkler said. "On the very first day, when everything was set up, we switched on the system and immediately observed an effect."

After a few days of fine-tuning, it was clear that the correction system was working as intended.

"This is also a result of the successful synergy between plasma acceleration and modern accelerator technology, as well as the collaboration between a large number of technical teams at DESY, who have extensive experience in building accelerators," said Reinhard Brinkmann, former director of the accelerator division.

"The results will help to further strengthen confidence in the young technology of laser-plasma acceleration," Maier said.

The newly shown technique could be used to generate and accelerate electron bunches to be injected into x-ray sources such as PETRA III or its planned successor, PETRA IV. To date, such particle injection has required relatively large and energy-intensive conventional accelerators. Laser-plasma technology offers a more compact and economical alternative.

"What we have achieved is a big step forward for plasma accelerators. We still have a lot of development work to do, such as improving the lasers and achieving continuous operation," said Wim Leemans, director of the Accelerator Division at DESY.

"But in principle, we have shown that a plasma accelerator is suitable for this type of application."

The research was published in *Nature* (www.doi.org/10.1038/s41586-025-08772-y).

Laser welding method streamlines durable PIC-to-fiber connections

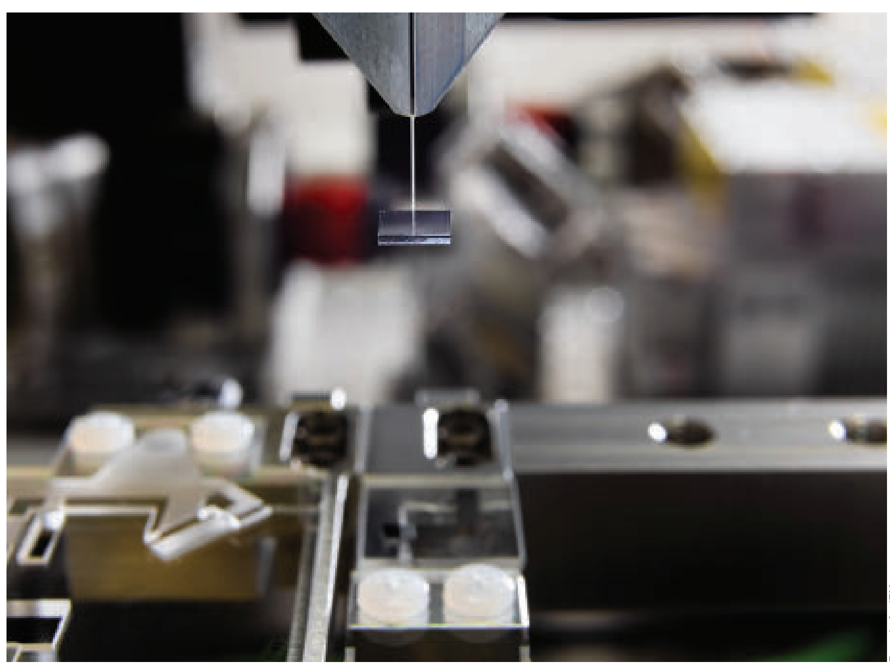
BERLIN — Researchers at the Fraunhofer Institute for Reliability and Microintegration IZM (Fraunhofer IZM) developed a laser welding process to connect photonic integrated circuits (PICs) to optical fibers without adhesives. Uniquely, the technology can be used at cryogenic temperatures as low as 4 K. The direct quartz-to-quartz connections created by the technology promise more reliable, faster, and cheaper fiber-PIC connections that will enhance quantum technology applications.

Extremely low temperatures are necessary to observe quantum effects in action, and a great deal of attention and effort is going into the development of cryogenic quantum computing systems. Quantum technology systems implemented with PIC-based modules promise a more compact solution for safe communication and connections in quantum computing. But, photonic systems such as these require reliable glass fiber connections.

As part of the QWeld project, researchers at Fraunhofer IZM developed a novel laser welding technology for vertical optical connections. It uses the prototype PIC-Weld processing unit that was assembled and installed at the institute during a previous research project. The facilities made it possible to form a direct laser-welded connection between glass fiber and silica-glass PICs, which is more durable and thermally robust than conventional adhesive connections.

The QWeld project uses PICs that were made via a standard CMOS process, but designed with one special feature: a silicon dioxide (SiO_2) top layer that is needed for glass-on-glass laser welding. The fiber is connected vertically to the PIC, usually at a specific inclination. During welding, the laser hits the contact point between the PIC and the glass fiber on both sides and creates a material bond between both in only a few seconds, promising a major acceleration of the manufacturing process.

For the QWeld project, Fraunhofer researchers created a stable, adhesive-free, optical bonding solution for photonic integrated circuits (PICs) that could be used at temperatures as low as 4 K. The project's focus was on vertical connections.



Fraunhofer IZM

Making this possible under the new conditions set for the project — primarily the combination of SiO_2 materials and the exacting standards in terms of high-precision alignment — meant that the entire process and the production system had to be refined and redeveloped, with the addition of a local preheater, added alignment features, and sensors. The welded bond is durable, and the process is reproducible. Additionally, the process can be automated.

"The novel laser welding process uses a CO_2 laser to heat up a specific part of the PIC's SiO_2 layer to minimize the temperature difference between the fiber and the PIC during the actual welding," said Alethea Vanessa Zamora Gómez, a researcher at Fraunhofer IZM and coordinator of the project. "The innovative preheater technology is likely to solve all of the current challenges we encounter when bonding fibers to PICs at cryogenic temperatures."

The researchers expect the technology to have applications beyond enabling cooperation opportunities in cryotechnology and quantum PICs. These additional applications, the researchers said, could be in biophotonics, sensor technology, and/or high-performance lasers.

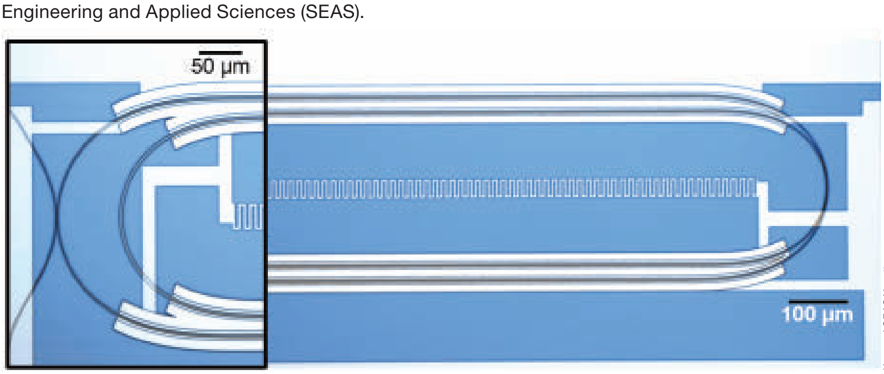
Photon router could enable superconducting quantum networks

CAMBRIDGE, Mass. — Applied physicists at the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) created a photon router that could plug into quantum networks to create robust optical interfaces for noise-sensitive microwave quantum computers. The advancement is a step toward modular, distributed quantum computing networks that leverage existing telecommunications infrastructure.

Led by Marko Lončar, the Tiantsai Lin Professor of Electrical Engineering and Applied Physics at SEAS, the researchers created a microwave-optical quantum transducer, a device designed for quantum processing systems that use superconducting microwave qubits.

The transducer is effectively a router for photons, and bridges the large energy gap between microwave and optical photons, thereby enabling control of microwave qubits with optical signals generated many miles away. The device is the first of its kind to demonstrate control of a superconducting qubit using only light, according to the researchers.

An optical micrograph of the microwave-optical quantum transducer developed by researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS).



Harvard SEAS/ Lončar group

First author and graduate student Hana Warner said that the transducer specifically offers a pathway to harness the power of optics when dreaming up quantum networks. "The realization of these systems is still a ways out, but in order to get there, we need to figure out practical ways to scale and interface with the different components," Warner said. "Optical photons are one of the best ways you can do that, because they're very good carriers of information, with low loss, and high bandwidth."

Superconducting qubits, which are nanofabricated circuits engineered for different energy states, are an emerging quantum computing platform due to their scalability, compatibility with existing manufacturing processes, and ability to maintain quantum superposition long enough to perform calculations. However, the extremely low temperatures at which they must operate necessitates the use of large cooling systems, called dilution refrigerators. Since future quantum computing will require millions of qubits to operate, scaling these systems only on microwave-frequency signals is challenging.

A solution lies in using microwave qubits to perform the quantum operations, and to use optical photons as efficient and scalable interfaces.

The team's 2-mm optical device resembles a paper clip and sits on a chip that is ~2 cm in length. It works by linking a microwave resonator with two optical resonators, allowing a back-and-forth exchange of energy enabled by the properties of their base material, lithium niobate. The team leveraged this exchange to eliminate the need for bulky, hot microwave cables for controlling qubit states.

Additionally, the same devices used for control could be used for qubit state readout, or for forming direct links to convert finicky quantum information into sturdy packets of light between quantum computing nodes. The work could lead to superconducting quantum processors connected by low-loss, high-powered optical networks.

"The next step for our transducer could be reliable generation and distribution of entanglement between microwave qubits using light," Lončar said.

Working in an industry collaboration with Rigetti Computing, which provided the superconducting qubit platform on which the researchers tested their transducer and mapped out different experiments, the Harvard team additionally collaborated with researchers from the University of Chicago and MIT.

The research was published in *Nature Physics* (www.doi.org/10.1038/s41567-025-02812-0).

Thulium fiber laser system shatters performance record

JENA, Germany — Researchers at the Fraunhofer Institute for Applied Optics and Precision Engineering IOF (Fraunhofer IOF) developed thulium fiber laser systems that almost double the previous performance world record, according to the developers. The laser system is made up of three high-power thulium fiber lasers that emit light in the spectral range of 2030 to 2050 nm and achieve an outpower of up to 1.91 kW — close to double that of conventional systems at ~1.1 kW.

High-power fiber lasers are a versatile tool for numerous technological applications, such as materials processing and free space communications. The choice of the right spectral range plays a decisive role, especially over long distances — from Earth to satellites, for example. The spectral region >2030 nm is considered particularly suitable, because atmospheric losses are low in this region and the laser light is relatively eye-safe.

The principle of spectral beam combining is central to optimizing the necessary technological basis using individual sources. In this process, laser beams of different wavelengths are directed onto special optical reflection gratings at adapted angles. Diffraction combines the laser beams into a single beam. This not only increases the performance of the fiber laser system but also preserves the beam quality and thus the focusing ability of the laser beam.

Previous systems reach their physical limits at high power levels, in particular, due to overheating caused by low combination and laser efficiencies.

The Fraunhofer IOF team addressed these challenges with more efficient individual sources and improved cooling systems. Specifically, a special connection technique for fibers, known as cold splicing, enables low-loss fiber-to-fiber coupling and effective temperature regulation.

Another key component is a specially developed diffraction grating with an efficiency of >95% and excellent thermal performance.

"The combination grating is the heart of our system," said Friedrich Möller, scientist in the Laser Technology department at Fraunhofer IOF. "Up to now, optical combining elements such as gratings and dichroic mirrors for wavelengths around 2 µm were only available for laser powers of a few hundred watts. However, our colleagues at the institute have developed a special diffraction grating that also works excellently in the multi-kilowatt region under challenging parameters. It enables a low-loss beam combination with overall efficiencies greater than 90% and is the baseline for our next leaps in performance."

According to Till Walbaum, group leader for laser technology at Fraunhofer IOF, the next big challenge that the team will face is reaching the 20-kW level. The high-performance thulium fiber lasers open a wide field of applications, including medical procedures, polymer processing, and optical data transmission.

Additionally, an important advantage of the lasers is their improved eye safety. Scattered light with a wavelength of 2 µm is absorbed by the cornea and does not reach the retina, which enables safer use in industrial and medical applications.

Chip-size amplifier increases data transmission tenfold

GOTHENBURG, Sweden — A research team from Chalmers University of Technology introduced an amplifier design that enables the transmission of 10× more data/s than those that are used in current fiber optic systems. The amplifier, which fits on a small chip, holds potential for various critical laser systems, including those used in medical diagnostics and treatment.

To ensure that the information maintains a high quality and is not overwhelmed by noise, optical amplifiers are essential. The data transmission capacity of an optical communication system is largely determined by the amplifier's bandwidth, which refers to the range of light wavelengths that it can handle. "The amplifiers currently used in optical communication systems have a bandwidth of approximately 30 nm," said lead author and professor of photonics Peter Andrekson. "Our amplifier, however, boasts a bandwidth of 300 nm, enabling it to transmit [10×] more data per second than those of existing systems."

The amplifier, made of silicon nitride, features several small spiral-shaped, interconnected waveguides that efficiently direct light with minimal loss. By combining this material with an optimized geometric design, several technical advantages have been achieved. According to Andrekson, the tenfold increase in data bandwidth, occurring as the amplifier reduces noise in a way that is more effective than other types of amplifiers, is the key innovation to the device. "This capability allows it to amplify very weak signals, such as those used in space communication," Andrekson said.

Additionally, the researchers miniaturized the system to fit on a chip just a few centimeters in size — more precisely, they integrated multiple amplifiers onto the chip, allowing the concept to be easily scaled up as needed. Since optical amplifiers are crucial components in all lasers, the researchers' design can be used to develop laser systems capable of rapidly changing wavelengths over a wide range.

According to the researchers, the innovation as it stands opens up numerous applications in society. "Minor adjustments to the design would enable the amplification of visible and infrared light as well," Andrekson said. "This means the amplifier could be utilized in laser systems for medical diagnostics, analysis, and treatment. A large bandwidth allows for more precise analyses and imaging of tissues and organs, facilitating earlier detection of diseases."

In tests, the researchers demonstrated that the amplifier functions effectively within the optical communication spectrum, between 1400 and 1700 nm. Adapting the device for use at other wavelengths charts a course for additional applications, including in imaging, holography, and materials characterization, among others.

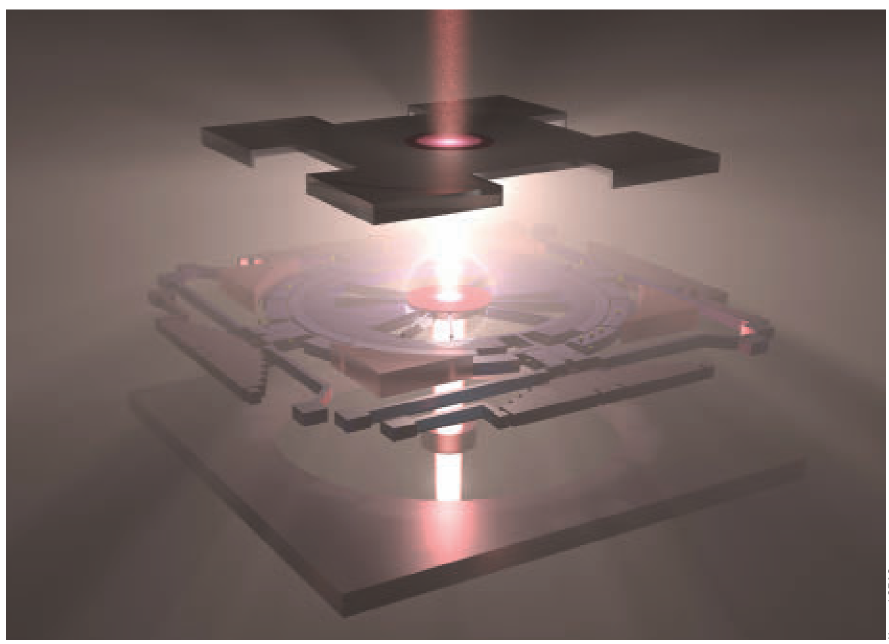
The research was published in *Nature* (www.doi.org/10.1038/s41586-025-08824-3).

Photonic crystal sensor measures key parameters simultaneously

CAMBRIDGE, Mass. — Twisted moiré photonic crystals, an advanced type of optical metamaterial, have shown enormous potential in the race to engineer smaller, more capable, and more powerful optical systems. In twisted moiré photonic crystals, the way in which the layers twist and overlap can change how the material interacts with light. By changing the twist angle and the spacing between layers, these materials can be fine-tuned to control and manipulate different aspects of light simultaneously. This means that the multiple optical components that are typically needed to simultaneously measure light's phase, polarization, and wavelength can be replaced by a single device.

However, scientists have been unable to integrate twisted moiré photonic crystals into devices that can actively control the twist and distance between layers in real time. This bottleneck has severely limited their application to-date.

Against this backdrop, researchers from the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS), in collaboration with researchers from Stanford University and the University of California, Berkeley, developed an on-chip twisted moiré photonic crystal sensor that controls the gap and angle between the crystal layers in real time. The solution uses microelectromechanical systems technology and enables users to detect and collect detailed polarization and wavelength information simultaneously.



Harvard SEAS

An on-chip twisted moiré photonic crystal sensor that uses microelectromechanical systems technology actively controls the twist and distance between layers in real time. The device is promising for optical systems, offering highly tunable optical properties in a compact and scalable design.

In the researchers' device, the layers of photonic crystals sit on vertical and rotary actuators connected to an electrode. The whole device is only a few millimeters in scale and can be fabricated using CMOS-compatible processes.

By using the actuators to change the distance and rotational position of the layers of photonic crystals, the researchers could perform simultaneous hyperspectral and hyperpolarimetric imaging — meaning every pixel captured by the sensor contained information from across the electromagnetic spectrum and detailed information about the polarization state.

To the researchers' knowledge, the solution is the first device with active tuning to demonstrate such detailed information about multiple properties of light. And, according to Eric Mazur, the Balkanski Professor of Physics and Applied Physics at SEAS and senior author of the paper, the characteristic qualities that twisted moiré photonic crystals deliver give them broad application potential across advanced photonic technologies, especially for smaller and more powerful optical systems.

"These devices could be used for a range of applications, including quantum computing, data communications, satellites, or medical scans, where getting a clear image and detailed information about light and color is really important," said Haoning Tang, a postdoctoral fellow at SEAS and first author of the paper.

"Our research demonstrates how powerful these materials can be when we have precise control, and establishes a scalable path toward creating comprehensive flat-optics devices suitable for versatile light manipulation and information processing tasks," Tang said.

In the future, devices such as those fabricated by the researchers could be developed with increasingly complex tuning capabilities, including actuators with even more degrees of freedom.

The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-025-01650-z).

Researchers unleash frequency excitations' untapped potential

NEW YORK — In a conventional wave-based system, the properties of the materials used to build the system limit the control over wave phenomena. Limitations on bandwidth and efficiency are among the performance metrics that are typically resolved by using exotic materials to build the device. The additions, however, add energy to the system, or increase the complexity of the device.

Researchers at City University of New York (CUNY) and Florida International University (FIU) explored an alternative approach that uses complex frequency excitations to enhance wave control in conventional materials. By tailoring the excitation form to oscillate at complex-valued frequencies, the researchers imitated the presence of gain and loss in a system and achieved favorable effects, including perfect absorption and super-resolution imaging.

Additionally, the researchers showed that they could surpass passivity limitations in wave-matter interactions and access non-Hermitian responses without relying on complex, active, and potentially unstable components. Enhanced light-wave control using complex frequency excitations could lead, for example, to higher resolution medical imaging, more efficient wireless communication systems, and improved control over wave-based quantum states used in quantum sensing and computing.

"This approach provides a fundamentally new strategy for wave control," said professor Andrea Alù, principal investigator for the study. "We are no longer limited by the material platform to enhance the device performance. We can now shape how wave-based systems respond simply by designing the right kinds of excitations."

The researchers used excitation signals with tailored waveforms, whose amplitudes grew or decayed exponentially over time, to mimic the effect of gain and loss in passive systems. Under suitable conditions, the signal excitations could engage the natural resonances and antiresonances of the system. This dynamical behavior facilitated access to non-Hermitian responses without the need to modify the systems' material properties, and enabled exotic optical effects.

After tailoring the excitation form to oscillate at complex-valued frequencies and emulate the existence of gain and loss, the researchers demonstrated controllable, enhanced energy storage, superresolution imaging, enhanced wireless power transfer, and wave manipulation beyond the passivity limits.

"While the initial demonstrations of complex frequency excitations have been limited to radio and acoustic frequencies, scaling this technique to higher frequencies, such as optical systems, remains a challenge," researcher Seunghwi Kim said.

The experimental use of complex frequency excitations has enabled phenomena previously unattainable in passive systems. By bridging theoretical concepts with experimental implementations, these advancements demonstrate the feasibility of accessing non-Hermitian responses in passive linear systems. In optics and photonics, this approach could offer opportunities to alter how light interacts with matter in a highly dynamic and tunable fashion, enabling enhanced control over light emission and transport. Complex excitations are applicable to wave systems in general, and could be applied to developments in metamaterials, optical computing, sensing, and image processing.

"Our work lays the foundation for future breakthroughs by providing a road map for researchers across various wave physics domains to explore the untapped potential of complex frequency excitations," Kim said.

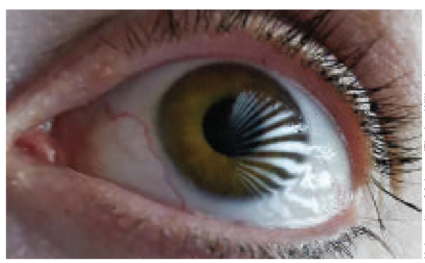
The research was published in *Science* (www.doi.org/10.1126/science.ado4128).

Eye-tracking innovation merges the powers of deflectometry, AI

TUCSON, Ariz. — Eye-tracking technology is critical in AR/VR headsets, scientific research, medical and behavioral sciences, automotive driving assistance, and industrial engineering. Tracking the movements of the human eye with high accuracy, a necessary aspect of AR/VR, is a technical challenge itself.

In response, researchers at the University of Arizona Wyant College of Optical Sciences demonstrated an eye-tracking approach that integrates the 3D-imaging technique of deflectometry with advanced computation. The method has the potential to significantly improve state-of-the-art eye-tracking technology, the researchers said.

"Current eye-tracking methods can only capture directional information of the eyeball from a few sparse surface points, about a dozen at most," said Florian Willomitzer, associate professor of optical sciences and principal investigator of the study. The newly demonstrated technique, he said, uses the information from >40,000 surface points, theoretically even millions, all of which



University of Arizona/Florian Willomitzer

A pattern of distorted lines is visible as a reflection in this close-up view of a human eye. By observing the deformation of illumination patterns reflected off the eye's surface, researchers captured the gaze direction information from tens of thousands of surface points, instead of the dozen or so used by conventional eye-tracking methods. This advancement holds important implications for AR/VR applications.

are extracted from a single instantaneous camera image.

"More data points provide more information that can be potentially used to significantly increase the accuracy of the gaze direction estimation," said Jiazhang Wang, postdoctoral researcher in Willomitzer's lab and the study's first author. "This is critical, for instance, to enable next-generation applications in virtual reality. We have shown that our method can easily increase the number of acquired data points by a factor of more than 3000, compared to conventional approaches."

The researchers conducted experiments with human participants and a realistic, artificial eye model. They measured the study subjects' viewing direction and tracked their gaze directions with accuracies between 0.46° and 0.97°. When tested on the artificial eye model, the error was only ~0.1°.

Instead of depending on a few IR point light sources to acquire information from eye surface reflections, the method uses a screen that displays known structured light patterns as the illumination source. Each of the >1 million pixels on the screen can thereby act as an individual point light source. By analyzing the deformation of the displayed patterns as they reflect off the eye surface, the researchers obtained accurate and dense

3D surface data from both the cornea and the white area around the pupil, known as the sclera, Wang said.

"Our computational reconstruction then uses this surface data together with known geometrical constraints about the eye's optical axis to accurately predict the gaze direction," he said.

In a previous study, the team explored how the technology could seamlessly integrate with AR/VR systems by potentially using a fixed embedded pattern in the headset frame or the visual content of the headset itself — via images or video — as the pattern that is reflected from the eye surface. According to the researchers, this can significantly reduce system complexity. Moreover, future versions of this technology could use IR light instead of visible light, allowing the system to operate without distracting users with visible patterns.

"To obtain as much direction information as possible from the eye's cornea and sclera without any ambiguities, we use stereo-deflectometry paired with novel surface optimization algorithms," Wang said. "The technique determines the gaze without making strong assumptions about the shape or surface of the eye, as some other methods do, because these parameters can vary from user to user."

In a desirable side effect, the technology additionally creates a dense and accurate surface reconstruction of the eye, which could potentially be used for on-the-fly diagnosis and correction of specific eye disorders in the future, the researchers said.

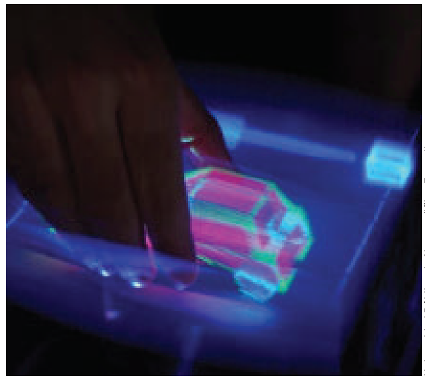
The researchers plan to embed additional 3D reconstruction methods into the system and take advantage of artificial intelligence to further improve the technique. "Our goal is to close in on the 0.1° accuracy levels obtained with the model eye experiments," Willomitzer said. "We hope that our new method will enable a new wave of next-generation eye-tracking technology, including other applications, such as neuroscience research and psychology."

The research was published in *Nature Communications* (www.doi.org/10.1038/s41467-025-56801-1).

'Holograms' can be manipulated with human hands

PAMPLONA, Spain — Researchers at Universidad Pública de Navarra (UPNA) produced 3D graphics, in midair, that can be manipulated by a user's hands. According to the researchers, the innovation allows users to interact with 3D graphics, enabling them to grasp and manipulate the virtual objects naturally.

"What we see in films and call holograms are typically volumetric displays," said Elodie Bouzbib, first author on the study describing the research. "These are



Universidad Pública de Navarra/Iñigo Ezcurdia

An approach to volumetric displays allows users to interact directly with 3D images. The development supports applications in education and other interactive fields of study.

graphics that appear in midair and can be viewed from various angles without the need for wearing virtual reality glasses. They are called true-3D graphics."

The displays, she said, enable the come-and-interact paradigm; users can simply approach a device and use it. Though the researchers said that commercial prototypes of volumetric displays already exist, such as those from Voxon Photonics and Brightvox Inc., commercial solutions that are currently available do not allow for direct interaction.

"We are used to direct interaction with our phones, where we tap a button or drag a document directly with our finger on the screen — it is natural and intuitive for humans," said lead researcher Asier Marzo. "This project enables us to use this natural interaction with 3D graphics to leverage our innate abilities of 3D vision and manipulation."

Volumetric displays have a rapidly oscillating sheet called a diffuser, and images are projected synchronously at a high speed (2880 images/s). The images projected onto the diffuser at different heights are perceived by human eyes as a complete volume.

The problem with this, the researchers said, is that the diffuser is usually rigid and can cause injury or break if it comes into contact with a user's hand.

To address this, the researchers replaced the rigid diffuser with an elastic one after testing different materials for their optical and mechanical properties. The challenge that the researchers overcame stems from the tendency of elastic materials to deform and require image correction, Bouzbib said.

3D graphics that can be directly manipulated, such as those from the researchers, could have applications in education, for example, in visualizing and assembling the parts of an engine, the researchers said. Further, multiple users can interact collaboratively without the need for VR headsets, they said. The team expects that the displays could find use in museums to allow visitors to simply approach and interact with the content.

The work was conducted under the InteVol project, led by UPNA and funded by the European Research Council.

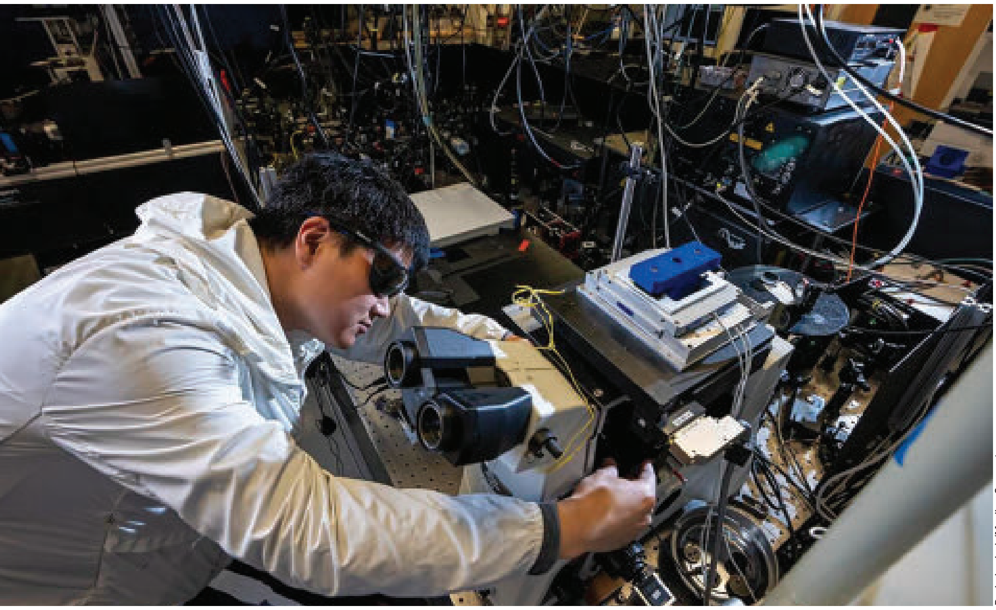
The research was presented at the CHI 2025 conference (www.hal.science/hal-04981007v1).

Dynamic optical material drives next-generation compute

BERKELEY, Calif. — Researchers at Lawrence Berkeley National Laboratory (Berkeley Lab), Columbia University, and Universidad Autónoma de Madrid believe that they may have found a key to smaller, faster components for next-generation computers. The collaborating researchers developed an optical material that demonstrates intrinsic optical bistability (IOB), an optical phenomenon that enables a material to use light to switch between two different states.

The material shows a disproportionately large increase in the light that it emits when it is exposed to a small increase in laser power. The material, which is made of photon-avalanching nanoparticles, could be used to fabricate small components, such as memory, transistors, and interconnects, at high density for optical computing on a scale comparable to the size of current microelectronics, the researchers said.

At the Molecular Foundry at Berkeley Lab, the researchers fabricated 30-nm nanoparticles from a potassium-lead-halide material doped with neodymium. They excited the nanoparticles with IR



Berkeley Lab/Marilyn Sargent

Researcher Xiao Qi was part of a team that developed an optical computing material from nanoparticles that exhibit a phenomenon known as photon avalanching, in which a small increase in laser power results in a giant, disproportionate increase in the light emitted by the nanoparticles.

light. When the nanoparticles were excited, they exhibited photon avalanching.

The neodymium-doped avalanching nanoparticles demonstrated >3× the nonlinearity of the avalanching nanoparticles used in earlier work from the same team of researchers. In fact, according to researcher Emory Chan, the neodymium-doped avalanching nanoparticles used in the current study exhibit the highest nonlinearities that have ever been observed in a material.

Even when the laser power was reduced to less than the designated threshold for laser power, the researchers found that the nanoparticles continued to emit brightly. Photon avalanching was only turned off completely when the laser power became extremely low. The nanoparticles switched, with high contrast, between luminescent and nonluminescent states, with hysteresis characteristic of bistability. A significant difference between the "on" and "off" threshold powers was observed, indicating that if mid-range-intensity lasers were used, the nanoparticles could be either bright or dark, depending on their excitation history.

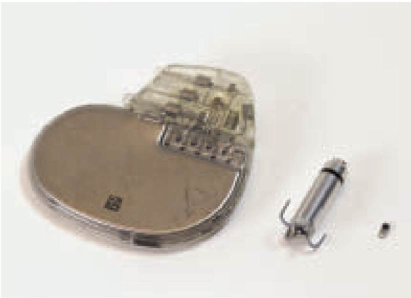
Using computer models to investigate the source of the bistability, the researchers found that the IOB in the nanoparticles stemmed from the extreme nonlinearity of photon avalanching and from a structure that dampens vibrations in the particles. They uncovered a nonthermal mechanism in which IOB originates from suppressed, nonradiative relaxation in neodymium ions and from the positive feedback of photon avalanching, resulting in >200th-order optical nonlinearities.

Until now, a limited understanding of IOB has inhibited the development of nanoscale IOB materials for devices; IOB has been observed almost exclusively in bulk materials, which are too large for a microchip and challenging to mass-produce. In earlier reports of nanoscale IOB, the process was assumed to occur by heating the nanoparticles, which is inefficient and difficult to manage.

Obtaining control over nanoscale IOB could enable the use of avalanching nanoparticles for photonic devices. Photon-avalanching nanoparticles that switch optical properties, without any changes being made to the material, suggests that they could be used for optical memory at the nanoscale, particularly volatile random-access memory.

The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-024-01577-x).

Light-activated pacemaker combines multiple optical technologies



Northwestern University

(From left) A traditional pacemaker, a leadless pacemaker, and the pacemaker developed by researchers at Northwestern University. The developed device, an all-optical solution, could make the placement and removal of temporary pacemakers safer for cardiac patients — and provide a minimally invasive solution for small children following cardiac surgery.

EVANSTON, Ill. — A tiny, light-activated pacemaker could make the placement and removal of temporary pacemakers safer for cardiac patients and provide a minimally invasive solution for newborns and children who require temporary pacing after cardiac surgery. The device delivers pulses in the IR, a wavelength that penetrates the body deeply and safely. Researchers at Northwestern University developed the millimeter-scale pacemaker, which has an onboard power supply that is optically controlled. It operates through a galvanic cell — a type of battery formed by the interaction between two metal electrodes and the biofluids surrounding them.

When the electrodes contact the biofluids, they form a battery, and the resulting chemical reaction causes the electrical current to flow and stimulate the heart.

The pacemaker is then paired with a wireless, wearable patch that is placed on the patient's chest. When the patch detects an irregular heartbeat, it automatically activates an LED, which emits a light pulse that activates the pacemaker. The light flashes on and off at a rate that corresponds to the normal heart rate of the patient. These short pulses penetrate through the patient's skin, breastbone, and muscles to control the pacing.

An external, light-activated switch controls the device's on-off status. The switch turns on when light illuminates the device. When the device does not receive light, it remains off. Electrical stimulation is not delivered to the heart unless the device is exposed to light.

The researchers demonstrated the device's efficacy across a series of large and small animal models and on human hearts from deceased organ donors, at both single-site and multisite locations. The tiny scale of the pacemaker makes the implantation a minimally invasive procedure. Smaller than a grain of rice, the light-activated device can fit inside the tip of a syringe and be injected into the body.

Although the device is only 1.8 mm wide, 3.5 mm long, and 1 mm thick, it delivers as much stimulation as a full-size pacemaker.

"The heart requires a tiny amount of electrical stimulation," said John Rogers, who led the device development team. "By minimizing the size, we dramatically simplify the implantation procedures, we reduce trauma and risk to the patient, and, with the dissolvable nature of the device, we eliminate any need for secondary surgical extraction procedures."

When pacing is no longer needed, the bioresorbable pacemaker dissolves in the patient's body. All its components are biocompatible and dissolve naturally into the body's biofluids, eliminating the need for surgery. Conventional devices that are temporarily implanted in patients must be surgically removed, which introduces the risk of infection and other complications.

In addition to functioning as a temporary pacemaker for adults, the miniaturized light-activated device is well suited for newborns as well as for children who may be living with congenital heart defects.

"Our major motivation was children," said professor Igor Efimov. "About 1% of children are born with congenital heart defects, regardless of whether they live in a low-resource or high-resource country. The good news is that these children only need temporary pacing after a surgery. In about seven days or so, most patients' hearts will self-repair. But those seven days are absolutely critical."

The tiny pacemaker can be placed on an infant's heart, stimulated with a soft, gentle, wearable device, and nonsurgically removed.

According to the researchers, physicians could use several of the miniaturized devices across the heart to enable synchronized pacing. A different color of light could be used to independently control each device. "We can deploy a number of such small pacemakers onto the outside of the heart and control each one," Efimov said. "Then we can achieve improved, synchronized, functional care. We also could incorporate our pacemakers into other medical devices like heart valve replacements, which can cause heart block."

Arrays of the millimeter-size pacemakers could be placed on the frames of transcatheter aortic valve replacement systems to address risks for atrioventricular block following surgeries.

"Because it's so small, this pacemaker can be integrated with almost any kind of implantable device," Rogers said. "We also demonstrated integration of collections of these devices across the frameworks that serve as transcatheter aortic valve replacements. Here, the tiny pacemakers can be activated as necessary to address complications that can occur during a patient's recovery process."

The research was published in *Nature* (www.doi.org/10.1038/s41586-025-08726-4).

In this photo from the 1970s, celebrated physicists John Emmett **(left)** and John Nuckolls, visionaries in early laser fusion technology, discuss flashlamp-pumped, solid-state laser technology.

Lawrence Livermore National Laboratory

Decades of Discoveries Broadened the Laser Spectrum

Visible lasers debuted with just a couple of shades of red. A series of advancements has grown over the years into a cascade, yielding an amazing range of colors to feed innovation.

BY JEFF HECHT
SPECIAL TO *PHOTONICS SPECTRA*

At the dawn of the laser age, any color could be attained from a laser, as long as it was red. Theodore Maiman's first laser was a ruby rod that emitted pulses at 694 nm, the long end of the visible spectrum. The first laser to emit a visible, continuous beam was a glass tube containing a mixture of helium and neon emitting at 632.8 nm, also in the red. Through most of the 20th century, the first laser beams that were most likely to be seen were red.

Engineers and physicists added a handful of new visible laser colors from gases throughout this first decade. Later, new semiconductor compounds brought more shades of red and eventually blue laser light to the toolboxes of engineers and scientists, leading to new products. In the 21st century, lasers continue to reveal more colors to the human eye.

Spectra and lasers

Maiman did not set out to make a beam he could see. He wanted to demonstrate that the laser concept could work, so he started with a material he knew well, ruby, which only happened to emit in the visible. He calculated that it would require a significant amount of light to excite the laser, so he chose a photographic lamp that generated extremely bright, yet brief, flashes.

On May 16, 1960, at Hughes Research Labs, Maiman fired a series of pulses, turning up the energy each time, until the pump light reached the threshold and the ruby rod flashed the world's first bright red pulse of laser light.

For Maiman, the technology worked on his first demonstration. Within weeks of reporting his success, others had already replicated his results and experimented with ruby lasers. They are still in use today.

At the same time, others bought large, bright flashlamps and flashed them at different materials. Peter Sorokin at the IBM Watson Research Lab picked uranium doped in calcium fluoride, which emitted at 2.5 µm, a value that he could measure with the instruments in his lab. It worked but never proved to be practical. L.F. Johnson and K. Nassau at Bell Labs used a flashlamp to excite 1.06-µm laser pulses from neodymium in calcium tungstate in 1961. The beam was not visible, but neodymium in glass and crystals would be the best-selling solid-state laser for decades. Soon afterward, Elias Snitzer at American Optical flashlamp-pumped neodymium in a clad rod of optical glass, demonstrating the first fiber laser.

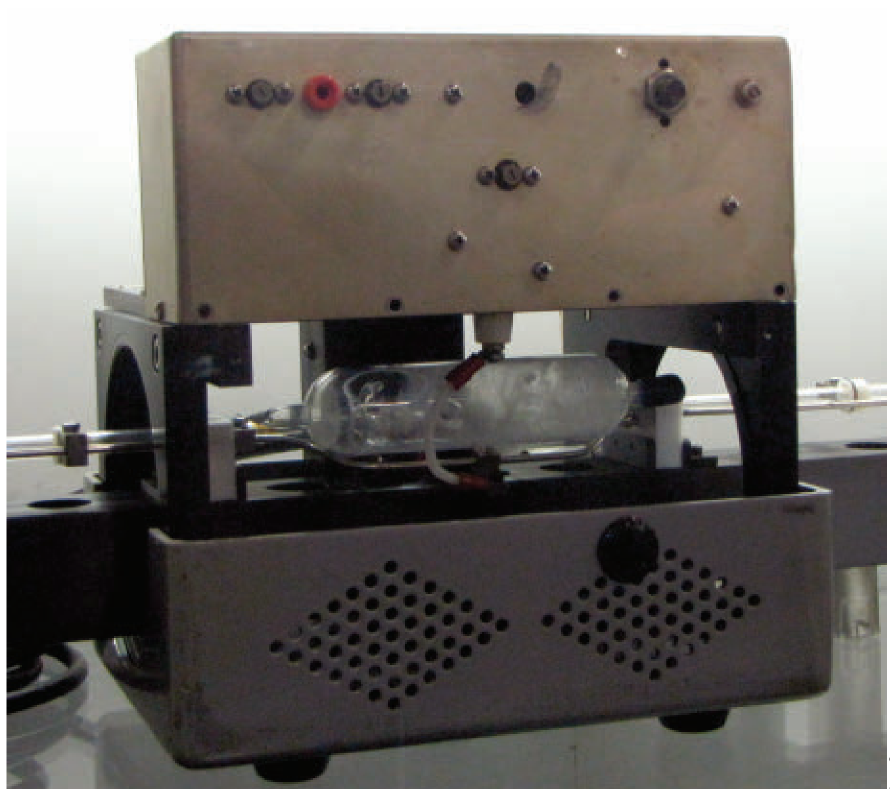
Flashlamp-pumped ruby was on the market by early 1961 and would remain the only visible solid-state laser on sale for decades. Yet, others wanted lasers that could emit a continuous beam.

Gas lasers and gaseous electronics

Semiconductors and solid-state physics were burgeoning areas of innovation in the 1960s, but gaseous electronics were a tried-and-true technology for generating light continuously by passing an electric current through gas, such as in televisions and fluorescent lights. At Bell Labs, Ali Javan thought starting with a mature technology would be the best way to make a continuous laser. "Helium-neon (He-Ne) was one of the cleanest systems I could find. It also was a medium where I could show there was gain without first having to make the laser," Javan said in an interview[1]. He collaborated with three colleagues to determine the physics and optics required for a low-gain gas medium.

Seven months after Maiman's demonstration, members of Javan's group spotted gain at 1.15 µm on their continuous-wave HeNe laser. They did not see the beam because they had designed their laser to operate at 1.15 µm, where they had expected the highest gain. The now-standard 632.8-nm neon line did not lase until 1962, after Alan White and Dane Rigden at Bell added large amounts of helium to their tube, increasing its red neon emission 50-fold.

The 1962 PerkinElmer/Spectra-Physics Model 110 helium-neon (HeNe) laser was among the first of the commercially available lasers with a continuous visual beam.



Lynn Savage

The red HeNe was both a breakthrough and an eye-opener; its pencil beam and the effects of laser coherence could be seen. The red laser light brought 3D laser holography to life when Emmett Leith and Juris Upatnieks used a factory-made HeNe laser to illuminate a toy train, and, with it, a red 3D image hung in the air in front of them. When they displayed a hologram at an Optical Society meeting, a long line of witnesses — amazed by the image — formed in the hallway. The fascination with holography would make HeNes the best-selling lasers of the 1960s and they would remain so until the 1980s.

The color of argon

If electricity could produce a bright red laser beam from neon, what could it produce from other gases? This question stimulated many experiments in the mid-1960s. One experimental failure led to the development of the family of rare-gas ion lasers.

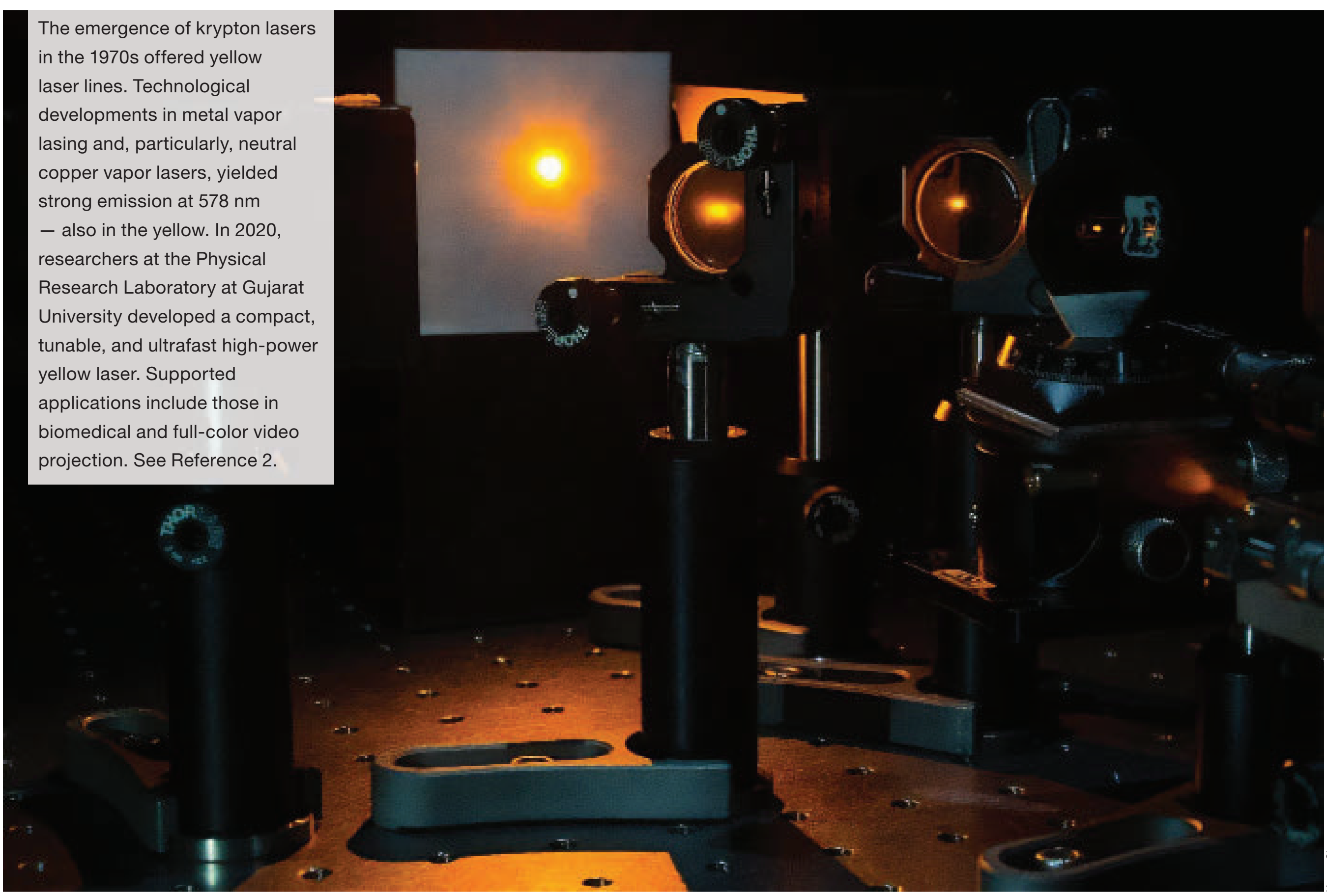
Disappointed with a mixture of argon and mercury, in February 1964, Bill Bridges at Hughes blew the old mercury out of the tube with helium and was surprised to see a discharge through the tube produce a blue emission at 488 nm from traces of argon ions. The unexpected laser light was not just blue — it was also very bright. Bridges soon found a somewhat stronger green argon line, at 514.5 nm. The brightness of the argon-ion laser established it as an altogether new tool for laser experimenters: The red HeNe laser peaked at only tens of milliwatts at best, but cranking up the discharge current through the argon tube could generate much more light. Laser designers eventually reached tens of watts of output, by far the brightest visible continuous beams on the market for many years.

Although not as bright, krypton lasers offered other wavelengths. Output(s) could reach watts at 647 nm in the red. It also offered lines where no other lasers were yet available, including in the yellow.

By combining argon and krypton in a tube, one could make a multi-colored laser light show. Laser entertainment surged in the 1970s and attracted tens of millions of people over the years. As the brightest lasers in the visible spectrum, argon-ion lasers also found a variety of other applications that needed bright beams at short wavelengths, including in medicine and avionics.

Metal vapor gas lasers

A systematic study for ionized metal vapors by Bill Silfvast at the University of Utah yielded the helium-cadmium (HeCd) laser, which long held the brightest visible line at 441.6 nm, in the blue. It was less powerful but more economical than argon-ion lasers, making it a more attractive option for some applications. Xerox, for example, selected a 15-mW HeCd because other drum laser printers

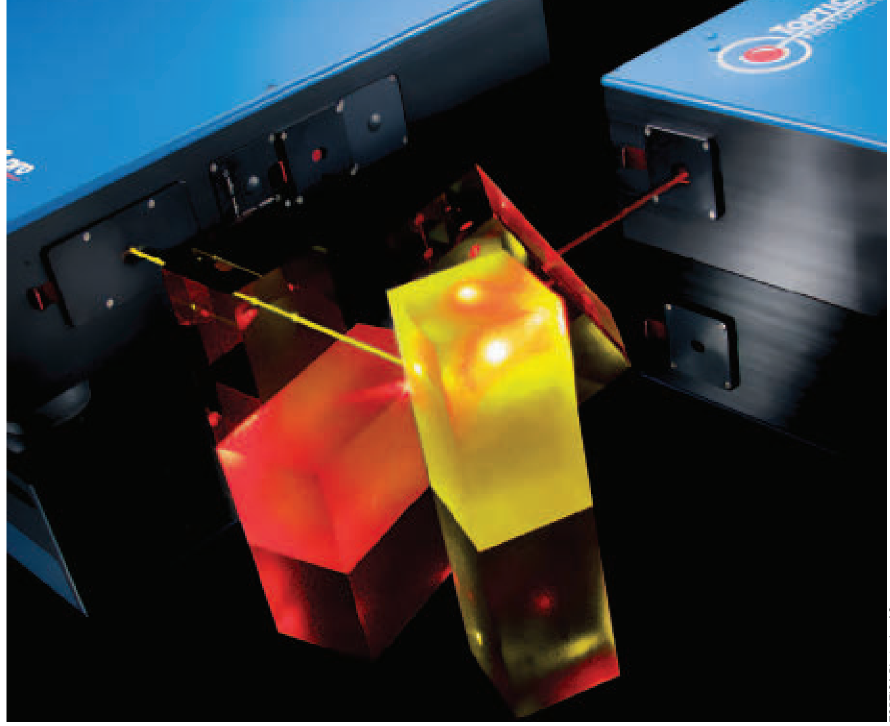


The emergence of krypton lasers in the 1970s offered yellow laser lines. Technological developments in metal vapor lasing and, particularly, neutral copper vapor lasers, yielded strong emission at 578 nm — also in the yellow. In 2020, researchers at the Physical Research Laboratory at Gujarat University developed a compact, tunable, and ultrafast high-power yellow laser. Supported applications include those in biomedical and full-color video projection. See Reference 2.

Varun Sharma

Tunable diode lasers — shown here using tapered semiconductor amplifiers — provide high power and more wavelengths **(right)**. Their emergence sparked possibilities in industrial and medical laser applications.

A detailed look at a frequency-converted system diode laser **(below)**. This system is tunable and can be used in a range of applications, including spectroscopy, laser cooling, holography, and interferometry.



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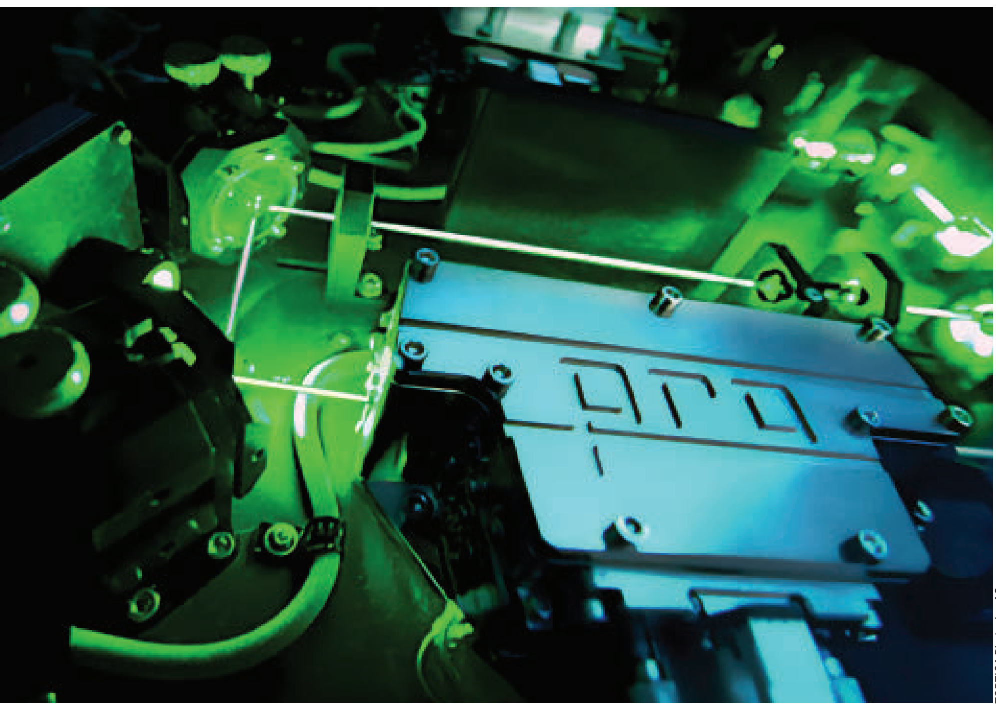


TOPTICA Photonics AG

designed for mainframe printers were insensitive to red HeNe emission. The combination of its simplicity and favorable wavelengths, Silfvast said, ultimately established the HeCd as the most successful metal vapor laser.

The highest visible power from metal vapor lasers came from a neutral copper vapor that only operates in a repetitively pulsed mode and has strong emission at 510 nm in the green and at 578 nm in the yellow. It was used for pumping dye lasers, and it was also seriously studied as a pump source for enriching uranium isotopes.

Optically pumped dye lasers

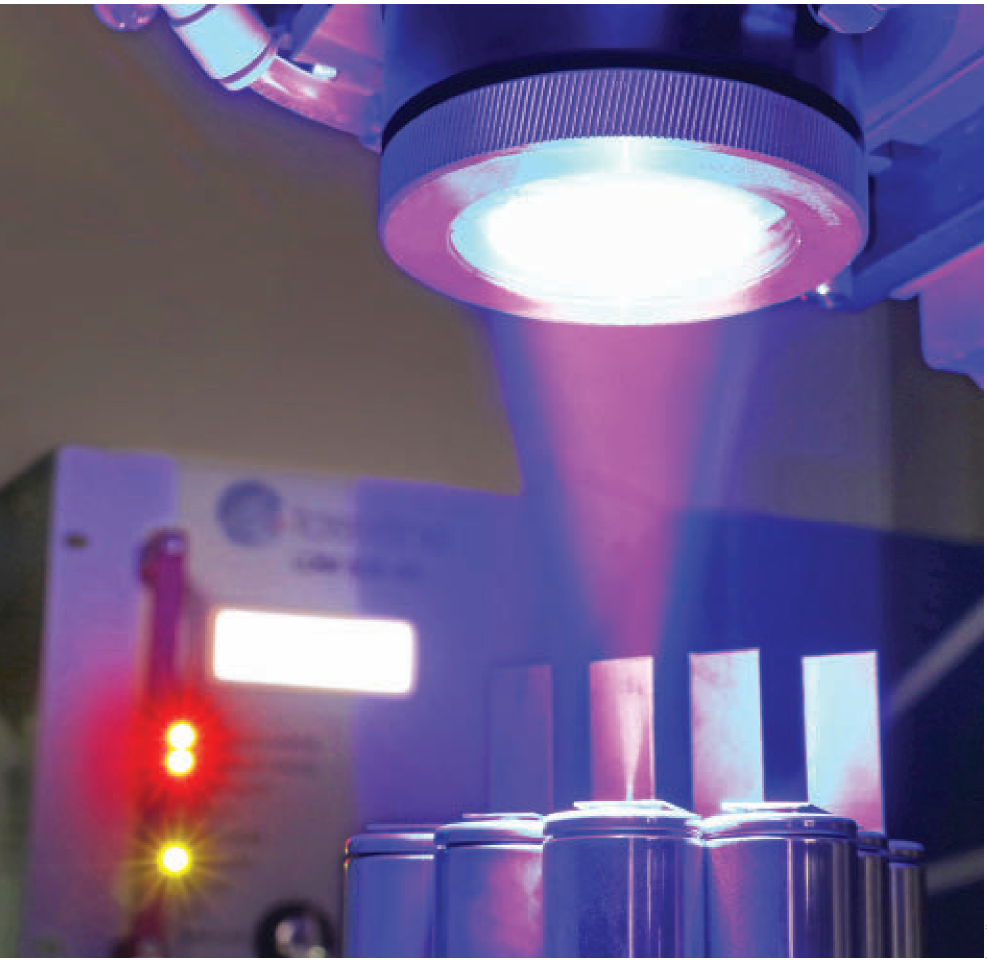
While experimenting with effects of firing a ruby laser into fluorescent dyes in 1966, Sorokin observed laser emission in the fluorescence. Around the same time, Mary Spaeth, then at Hughes, realized that putting dye in a suitable solvent greatly increased its absorption bandwidth — which would allow wavelength tuning in a laser cavity with dispersive optics. Spaeth performed this demonstration by pumping the dye with a ruby laser. With the idea of pumping dyes trialed, others followed with demonstrations of continuous-wave pumping, with argon-ion lasers, and pulsed pumping, with flashlamps.

The tunability of dye lasers offered wavelength selection across a wide range, including through the visible, making them a boon for spectroscopists. In practice, tunable dye lasers had significant limits, and their main uses were restricted to laboratory applications; dyes were short-lived, individual dyes had limited ranges, and continuous-wave pump lasers carried a high price tag.

The diode laser revolution

Laser choices remained limited at visible wavelengths well into the 1980s. The only solid-state laser on the market emitting in the visible was ruby. Dye lasers required either pump lasers or flashlamps for pumping. And the most widely used visible lasers were gas.

During this time, HeNe lasers were the bestsellers by far, with consumer markets in supermarket scanners as well as industry. Argon-ion laser sales were several thousand per year, hindered by cooling requirements and a wall plug efficiency of only ~0.01%. Beam powers ranged from a fraction of 1 W to as much as 40 W, with the largest lasers requiring a fire hose to cool. Annual HeCd laser sales, meanwhile, reached around 1000 in 1983. By then, researchers had cataloged more than



Laserline

Welding, cutting, and foil joining of high-reflectance materials are among the target applications for blue diode lasers. These sources have also proved to be vital in the manufacture of electric vehicles and battery cells.

6000 wavelengths emitted by gas lasers. Only around 600 were in the visible, and only a handful of those were produced commercially in significant quantity. The first diode lasers, demonstrated in 1962, were made of gallium, aluminum, and arsenic and emitted at 710 to 900 nm, in the near-infrared. Adding more aluminum decreased the wavelength, but at the cost of reducing the lifetime, which was a serious problem. Not until 1970 could diode lasers operate continuously at room temperature — a feat which earned Zhores Alferov and Herbert Kroemer the 2000 Nobel Prize in physics.

Gallium-aluminum-arsenide diode laser lifetimes remained problematic at visible wavelengths through the mid-1980s. Eventually, improvements in diode structure extended to the point where red laser pointers emitting at 625 to 700 nm became essential parts of photonics presentations and diode lasers were finally established in the visible spectrum. Red laser pointers were only a small (though ubiquitous) part of the diode laser revolution. Development of high-power diode lasers emitting at 780 to 1000 nm based on gallium-arsenide technology opened the door to diode pumping of solid-state lasers. Flashlamps had long been used because of their high intensity, but they emitted across a wide range of wavelengths, meaning that minimal pump light excited light emission by the laser. Diode lasers emit at a narrow range of wavelengths, and their composition can be adjusted to match the peak absorption of the laser material. For example, diodes are designed to emit at 808 nm to be absorbed at the 808-nm absorption peak of Nd:YAG.

The match between narrowband pump-diode emission and the peak absorption of the laser material makes diode pumping inherently more efficient than broadband flashlamp pumping. The higher efficiency of diode pumping has created a new class of products: continuous-wave solid-state lasers. Still, it would require further innovation to reach visible wavelengths.

Nonlinear optics and new wavelengths

The concept of nonlinear optics has a long history with lasers. Shortly after Peter Franken at the University of Michigan obtained one of the first commercial ruby lasers in 1961, he fired a high-energy red pulse at crystal quartz and produced a much smaller pulse of the second harmonic at 347 nm, in the UV. This experiment demonstrated that a laser beam's combination of coherence and light intensity could produce interesting effects, including harmonic generation and producing sum frequencies from two beams. It led to much research in nonlinear optics, although it required high beam intensity and strong linearities to accomplish much in application.

Diode pumping could produce the high intensities needed to make changes. Initially, efforts were small, such as the development of green laser pointers. Students in the Stanford University lab of Bob Byer pioneered another early achievement. They used pump diodes to produce a 1064-nm neodymium beam, then put it through a frequency doubler to get 532-nm green light. The impetus for the achievement was that Byer is color-blind, so he cannot see red pointers.

Frequency doubling can accomplish much more, including stretching the spectrum of Ti:sapphire lasers into the visible range. Ti:sapphire is tunable from 660 to 1100 nm, with a pump band at 500 nm. Frequency doubling light from neodymium or other near-infrared solid-state lasers, such as ytterbium, can easily supply a pump source. Then, frequency doubling of the Ti:sapphire will cover much of the visible spectrum. These capabilities have helped Ti:sapphire replace many tunable dye lasers and meet application needs that their predecessors could not. Frequency doubling (and tripling) also can be used with fiber lasers to make both high-power green and UV lasers.

Blue diode lasers

The advent of blue diode lasers in the 1990s was an unexpected revolution in semiconductor lasers. Years of research had convinced many researchers that gallium indium nitride, with bandgaps from the visible green to the UV, was a material too flawed to make effective diode lasers.

Imasu Akasaki at Nagoya University was unconvinced. In 1991, he pulled a bright blue diode out of his pocket and showed it at a materials research conference. A few years later, Shuji Nakamura showed off an impressively bright violet laser diode and detailed his progress before a packed conference room.

What excited the photonics world initially about this innovation was the prospect of high-capacity video-discs for high-definition television using short-wavelength laser diodes. The technology worked, but streaming video won the high-definition market over Blu-ray discs.

In parallel, other markets appeared for blue laser diodes, which now span 375 to 525 nm. However, the biggest success of indium gallium arsenide has been in high-efficiency solid-state lighting, for which Akasaki; Nakamura at University of California, Santa Barbara; and Hiroshi Amano at Nagoya shared the Nobel Prize in physics in 2014.

A rich spectrum of visible lasers

Looking at today's laser market in the broader context of photonics, one cannot help but be amazed by the range of technology. Many years ago, it would have been unfathomable to have lasers that could be tuned across the spectrum. We have come a long way to that somewhat fanciful ideal.

There is also a great variety of tools to be deployed for shaping today's spectrum of lasers. Tailoring our selection of structures and chemistry in semiconductors, optimizing how we shape optics and resonances, and the use of nonlinear optics are just some of the available techniques. Some ideas proposed in the boom years of fiber optics — some of which did not get off the ground then — currently appear to be both possible and useful.

One strength of the photonics community, beyond laser science, is the tremendous diversity of technology. As this rich selection of tools and techniques to manipulate light continues to expand, it is imperative to maintain this theme.

Meet the author

Jeff Hecht is a veteran science and technology writer with a specialty in optics and an Optica Fellow. He is the author of *Understanding Lasers*, *Understanding Fiber Optics*, *City of Light: The Story of Fiber Optics*, and *Beam: The Race to Make the Laser*; email: jeff@jeffhecht.com.

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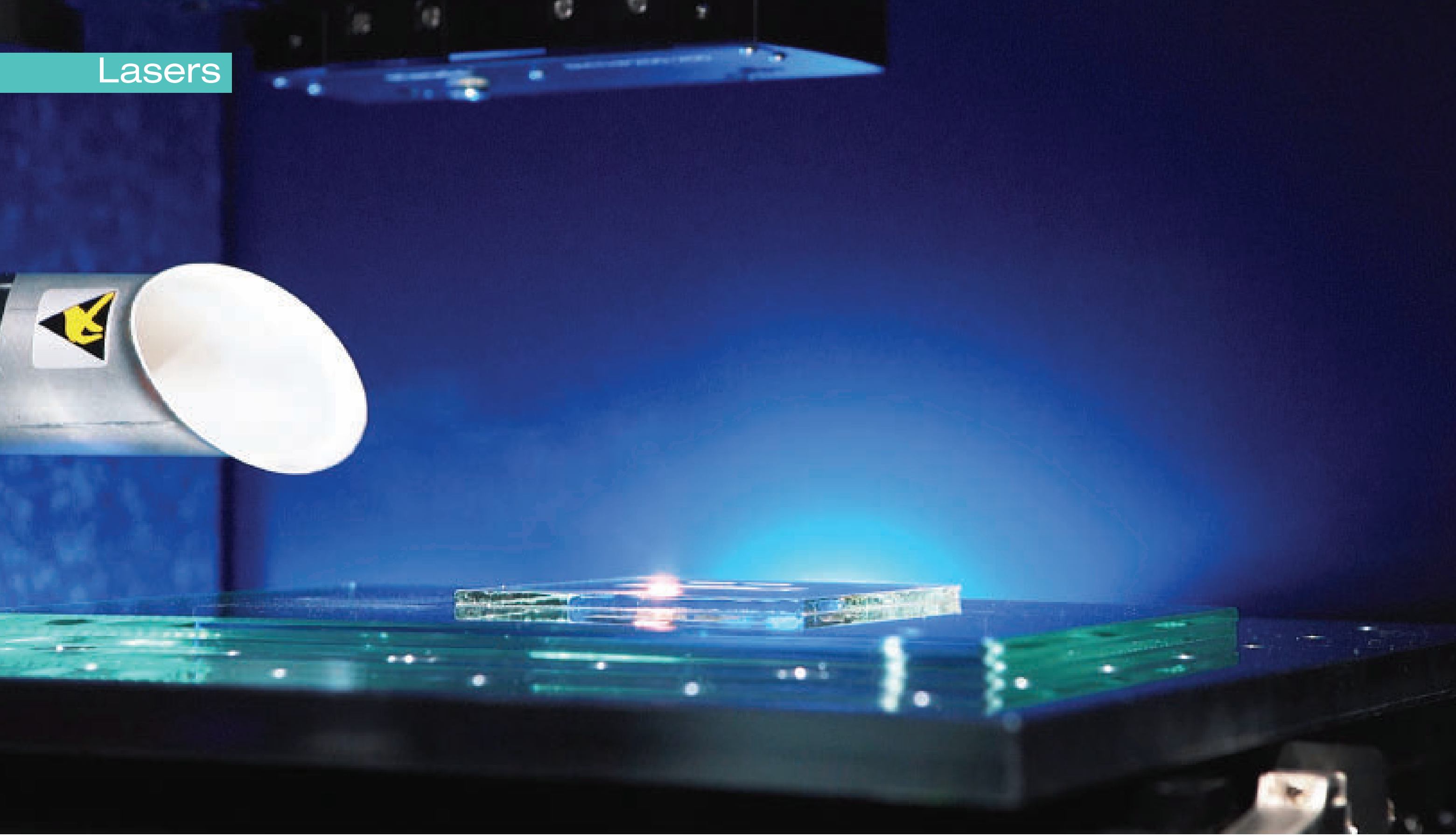


The Future of Precision Manufacturing is Measured in Femtoseconds

Advanced femtosecond laser technology is a transformative force for chip manufacturing with microscopic glass connections, helping to overcome size barriers for next-generation electronics.

All images courtesy of Fluence.technology.

BY BOGUSZ STĘPAK
FLUENCE.TECHNOLOGY

The pursuit of miniaturization and enhanced performance in microelectronics is placing unprecedented demand on the next generation of manufacturing technologies. As devices shrink and complexity grows, reliable, high-density interconnections are increasingly important to component and device design.

Through-glass vias (TGVs), the microscopic pathways that enable electrical connections between layers in advanced semiconductor packages, are among the most critical components in microelectronics. Glass is steadily replacing silicon and organic substrates as the preferred substrate material, due to its advantageous thermal properties, lower costs, and superior performance for next-generation devices. However, this shift also heightens certain manufacturing challenges as conventional and established processes struggle to optimize efficiency and sustainability when they are implemented with/for glass.

For glass, ultrafast laser processing stands out as the essential enabling technology, offering high speeds and precise control over via diameter and pitch while preserving the structural integrity of the glass wafer. Femtosecond lasers are rapidly gaining popularity in this context. These lasers offer ablation efficiency and quality benefits compared with nanosecond and picosecond laser sources. Current femtosecond sources are available with exceptional beam quality, parameter stability, and extended operational lifetimes as a result of recent advancements in ultrashort-pulse generation in fibers. Robust all-fiber modules limit the use of traditional free-space and degradable components, significantly enhancing laser system reliability and reducing maintenance requirements.

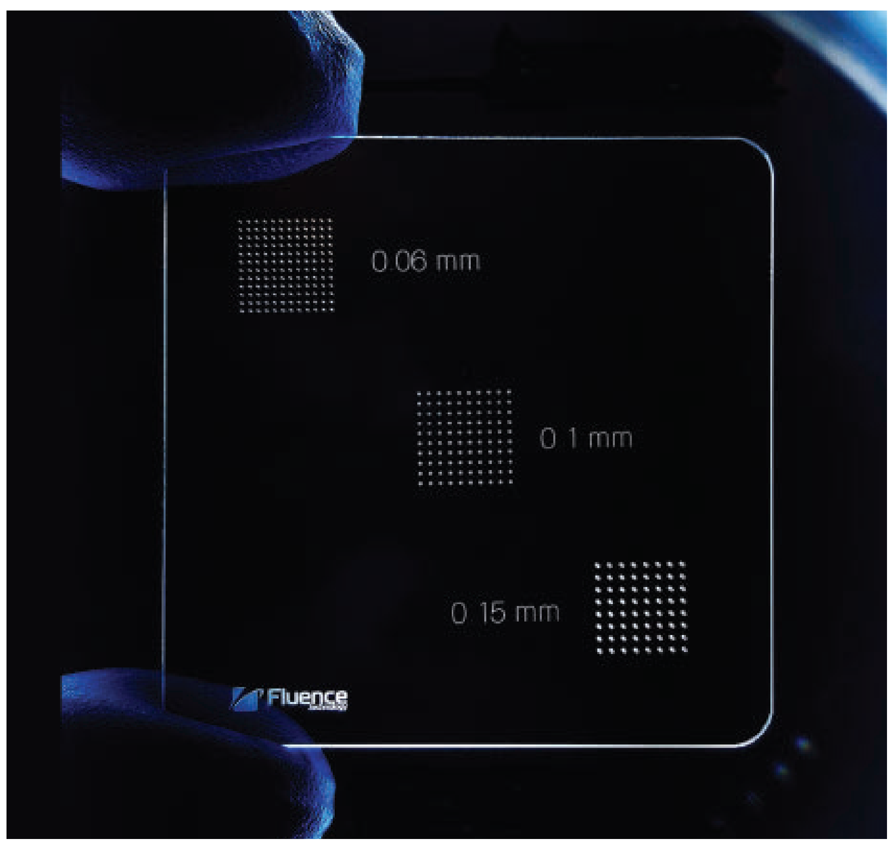
A pivotal breakthrough relates to recent advancements in percussion drilling of high-aspect-ratio TGVs. Using ultrashort pulses with precisely controlled energy and timing, femtosecond laser technology is enabling process engineers and manufacturers to achieve what was once impossible: faster, cleaner, and more precise micromachining from a single step in support of next-generation electronics.

A shifting landscape: From silicon to glass

The transition from organic substrates and silicon interposers to glass represents one of the most significant material shifts in the history of microelectronics manufacturing. This change is driven by several factors, spanning both intrinsic material properties and broader trends shaped by the evolving trajectory of Moore's law.

As it compares to silicon, glass offers numerous cost benefits, particularly for applications that require larger substrates or higher production volumes. This cost difference becomes increasingly important as devices become more complex.

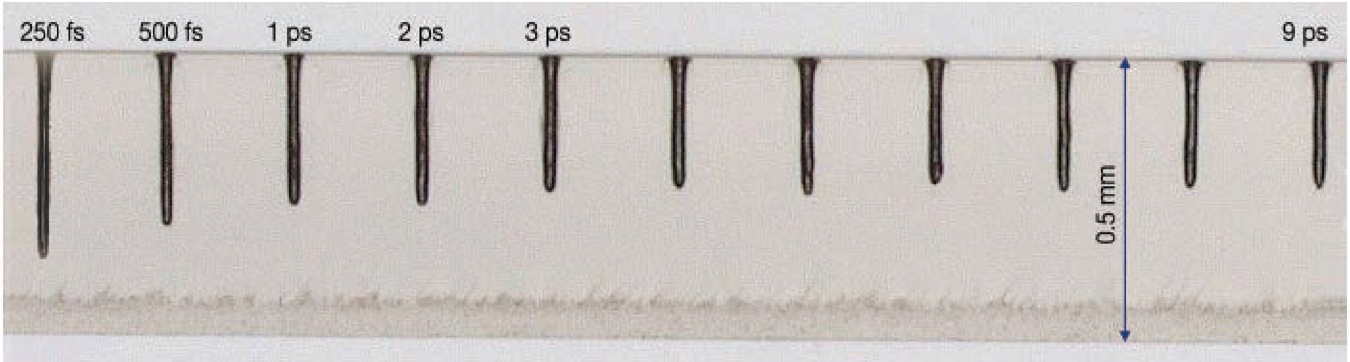
Through-glass vias (TGVs) in borosilicate glass fabricated using a femtosecond laser bottom-up process. TGV diameters: 60 µm, 100 µm, and 250 µm.



Additionally, glass exhibits superior thermal stability over silicon. Thermal management and tolerance are essential parameters for maintaining dimensional stability across operating temperatures.

At the same time, glass exhibits a coefficient of thermal expansion that is similar to silicon die, making this combination of materials a perfect match for achieving high performance. On its own, glass allows more chips to be placed on larger substrates since the material is more rigid, flat, and stable than organic substrates. Glass also maintains structural integrity across wider temperature ranges than organic substrates. This expanded operating envelope enables devices to function reliably in challenging and extreme environments. And it offers a lower dielectric constant than many commonly used substrates. This translates to faster signal propagation and improved performance at high frequencies.

Additionally, glass enables co-packaged optics and photonics integration



Percussion drilling of 0.5-mm-thick Eagle XG glass **(above)**. Taper-free holes are fabricated by depositing only 800 single femtosecond pulses/hole with varying pulse duration between 250 fs and 9 ps. Taper does not appear until a hole depth of ~450 μm is reached.

on a chip. This important quality opens possibilities for advanced designs where a reduction of energy consumption is critical. Specific applications include high-performance compute, 5G communication, and Internet of Things and/or AI accelerators.

Another advantage for microelectronics manufacturing exists: Glass allows for smaller hole diameters and lower spacing than organic substrates, thereby enabling denser connection patterns without compromising performance. This is vital while chip designs are growing ever more complex, and interconnection density is increasing in lockstep.

The combination of these advantages makes glass an attractive option for use in next-generation microelectronics. But the material presents its own set of challenges for micromachining processes. When it comes to creating densely packed, high-aspect-ratio holes, these challenges are particularly dynamic.

Creating high-aspect-ratio TGVs

Creating microscopic holes in glass with high-aspect ratios requires fabricators and process engineers to overcome significant technical barriers. Traditional mechanical drilling methods lack necessary precision, while conventional laser approaches often produce tapered holes, micro-cracks, or other unwanted defects.

The ideal TGV must meet several criteria. It must feature a small diameter, often <30 μm, with a high aspect ratio, often >10:1. The fabricated TGV must also exhibit minimal, or, in some cases, zero taper; an absence of micro-cracks and/or heat-affected zones; and clean, precisely engineered edges. Critically, the TGV must also have a consistent, repeatable geometry.

Current widely adopted methods for achieving these characteristics can necessitate complicated multistep processes. Processes such as selective laser etching, for example, involve ultrafast laser modification followed by chemical etching. Though these methods are suitable for dense hole array manufacturing, they can raise environmental concerns.

The benefits of advanced femtosecond laser technology are the most noticeable in this sequence of operations. Even as laser modification and chemical etching remain valuable and widely used, an alternative approach using direct drilling introduces an option that can be advantageous for specific manufacturing scenarios. This approach expands the toolbox of precision microfabrication by offering process engineers greater flexibility based on project needs.

A multiparameter breakthrough

Three parameters — pulse energy, pulse duration, and pulse timing — are most essential to enable single-step TGV fabrication while maintaining quality and efficiency. Of course, this is not to discount or diminish the significance of other parameters, including fluence/spot diameter, numerical aperture, and focal plane — all of which play important roles. Another important consideration is peak intensity, resulting from beam and pulse quality.

Modern industrial femtosecond lasers with pulse energies >200 µJ provide sufficient energy to efficiently drill through 0.5-mm-thick glass substrates. This high energy, when optimally deployed, enables higher aspect ratios and faster processing without sacrificing precision.

At the same time, pulse durations <270 fs are critical for high-quality glass micromachining, since, at these timescales, energy transfers to the material before the onset of thermal diffusion. Moreover, the higher intensity that is available at shorter pulses enables deeper holes to be drilled; in such conditions, the light governs the interaction with the material, changing its optical properties on a femtosecond to picosecond timescale. Research demonstrates that reducing pulse duration from picoseconds to 250 fs can increase drilling depth by up to 1.7×.

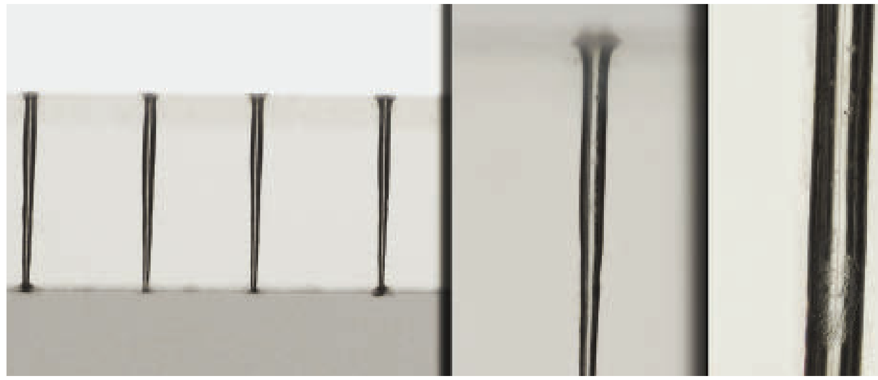
And precise control over pulse delivery, which advanced pulse-on-demand (POD) capabilities enable, ensures exact positioning even during high-speed scanning operations. This results in consistent, repeatable hole patterns with high throughput.

Femtosecond lasing enables two distinct single-step approaches to TGV fabrication: bottom-up drilling and percussion drilling. Each presents unique advantages depending on variables such as process parameters and production/scaling needs.

Precision without compromise

Bottom-up drilling, or rear-side ablation, represents a desirable alternative approach for TGV fabrication. Unlike conventional methods, bottom-up drilling commences at the bottom surface of the glass and works upward using nonlinear absorption characteristics. A femtosecond laser beam focuses through the glass substrate, positioning the focal point at the bottom surface. The high intensity at this point then triggers nonlinear absorption, removing material only at this specific location without affecting the material above. The progressive upward motion of the focal point creates a straight, non-tapered hole.

In addition to non-tapered holes with consistent diameters throughout, bottom-up drilling ensures angle flexibility; the holes are angled with inclinations of up to 50°. Further, the diameters of the drilled holes can range from <40 µm to several hundred micrometers. And bottom-up



A through-glass via (TGV) is fabricated by repetitive single femtosecond-pulsed percussion drilling in Eagle XG glass. Zoomed-in hole entrance and inner wall **(middle)**. Shiny inner walls, crack-free and without post-processing **(right)**. The substrate is 500 µm thick.

drilling can be completed without chemical etching or other post-processing.

These qualities make bottom-up drilling an accurate approach for prototyping devices with different diameters and hole profiles. Laboratory tests showed holes with diameters as small as 46 µm in 1.1-mm-thick BK7 optical glass, achieving aspect ratios of 24:1[1]. Even more impressive, holes with diameters of 32 µm have been created with aspect ratios reaching 34:1 using specialty focusing optics.

Moreover, the ablation process itself is fast enough to support many applications, typically requiring <500 ms of active processing time for a 70-µm-diameter hole in 500-µm-thick glass.

Speed without sacrifice

Bottom-up drilling excels in geometric control. For applications for which processing time is a critical consideration, the method of percussion drilling offers much higher speed. Percussion drilling is simple and fast. This technique delivers multiple laser pulses to the same location, progressively deepening the hole without moving the focal plane.

However, with ultrashort pulses, this method faces common challenges, such as conical shape formation (taper), drilling saturation, low aspect ratios, wing-shaped in-volume defects at the hole's entrance, heat-affected zones, and cracking. As a result, drilling through >0.5-mm-thick substrates is extremely challenging, especially in wide-bandgap dielectrics such as glass.

The current class of advanced femtosecond laser systems overcomes common percussion drilling limitations, such as nonrepeatable hole geometry and unwanted thermal defects, through precise pulse parameter control and optimized focusing. Pulse energies >200 µJ and optimized focusing conditions allow modern lasers to penetrate 0.5-mm-thick Eagle XG glass and 1-mm-thick fused silica, for example, in just 20 ms/hole with repetitive single pulses (aspect ratio 1:50). Research reflected that pulse duration significantly affects drilling efficiency, and tests that compared durations from 250 fs to 9 ps demonstrated that shorter pulses create substantially deeper holes with the same number of pulses. The 250-fs pulses created holes 1.7× deeper than those created with pulses >3 ps. This result, achieved with repetitive single pulses, was remarkable given the high quality. It showed shiny walls and minimal defects near the hole entrance.

The key factor in this case is high peak intensity. This is a product of energy and pulse duration, as well as laser beam quality (M^2) and temporal pulse shape, where the quality, among other factors, is defined by Strehl ratio. High laser intensity enables characteristic effects within the deep structure, particularly at the air-glass interface, where multiple internal reflections contribute to further deepen the microhole, resulting in taper-free >400-µm structures[1].

The narrow hole opening is a major challenge for both repetitive single pulses and burst modes. This effect appears at the onset of plasma evacuation, at the rear side of the substrate causing tapered hole exit. This will remain a bottleneck and must be addressed to enable and sustain future developments. However, single femtosecond pulses already show promise in achieving smaller hole diameters without melt ejection at the surface, enhancing precision and reducing the need for post-processing.

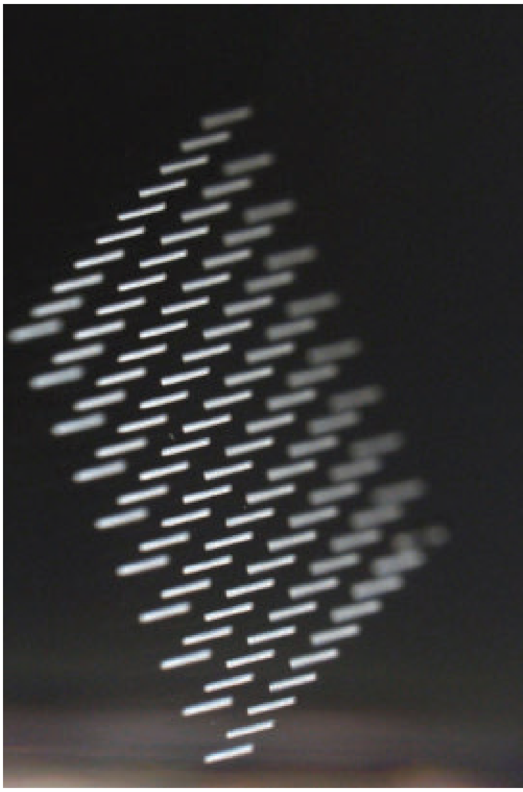
Pulses always on time

For industrial applications requiring thousands or even millions of TGVs, advanced POD enables on-the-fly drilling during continuous scanner movement. An advanced laser triggering scheme, with nanosecond-level timing jitter, enables distributed drilling by providing exact positioning of each laser pulse with sub-micron precision. Achieving a mode of such laser operation requires the laser to produce the pulses with the same energy, despite constantly changing conditions in amplification stages, due to varying pulse repetition rate. As such, this operation can be difficult to obtain.

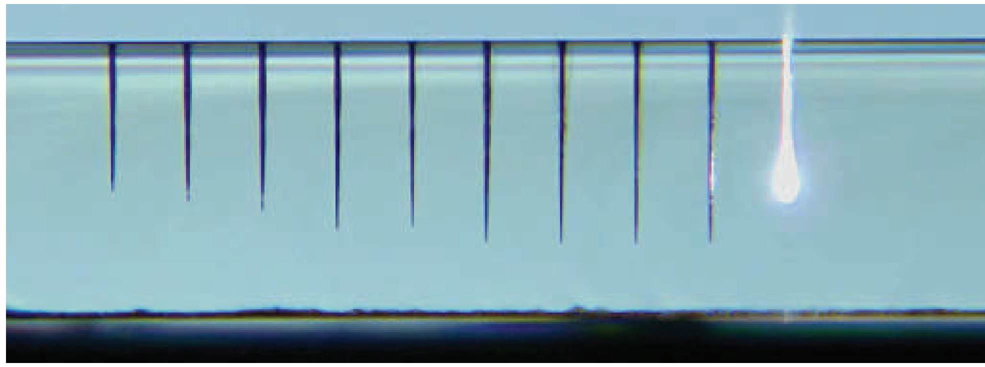
In a conventional approach, the beam must stop at each hole location to deliver pulses, limiting throughput. Advanced POD allows scanners to move continuously at speeds of tens of meters/s while delivering precisely timed pulses that consistently hit the same locations on each pass.

Advanced POD offers two main advantages in operation: distributed heat load and maximized laser use. Pulses are spread across many locations, minimizing heat accumulation at any single point. And the full laser repetition rate can be used across multiple hole locations.

Tests demonstrated significant productivity improvements with this approach; when drilling a 5- × 10-mm matrix of holes with 70-µm spacing, for example, the advanced POD feature enabled a user to achieve 69 holes/s, compared with 17 holes/s using conventional sequential drilling. These results marked a 4×



Through-glass vias (TGVs) fabricated in 1-mm-thick glass. The hole diameter is 65 µm, taper-free, and has an aspect ratio of 15:1. The use of the femtosecond source enables a single-step process that bypasses wet etching.



A side view of optimized percussion drilling with 250-fs pulses provides high-aspect-ratio holes of up to 800 μm in 1.1-mm-thick borosilicate glass. The number of pulses/hole is 2000, with a pulse repetition rate between 2 and 36 KHz.

improvement with a 30-W laser source[1]. This capability stems from a 100× improvement in positioning accuracy compared with standard triggering methods. Even after thousands of passes at high speeds, the holes appeared to be identical to those made with a stationary beam, but without heat-related issues.

Environmental and efficiency benefits

Beyond technical advantages, approaches based on direct femtosecond laser approaches offer significant environmental and efficiency benefits by eliminating the use of chemicals. Single-step laser processes offer flexibility in prototyping and testing while simultaneously offering the potential for future single-step mass-scale fabrication methods.

Additional advantages span energy efficiency, conservation of materials, and downstream process simplification. By concentrating energy precisely where it is needed with minimal heat losses, the minimization of material waste and reduced scrap rates conserves resources and improves manufacturing economics. And a decrease in required process steps leads to a reduction in handling requirements and mitigates errors and/or contamination.

Beyond microelectronics

Microelectronics presents the primary market for TGV technology, though the capabilities of advanced femtosecond laser machining extend to additional industries. The medical device industry increasingly requires microscopic features in biocompatible glass for applications including opto- and microfluidic devices for diagnostics; implantable sensors and electrodes; drug delivery systems; and lab-on-chip technology. The prospect of creating precise, high-aspect-ratio holes without chemicals is particularly valuable for medical applications, such as these, where material purity is critical.

Aerospace applications also benefit from glass' durability, optical properties, and thermal stability. Applications in this sector range from sensor systems that require high-precision optical and electronic integration to display technologies for cockpit instrumentation. Likewise, communication components that require radio frequency transparency, and the hermetic packaging for sensitive electronics in harsh environments, also benefit from the capabilities of sophisticated femtosecond industrial lasing.

In telecommunications, advanced cellular communications systems require complex glass substrates with precise micro-features. These include antenna arrays with integrated components; radio frequency filters and waveguides; and high-frequency circuit boards.

Industry adoption

Leading semiconductor packaging companies are integrating femtosecond laser processes into their manufacturing lines. Major glass manufacturers, including Corning, Schott, Nippon Electric Glass, and AGC, meanwhile, have developed specialized glass formulations that are optimized for electronic devices. Equipment manufacturers offering femtosecond laser solutions span established industry leaders to innovative startups. Companies around the world are offering systems specifically designed for high-volume TGV production.

The flourishing ecosystem surrounding this technology includes glass substrate suppliers, laser system manufacturers, process development specialists, and end-product manufacturers. This ever-growing range of participants indicates a maturing market with competition driving innovation.

Future outlook

As industry continues its evolution toward greater miniaturization and functionality, several trends are emerging. The first is achieving even higher aspect ratios, as research gets closer to exceeding 100:1. In addition, ongoing advancements in laser technology are poised to reduce processing times even further, with the potential of reaching <1-ms-hole creation times or even single-pulse laser piercing. And beyond simple hole geometries, future applications are also likely to require more complex designs, including holes that are tapered, curved, or characterized by variable-diameter features that can only be produced using advanced laser processing.

Combining femtosecond laser processing with complementary technologies is also poised to lead to breakthroughs. The combination of advanced femtosecond processing and plasma monitoring, for example, could enable even greater precision and quality control.

These opportunities stem from the shift from silicon to glass substrates, driven by compelling technical and economic advantages, and requiring innovative manufacturing approaches that overcome the distinct challenges posed by glass.

By enabling single-step processing with greater precision, speed, and quality, advanced femtosecond laser technologies are helping manufacturers to meet next-generation application demands while reducing environmental impact and improving efficiency. The demonstrated capabilities — such as sub-50-µm-diameter holes with aspect ratios >24:1; processing speeds as fast as 20 ms/hole; and angled holes — open possibilities for advanced package designs and applications. Further, the development of direct-laser TGV fabrication using advanced spatial and temporal shaping of femtosecond pulses could enable the manufacture of repeatable single-micron vias with extreme aspect ratios.

Meet the author

Bogusz Stępak, Ph.D., is the R&D director of laser microprocessing at Fluence's Ultrafast Laser Application Laboratory; email: bstepak@fluence.technology.

Reference

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Chasing the Wind: Ultrafast Spectroscopy Captures Nature's Fastest Processes

All images courtesy of Light Conversion.

Ultrafast spectroscopy systems continue to become more compact without any compromise to integration, automation, and accessibility.

BY GRETA BUČYTĖ,
GABRIELĖ STANKŪNAITĖ,
AND MIKAS VENGRIS
LIGHT CONVERSION

Although ultrafast laser sources are integral to today's spectroscopy system designs and applications, the field of spectroscopy predates the invention of lasers. As early as 1940, researchers began to examine photochemical reactions on the microsecond timescale. Molecules in various solutions were excited, or even split, by brief flashes from xenon discharge lamps, resulting in changes in the absorption spectrum of the solution.

These observations were some of the first short-lived radical reactions — discoveries that ultimately earned Ronald G.W. Norrish and George Porter the Nobel Prize in chemistry in 1967. The acclaimed method, termed flash photolysis, remains in use for nano- and microsecond absorption experiments.

While early experiments, such as those from the Nobel laureates, relied on light flashes that split the molecules, laser pulses in modern systems merely excite them to track spectral changes. With the advent of lasers, scientists quickly learned to shorten the light flashes to nano-, pico-, and eventually femtosecond durations. By the early 1980s, picosecond spectroscopy had gained traction, with optical parametric amplifiers (OPAs) used to align laser wavelengths with experimental needs. Dye lasers initially dominated as tunable sources, enabling the generation of the first femtosecond pulses and broadband radiation.

The application of Kerr lens mode locking in gain media led to the subsequent rise of solid-state Ti:sapphire lasers in the market for wavelength-tunable sources[1]. This technological shift propelled spectroscopy experiments into the femtosecond domain, enabling the exploration of ultrafast processes that are relevant to materials science, biology, and chemistry. It became evident that nature is full of light-induced processes that operate on these incredibly short timescales: Charge relaxation in crystalline and amorphous materials, molecular vibrations, and photosynthesis all occur in mere femtoseconds.

The need to examine such rapid processes spurred the development of equipment capable of generating femtosecond pulses. Early manufacturers, such as Spectra-Physics, Coherent, Clark-MXR, and Quantronix, pioneered femtosecond laser sources. In parallel, groups including Light Conversion advanced innovation in ultrafast OPAs. The popularity of ultrafast spectroscopy using solid-state femtosecond laser sources and OPAs surged after Ahmed Zewail earned the Nobel Prize in chemistry in 1999 for his research in femtosecond spectroscopy.

A helpful analogy to better understand ultrafast spectroscopy is to think of this process as photography with short exposure times. Cameras with fast shutters capture athletes in lightning-fast motion, making them appear "frozen" in time. In the same manner, femtosecond lasers enable researchers to observe rapid molecular events on vastly shorter timescales, ranging from micro- to femtoseconds. These timescales are necessary to track essential light-induced processes in real time, such as molecule excitation, ionization, energy and/or charge migration, and regrouping as they leave distinct spectroscopic traces that function as signatures. Decades after its emergence as a core application for the technology, the study of photosynthesis remains among the most fascinating uses of ultrafast spectroscopy.

Photosynthetic absorption occurs in femtoseconds, after which pigments — carotenoids and chlorophylls — enter an excited state. Femtosecond spectroscopy enables scientists to observe each stage of this intricate process. By mapping the evolution of absorption and fluorescence in individual pigments over incredibly short time frames, researchers gained a deeper understanding of the complex chemical steps that convert light into energy-rich organic carbohydrates and oxygen.

Research into photosynthesis delves into foundational processes of life. It also stimulates the development of technologies, such as artificial photosynthesis, which is paving the way for sustainable energy solutions.

Ultrafast spectroscopy also drives advancements across various industries. By uncovering the intricate behaviors of materials, it contributes to the development of industrial technologies, offering

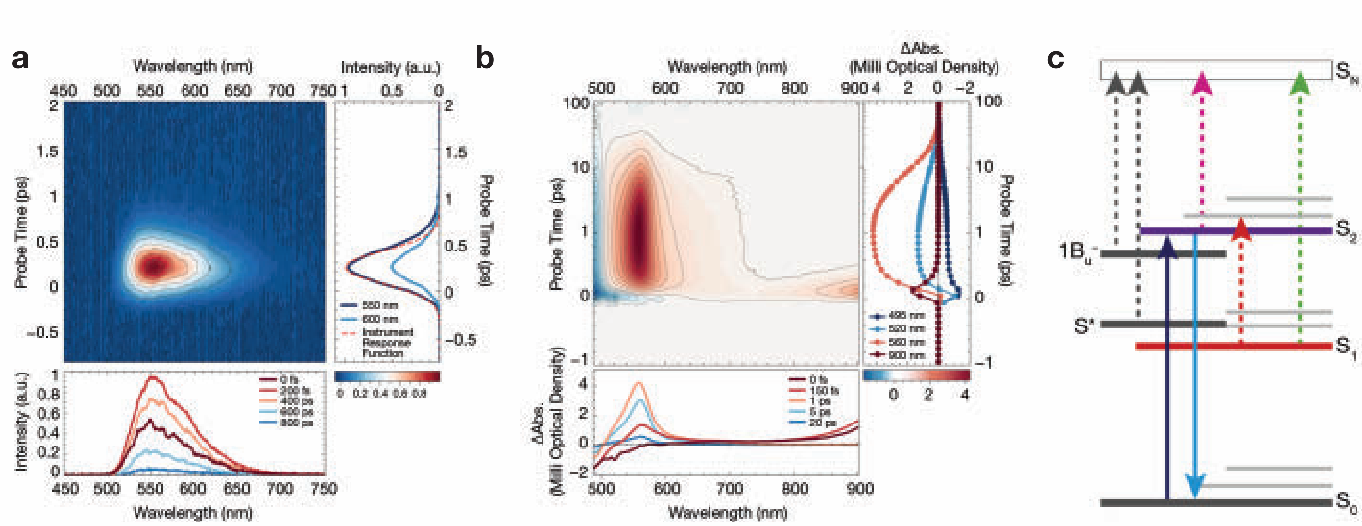


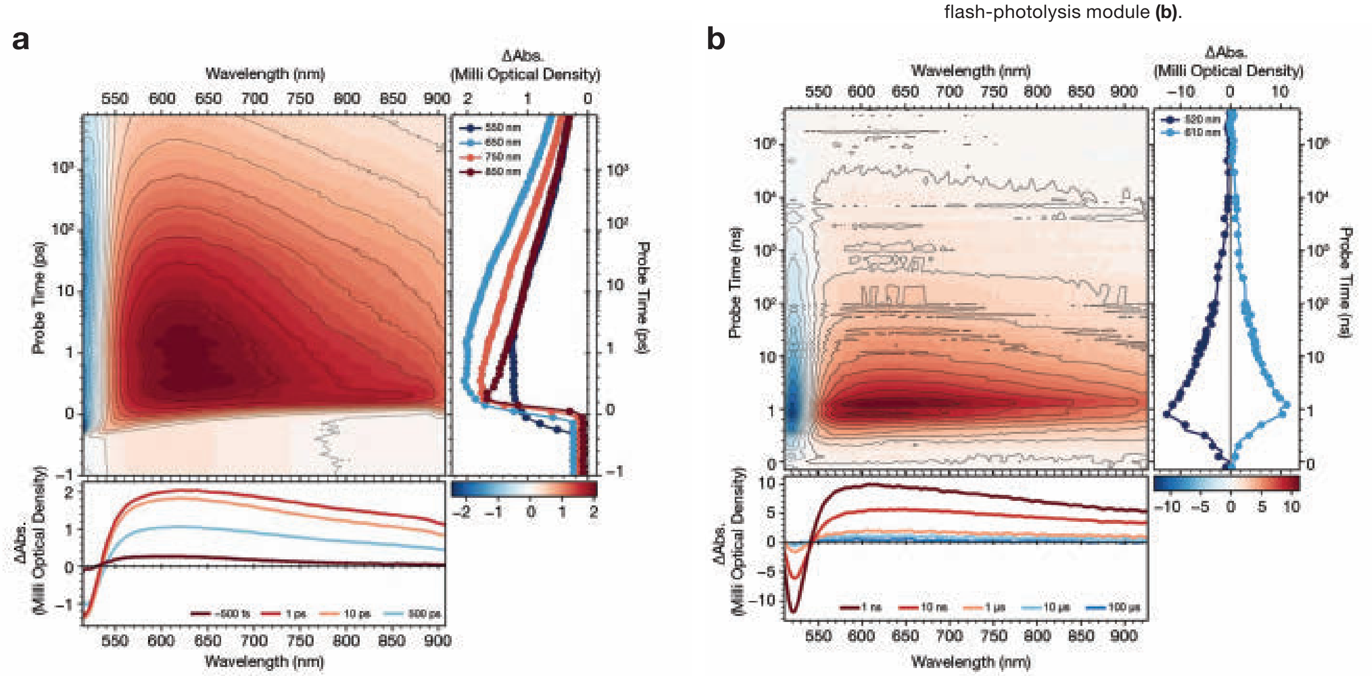
Figure 1. Kerr gate measurements in ß-carotene showcase the resolution of the measurement **(a)**. The second singlet excited state in the molecule to the ground state (S2 → S0) fluorescence of carotenoids is ultrafast (100 fs). Therefore, the measured data is instrument response function-limited. Spectral dynamics of ß-carotene in solution acquired using a transient absorption spectroscopy system **(b)**. Energy states of ß-carotene **(c)**. The first singlet excited state (S1) is referred to as a dark state because it does not emit fluorescence. Yet it plays a crucial role in energy dissipation and photoprotective mechanisms.

insights into processes occurring on pico- to femtosecond timescales. In OLEDs, for example, ultrafast spectroscopy provides a detailed understanding of exciton dynamics, revealing how excitons are generated, migrate, and decay. It helps to identify the timescales of recombination and energy transfer to optimize these sources. For solar cells, ultrafast spectroscopy plays a key role in addressing energy loss pathways[2]. It also detects trap states and defects that capture charge carriers, guiding the design of materials to minimize these efficiency losses, giving ultrafast spectroscopy utility in processes to enable semiconductor industry applications.

Exploring molecular dynamics

From photochemical reactions to energy transfer processes, ultrafast spectroscopy offers a powerful arsenal of techniques for unraveling the mechanisms underlying a wide array of phenomena. Many can

Figure 2. Pump-probe dynamics of a colored glass filter designed to transmit light >530 nm. Ultrafast dynamics in the femtosecond regime, acquired via transient absorption spectroscopy using a Light Conversion HARPIA-TA instrument **(a)**. Longer-lived dynamics on the nanosecond timescale, measured with the instrument's flash-photolysis module **(b)**.



be used to observe molecular processes and provide benefits that are unique to each method.

Time-resolved fluorescence spectroscopy techniques, such as time-correlated single-photon counting (TCSPC), fluorescence upconversion, and optical Kerr shutter, provide insights into the excited-state dynamics of molecules. TCSPC measures fluorescence and phosphorescence lifetimes, which correspond to the time that molecules spend in their excited states before returning to the ground state. These lifetimes reveal information about molecular environments, energy transfer processes, and interactions with surrounding molecules. However, the fastest events that TCSPC can capture are limited to tens of picoseconds due to detector response time.

Fluorescence upconversion achieves femtosecond resolution in tracking fluorescence decay using nonlinear optics. This enables researchers to observe rapid energy dissipation and relaxation processes that occur within molecules on timescales as short as a few tens of femtoseconds.

Kerr gating, meanwhile, simplifies the process of capturing the full spectra of emitted fluorescence without wavelength scanning. This can be a time-consuming task with wavelength scanning, because it is less efficient in capturing fast dynamic processes.

In fluorescence techniques, the detected light must be radiated by the sample; observations are inherently limited to emissive excited states, neglecting non-emissive states and ground-state processes. Time-resolved transient absorption spectroscopy addresses this limitation by capturing transient intermediates in both ground and excited states.

Using two ultrashort laser pulses, time-resolved transient absorption spectroscopy provides snapshots of molecular evolution, revealing vital processes that cannot be detected via fluorescence. For example, in β-carotene, a naturally occurring pigment known for its photoprotective properties, Kerr gating fluorescence spectroscopy enables the observation of only the fluorescence decay from the second singlet excited state in the molecule to the ground state ($S_2 \rightarrow S_0$) (Figure 1a). However, transient absorption spectroscopy reveals additional processes, such as excited-state reabsorption and the involvement of non-emissive states such as the first singlet excited state (S_1), or the "dark state," and intermediate species in energy transfer and photopro-

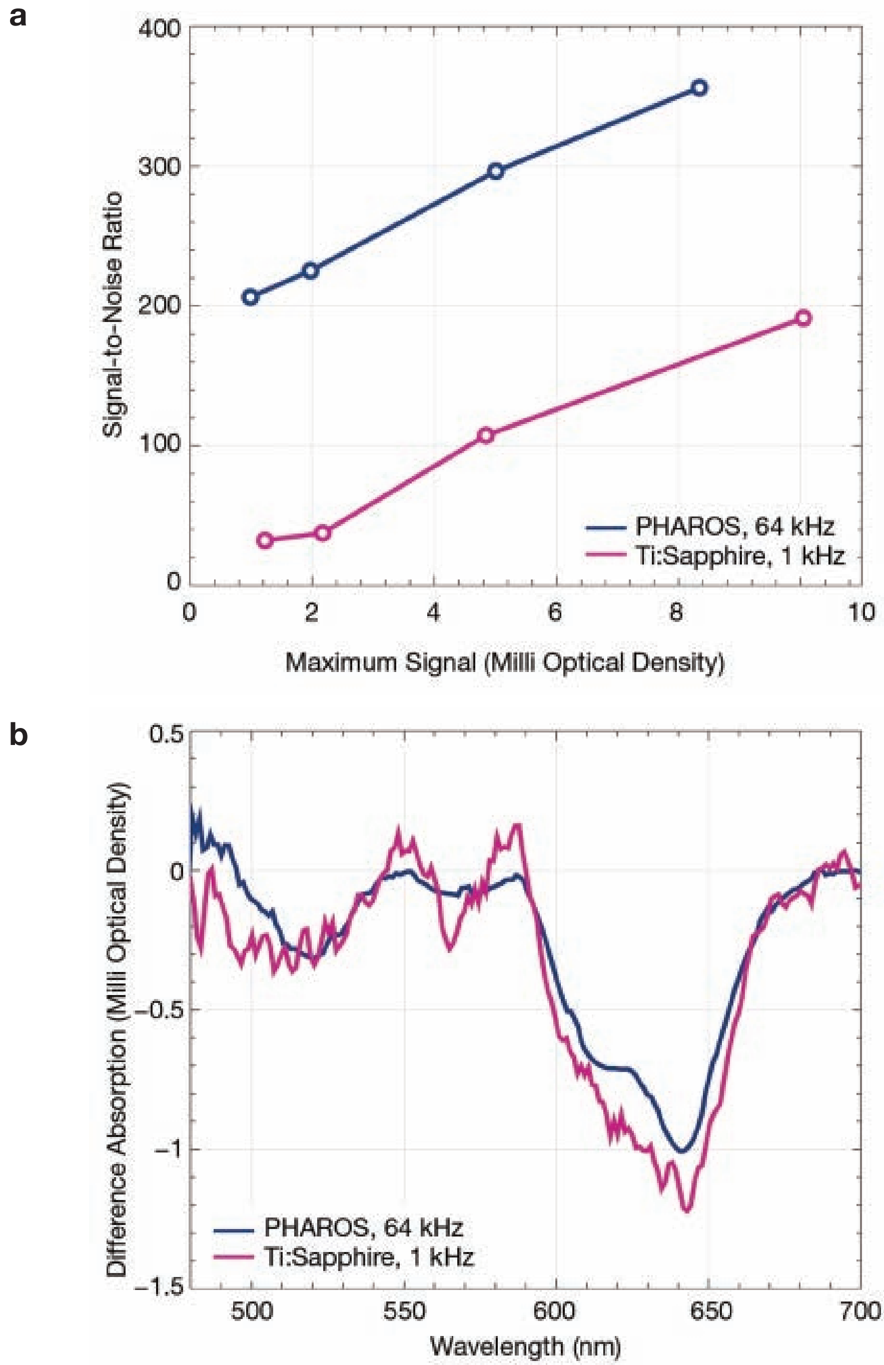


Figure 3. The measured difference absorption spectra of cadmium selenide/zinc sulfide quantum dots using low- and high-repetition-rate lasers with 5-s acquisition time **(a)**. Best-effort signal-to-noise ratios (SNRs), achieved via transient absorption spectroscopy driven by a Ti:sapphire laser at 1 kHz and a femtosecond laser at 64 kHz **(b)**.

tection (Figure 1b). The comprehensive nature of this approach enhances the understanding of complex molecular behaviors by providing a more complete picture of dynamics across all relevant states.

The significance of multiple timescales

Transient absorption measurements capture the earliest dynamics on the ultrafast timescale, such as vibrational relaxation and intersystem crossing of electronically excited molecules. These processes occur almost immediately after excitation and define the initial distribution of energy within the system.

Monitoring these ultrafast events can provide a foundational understanding of how energy is directed or dissipated before slower processes take over. However, this does not mean that the later-occurring events are less important for delivering essential information. After all, the real-life consequences of ultrafast events — such as sugar production in photosynthesis — manifest long after the process has consumed the initial photon energy.

To follow the dynamic initiated by ultrafast events, time-resolved methods must also cover timescales extending from nano- and microseconds all the way to seconds. Therefore, understanding long-lived states such as triplet-state formation, charge separation, and recombination, which are the products of photochemical reactions, is as important as accessing initial femtosecond dynamics. In fact, it is at these times that one can evaluate the stability and efficiency of molecular systems and materials. Molecules with extended excited-state lifetimes require careful investigation using nanosecond delays to fully characterize their nonradiative decay pathways and other significant dynamics. In this context, flash photolysis — or nano- to millisecond transient absorption — remains as useful today as when it was first conceived in the last century.

The principle of flash photolysis is analogous to the femtosecond transient absorption experiment but it operates with delays in the nano- to microsecond range. In femtosecond transient absorption, moving a mechanical delay stage — which increases the distance that the light must travel to reach the sample — adjusts for the delay between pump and probe pulses. The delayed probe pulse is obtained from an electronically triggered external probe laser. A practical example of studying dynamics across different timescales is the measurement of a colored glass filter designed to transmit light >530 nm, enabling the tracking of kinetics from pico- to nanoseconds (Figure 2).

Having a broad time window that spans pico- to nanoseconds is essential to construct a comprehensive kinetic picture of a system. In photochemistry, for example, such a broad window enables researchers to study ultrafast bond cleavage and slower product formation. By following through the entire temporal evolution from initial excitation to the final product of the captured photon, researchers can reconstruct the full dynamic sequence and avoid incomplete or incorrect conclusions.

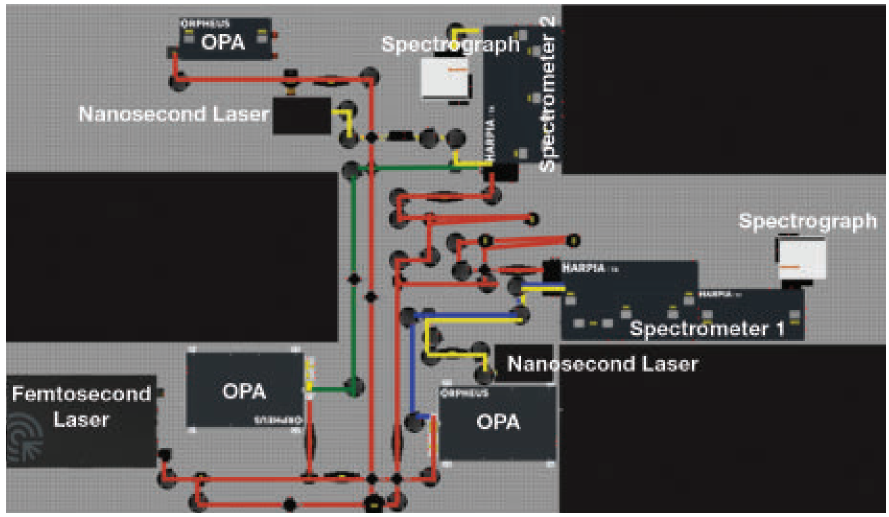


Figure 4. A dual-spectrometer system deployed at the University of Cambridge. The system, capable of performing transient absorption (TA) and reflection in bulk, microscopy, and flash photolysis experiments, was designed and manufactured by Light Conversion and supplied by Photonic Solutions. It also features a time-resolved fluorescence (TF) module, three optical parametric amplifiers (OPAs), two nanosecond-pulsed lasers, a femtosecond-pulsed laser, and two spectrographs.

Laser parameters define performance

Modern low-maintenance lasers free up valuable time and effort, allowing researchers to focus on their experiments and industrial end users to complete their tasks. Different laser types excel in various applications and spectral regions, and certain applications require multiple lasers for comprehensive studies. Researchers and system end users must carefully select the most suitable laser based on factors such as power, tunability, bandwidth, size, and cost. Modern-day solid-state femtosecond lasers, operating at high repetition rates, combine multi-millijoule pulse energy and high output stability, making them ideal light sources for scientific research. Additionally, they can be equipped with OPAs, offering a broad tuning range from the deep-ultraviolet to the mid-infrared to meet specific measurement needs for numerous applications.

Tunability is a fundamental requirement in modern spectroscopy, because it enables a wealth of experimental possibilities and new use cases as a result. The precise adjustment of the wavelength of the light source is key to spectroscopic versatility, allowing users to selectively excite specific energy levels within molecules and materials, enable powerful nonlinear spectroscopic techniques, conduct time-resolved studies, and characterize materials with wavelength-dependent properties.

Traditional lasers offer some degree of tunability, but they are often limited in their spectral range. To overcome these limitations, users in R&D environments frequently turn to systems that combine lasers with OPAs. This powerful pairing ensures high-intensity, highly tunable, and coherent light sources.

Signal-to-noise ratio (SNR) is another critical factor in obtaining high-quality spectroscopic measurements. Ytterbium-based lasers, known for their high repetition rates, achieve excellent SNR even with low-pulse energies (Figure 3). Ideally, scientists and users in research settings aim to illuminate samples under natural conditions, but ultrafast spectroscopy demands femtosecond pulses to capture molecular phenomena occurring on these ultrafast timescales. High repetition rates play a crucial role in this process. Rather than relying on a few high-energy pulses, users can accumulate a sufficient signal by using many low-energy pulses to enable precise and meaningful analysis of ultrafast dynamics.

In fields such as biophysics, physical

chemistry, photovoltaics, and semiconductor physics, a white light continuum (WLC) is often deployed as a probe source in femtosecond pump-probe experiments. These experiments require two laser pulses: The first excites the sample and the second arrives with a controlled delay to measure changes in transmittance caused by the excitation. Use of a WLC is particularly attractive as a probe source due to its broad multi-octave spectral range, which enables the study of multiple transitions within the investigated material. The sensitivity of these measurements depends on the number of photons in the probe pulse. Since the number of WLC photons detected per second scales linearly with the repetition rate, its increase significantly enhances the experiment's SNR. This reduces noise and improves measurement precision.

Toward single-box spectroscopy

Spectroscopy systems' remarkable transformation is marked by an evolution from complex, multicomponent setups to integrated, single-box solutions. This shift has created several key advantages, including enhanced ease-of-use, improved stability and reliability, and reduced maintenance requirements.

These advancements have increased the convenience and efficiency of spectroscopy while empowering researchers across diverse scientific fields by simplifying the access to powerful analytical techniques. Today, advanced spectroscopy setups may integrate a single laser with multiple OPAs, allowing researchers to perform a variety of operations within a single, cohesive system. Housing multiple functionalities in one system marks a significant step forward in efficiency and flexibility (Figure 4).

Driven by the goal of making spectroscopy more accessible, the industry continues to innovate as it moves toward more compact, single-box transient absorption systems. This dynamic — shrinking systems and growing capabilities — signals that the future promises even greater advancements in integration, automation, and accessibility.

Meet the authors

Greta Bučytė is a product manager for spectroscopy systems at Light Conversion; email; greta.bucyte@lightcon.com.

Gabrielė Stankūnaitė is head of marketing and communications at Light Conversion; email: gabriele.stankunaite@lightcon.com.

Mikas Vengris is a professor at the Laser Research Center, Faculty of Physics, Vilnius University, and an R&D engineer at Light Conversion. His research focuses on ultrafast laser applications for investigating dynamic processes in various materials; email: mikas.vengris@lightcon.com.

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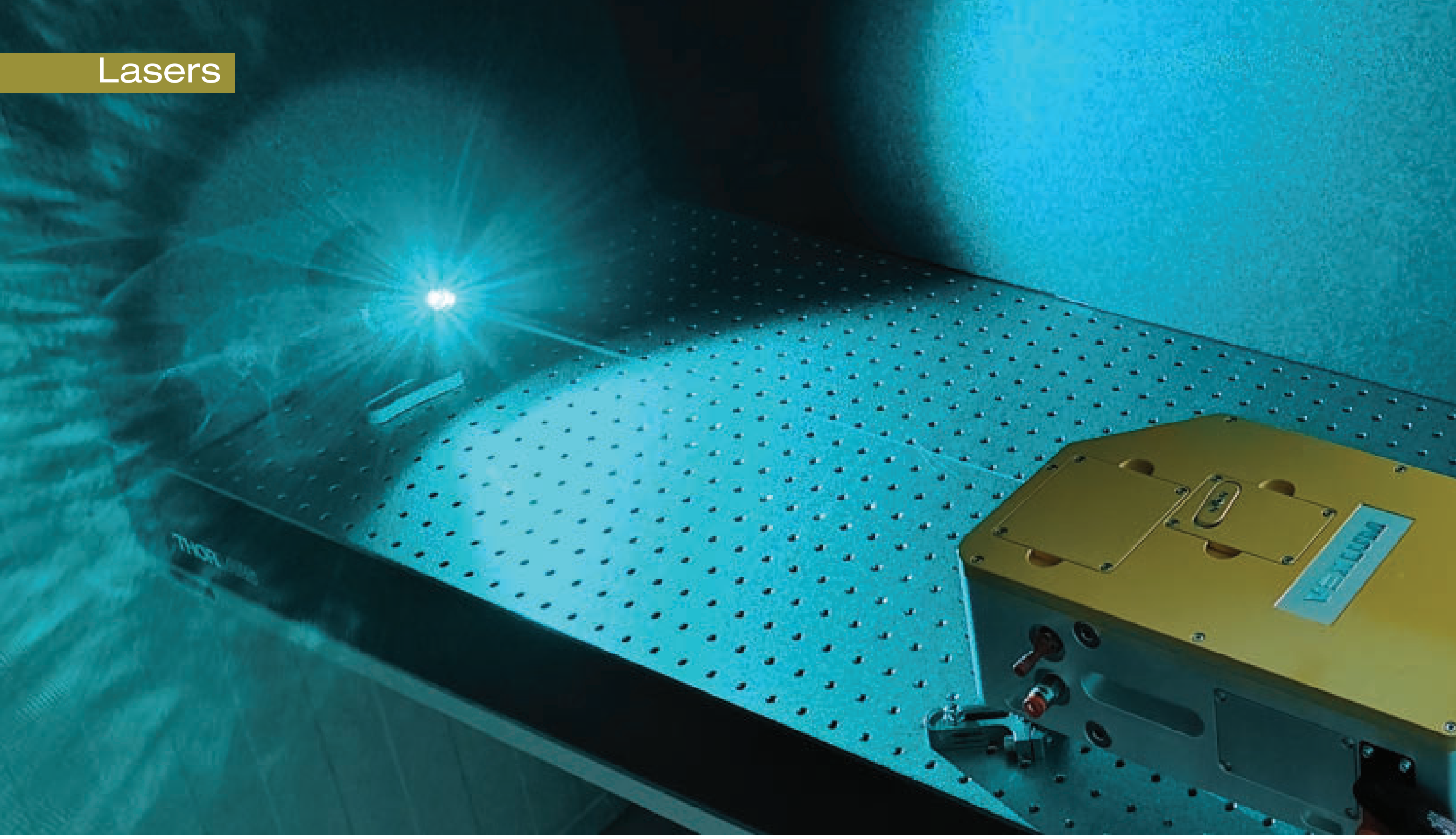


Into the Quantum Domain, Versatile Lasers Are Enabling an Era of an Emerging Technology

Vertical-external-cavity surface-emitting lasers offer a scalable solution that is necessary to support burgeoning quantum applications.

All images courtesy of Vexlum Ltd.

BY PHILIP MAKOTYN, MIRCEA GUINA, AND JUSSI-PEKKA PENTTINEN
VEXLUM LTD.

The vibrant quantum technology space is characterized by a seemingly impossible superposition of contradictory facts. In one sense, quantum technologies have arrived: Cutting-edge optical atomic clocks are enabling solutions for position, navigation, and timing systems, and atomic magnetometers used in oil and gas exploration are available today in the marketplace. On the other hand, other quantum technologies are still being developed, including quantum computers. Future large-scale quantum computers promise disruptive applications, most notably breaking modern cryptography standards. And at the same time, quantum networks have been deployed with the future aim of a quantum internet or unhackable communication channels.

Quantum is both fact and hype. Pioneering scientific advancements in quantum have featured on the front page of the *New York Times* and are (or support) the core science of many Nobel laureates. Yet quantum has also been a central theme in Hollywood blockbusters. Amid this dynamic, or as a result of it, large-scale investments from government and the private sector are driving incredibly fast progress in both research and technology development.

Quantum draws such considerable interest because of the nonintuitive laws that define the "quantum" behavior of objects of atomic scale. The laws of physics at atomic scales are vastly different from the familiar science that describes the macroscopic "classical" world. Properties such as superposition, in which objects are simultaneously in two or more places; entanglement, when the outcomes of measurements are connected; and wave-particle duality, a behavior that describes existence as both a wave and a particle, are among the foundations of quantum theory. In fact, quantum theory is so nonintuitive that Einstein famously never fully accepted all of quantum theory. His quotation, "God does not play dice with the universe," is often cited in various settings. Nevertheless, time and time again, experiments have demonstrated the quantum mechanical nature of the universe at microscopic scales.

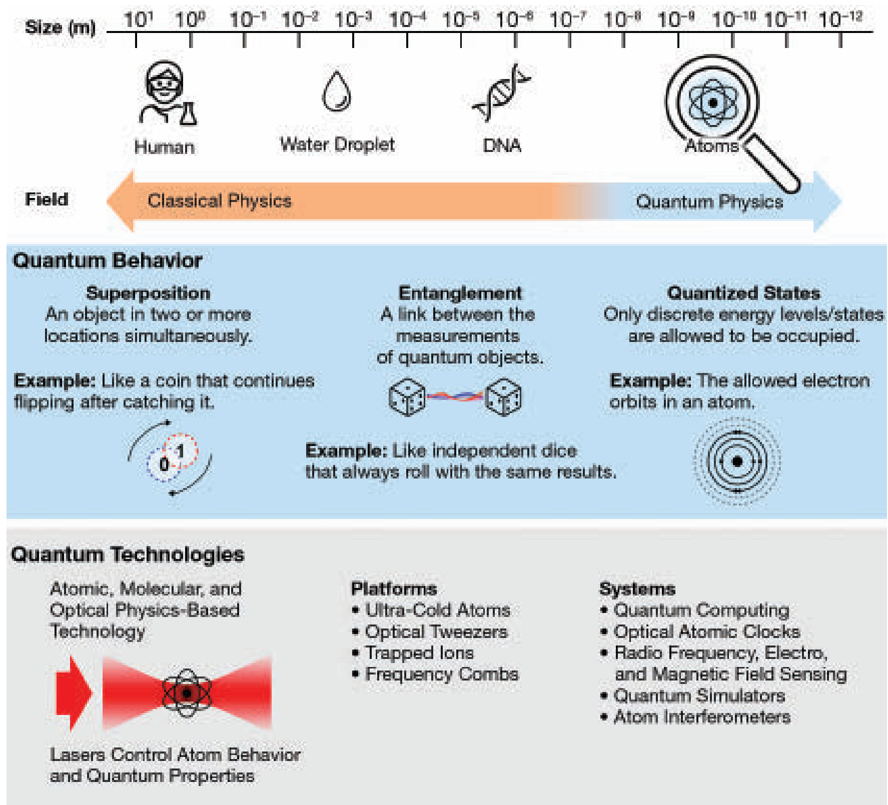


Figure 1. A description of quantum behavior and atomic, molecular, and optical technology platforms. At small scales, the behavior of objects is described by quantum theory rather than classical physics.

Quantum technologies

The development of quantum technologies is roughly separated into two categories, with two distinct characteristics. Following the discovery of quantum mechanics in the 1920s, the Quantum 1.0 era uses the understanding of quantum rules in the development of technologies. For example, the internet is built upon a foundation of telecommunication lasers exploiting the quantization of energy levels. In contrast, the quantum computers, quantum sensors, and quantum networks of Quantum 2.0, coined in 2002, are technologies that directly engineer quantum states (Figure 1)[1].

Quantum sensing, quantum computing, and quantum networking are the three main categories of Quantum 2.0 technologies. Quantum sensing uses the sensitivity (or insensitivity) of quantized energy levels to environmental conditions; the sensors can achieve unprecedented precision in measurements, supporting applications such as mineral exploration, medical imaging, and navigation in GPS-denied environments. Quantum computing relies on superposition and entanglement to enable computations that are impossible for classical computers. Using qubits instead of classical bits, quantum computers offer the potential to revolutionize many industries and sectors. Quantum networking aims to enable secure communication and distribute quantum information, paving the way for a quantum internet.

The emerging Quantum 2.0 technology capabilities promise transformative solutions to climate change, drug discovery, personalized medicine, precision agriculture, and more accurate global positioning systems. The wealth of potential applications, with further possibilities, contributes to the expectation of quantum's growth into a cross-vertical trillion-dollar industry.

Such a growth forecast shines a light on the foundational role of physical science as a key enabler to these quantum technologies and their applications. Various physical systems are used to access quantum states, each with advantages and disadvantages. To this end, a leading platform for engineering quantum technologies is atomic, molecular, and optical (AMO) physics-based systems, or simply atomic-based technologies. AMO quantum technology controls quantum behavior by shining laser beams on atoms, ions, or molecules.

As a result, the advent of lasers revolutionized the field of AMO quantum research. As research moved away from dye lasers or other early light sources, reliable and performant lasers sparked immense progress and capabilities in AMO-based quantum technologies. Today's laser systems are tasked with sustaining this growth in support of a rising number of applications.

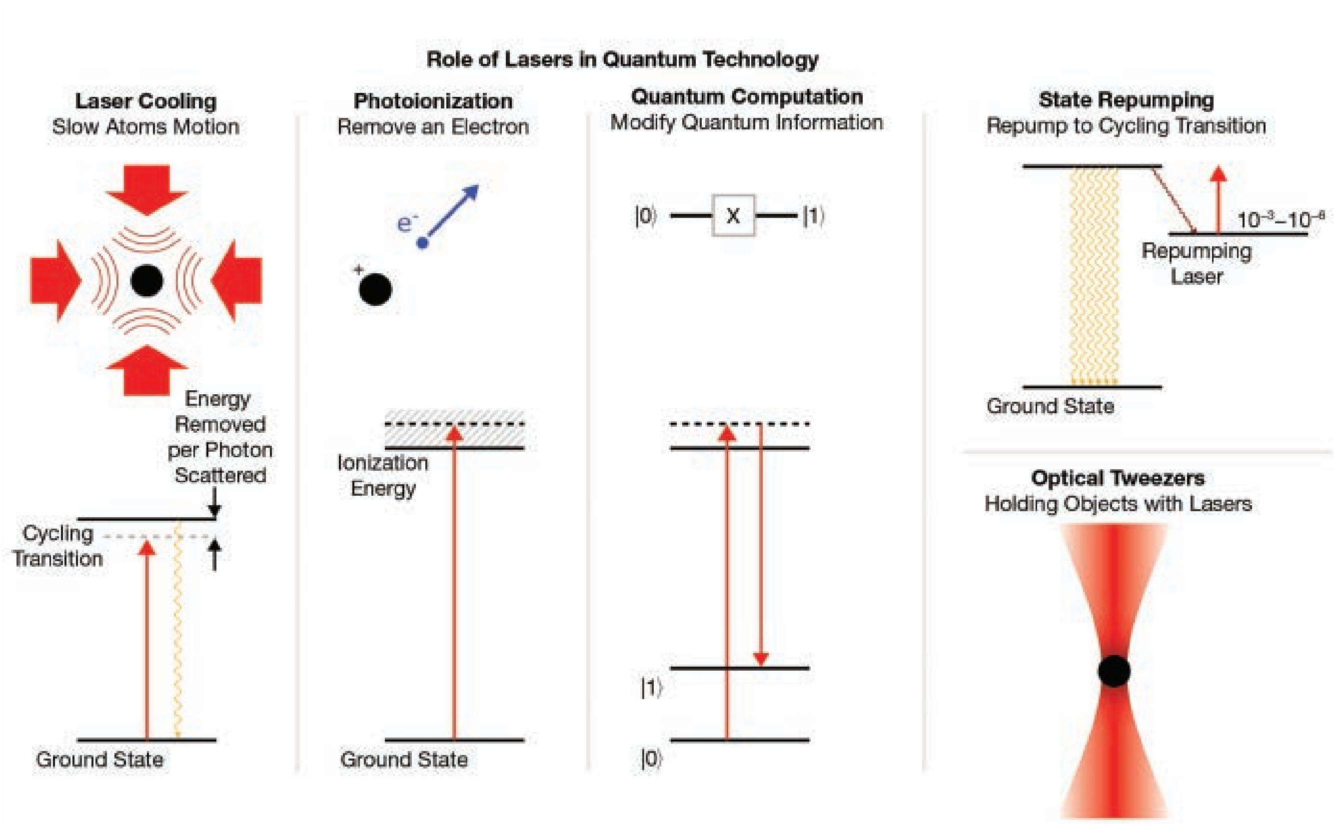
Lasers: The main tool in the toolbox

Due to the complex nature of interactions between light (photons) and atoms, lasers play multiple roles in atomic systems. Laser light is used for controlling particles, typically atoms, and interacting with quantum information — typically stored as properties of orbiting electrons. These operations are themselves broken down into categories. These include trapping atoms; cooling atoms (slowing their motion); the photoionization of atoms into ions with attractive quantum properties; quantum information operations; measuring a quantum state; and/or creating optical atomic clocks (Figure 2).

Each of these roles requires distinct laser properties that, in some cases, may require many wavelengths for a single atomic species. In many cases, power, linewidth, and/or modulation performance are essential parameters. As a result, when building quantum systems, lasers are either controlled with built-in capabilities or externally modulated to meet requirements. For example, to improve beam quality and pointing stability, beams are often fiber coupled — in some systems for <1 m. Absolute frequency stability is achieved by locking light to an atomic reference, a self-referenced frequency comb, or an ultra-stable cavity.

Even as the maturation of laser technology earns praise, many limitations of atomic-based quantum technologies are ascribed to lasers with low power, high noise, wavelength limits, poor practicality, or a combination of these characteristics. In addition, there is not a consensus regarding atom species for quantum sensing or computing technologies — every atom requires unique wavelengths,

Figure 2. The various roles of a laser's function in quantum technologies. The electromagnetic field can be used to control the entire atom by slowing down its motion, or to control the quantum state of an electron.



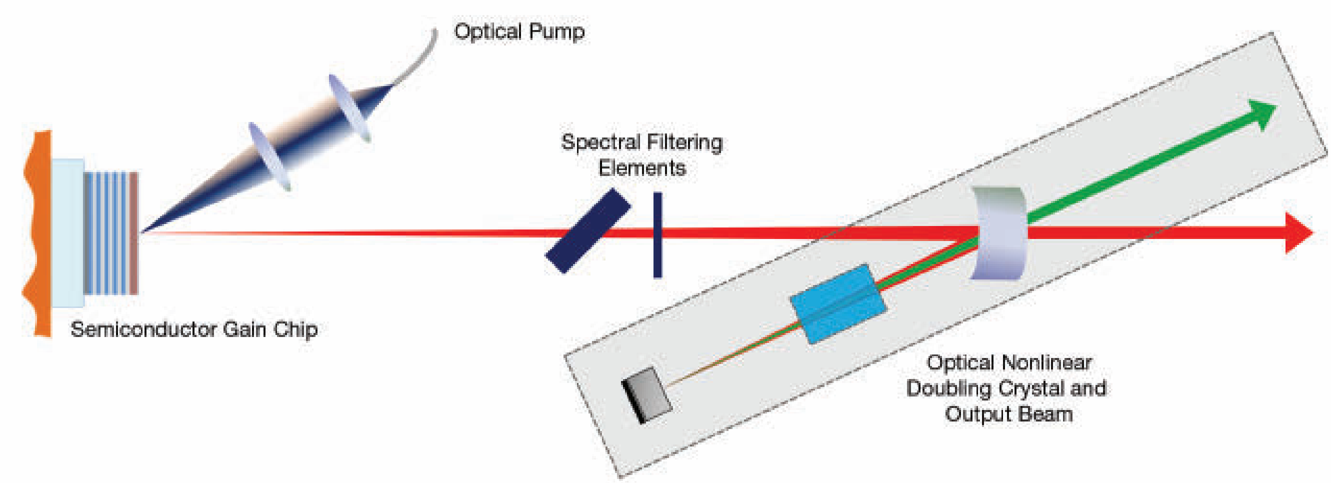
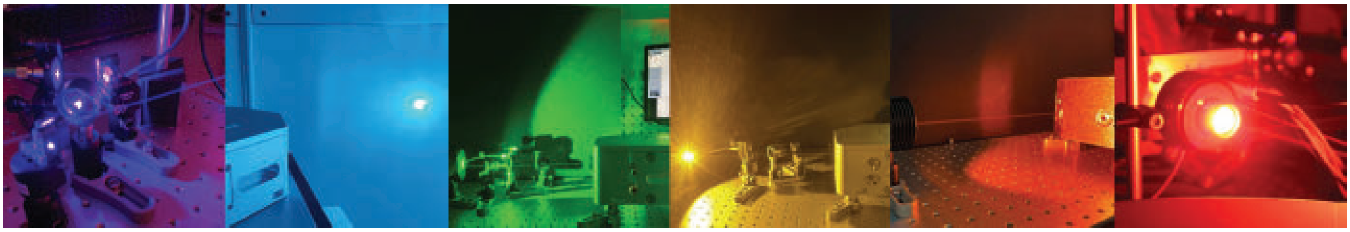


Figure 3. An architecture of a vertical-external-cavity surface-emitting laser (VECSEL). Optical elements include precise temperature stabilization. The laser system architecture commonly includes a Bragg reflector, integrated with the gain chip, and an external mirror. Additional elements may include those for filtering, such as birefringent filters and/or etalons.

and this presents a challenge to the development of laser platforms. On the other hand, the development of versatile, better-performing lasers that offer, for example, better wavelength coverage, would advance an increasing number of future applications.

Against this dynamic backdrop, optically pumped vertical-external-cavity surface-emitting lasers (VECSELs) have emerged as a practical tool for quantum technologies, pioneered with trapped-ion quantum computers and optical atomic clocks. Building on a legacy of VECSEL technology development since 2005, a collaboration between the Optoelectronics Research Centre, Tampere University (Finland), and the National



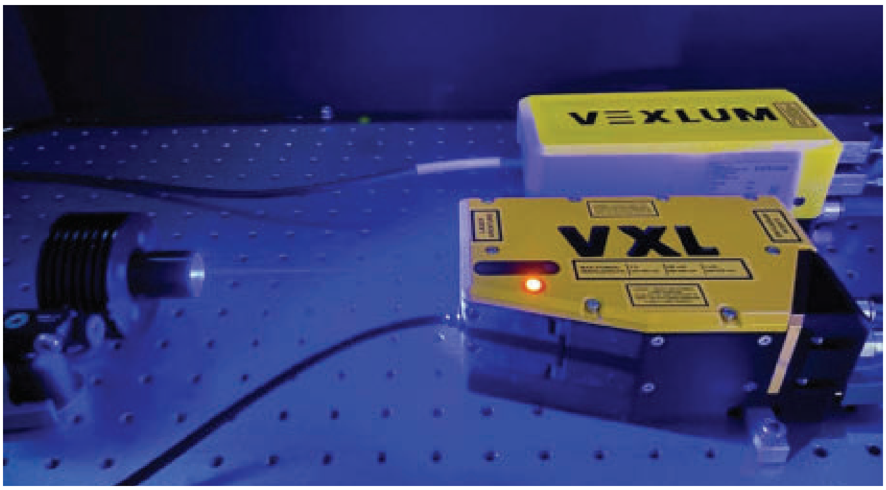


Figure 4. Uncorrected images of high-power single-mode laser output demonstrating the wavelength versatility of vertical-external-cavity surface-emitting lasers (VECSELs) **(above)**. Atomic-based quantum technologies require a broad wavelength spectrum of high-power single-mode lasers. VECSELs address the requirement, emitting from the ultraviolet into the infrared.

Figure 5. A compact vertical-external-cavity surface-emitting laser (VECSEL) designed to address the scaling needs of quantum computers and the environmental needs of quantum sensors **(left)**. A reduction in size is due to the inherent advantages of a laser architecture that uses a minimalistic number of elements and simple cavity design. Broadly, VECSELs are an ideal platform to address the scaling needs of quantum systems.

Institute for Standards and Technology demonstrated the benefits of optically pumped VECSELs in atomic-based quantum, ultimately leading to these semiconductor lasers being applied across a broad range of wavelengths to address numerous distinct quantum atomic technology platforms[1].

A solution for quantum

From a photon's perspective, a VECSEL, sometimes referred to as an optically pumped semiconductor laser (OPSL) or semiconductor disk laser, is like any other semiconductor laser. VECSELs are made up of III-V semiconductor quantum wells with specific energy levels engineered through design and epitaxy. By adjusting the composition of the semiconductors that form the gain structure, the output wavelength can be tailored in a broad range, typically extended from visible to beyond 2100 nm[2].

An important aspect of the gain structure is the integration of a Bragg reflector at one end of the laser cavity. The other end of the cavity is defined by an external mirror, which can be also equipped with a piezo-electric element to tune the cavity length and stabilize the operation. The cavity can incorporate spectral filtering elements, such as birefringent filters or etalons, and optional nonlinear optical elements for frequency conversion. Other important elements instrumental for VECSEL operation are precise temperature stabilization of the gain medium and pumping the semiconductor gain, which is ideally achieved using robust and inexpensive high-power laser diodes (Figure 3).

VECSELs emit light that is perpendicular to the surface of the chip, enabling symmetric optical pumping of the gain medium and generating an excellent spatial mode. In contrast, edge-emitting laser diodes or amplifiers exhibit an asymmetric spatial mode due to the asymmetric waveguide geometry for guiding the light. Long photon lifetimes and high intracavity powers, owing to high-reflectivity mirrors, allow for stable and efficient intracavity frequency conversion — for example, second-harmonic generation — and as a result an easy and efficient path to expanded wavelength coverage.

Specifically for quantum systems, VECSELs provide several essential characteristics. These lasers simultaneously offer high output powers, broad wavelength selection, single-mode operation, and low noise. These features, achieved inherently through the VECSEL architecture, further enable trade-offs in performance specifications through gain and/or cavity engineering. The deployment of quantum technologies often requires several or all of these characteristics for current or next-generation systems.

High output power, which is achieved via a large emission area and efficient thermal management, is a common requirement in atomic technologies — nearly every AMO system will benefit from higher-intensity beams. For example, optical tweezers used in optical atomic clocks and/or neutral atom quantum computers hold atoms tighter with increased laser power. Tighter and deeper traps are created from larger optical powers and larger electric fields, through a phenomenon known as the AC Stark shift. Alternatively, higher laser powers reduce errors in neutral-atom or trapped-ion quantum computing logic gates through an interplay of error contributions from laser power, detuning, and technical noise. Increases in laser power in these settings serve to directly improve performance of quantum compute — an application for which a main limitation stems from errors in computing operation(s).

Wavelength versatility is one of the most demanding laser requirements in atomic-based quantum technologies. The diversity of atom species used by hardware developers demands the use of lasers across a broad range of wavelengths. Further, the lack of consolidation to a single or few atomic species results in a broad spectrum of needed high-power single-mode lasers, from ~250 nm to 3 µm. Demonstrating how VECSELs are a solution to wavelength needs, the uncorrected images in Figure 4 show a rainbow of visible VECSEL outputs, from the broader available range of ultraviolet to near-infrared and into the shortwave infrared. The wavelength versatility of VECSELs through epitaxy design makes it possible to select practically every wavelength needed to drive atomic transitions.

Lasers with narrow linewidths and low noise are also critical among specific quantum operations. Optical atomic clocks and other quantum systems require ultra-stable sources with narrow linewidths. VECSELs can be easily locked to an atomic reference using the external cavity mirror piezo and narrowed to sub-hertz linewidths with an intracavity electro-optic modulator. Low-noise optical pumps and external cavity filtering can result in best-in-class amplitude and phase noise, critical for many quantum sensors as well as neutral-atom and trapped-ion quantum computers.

Practical and scalable architecture

The commercialization of quantum systems and devices is occurring as many of these next-generation quantum technologies are also transitioning from laboratory settings into real-world environments. For example, optical atomic clocks have been deployed on ships participating in naval demonstrations. And quantum antennas and magnetometers are under development to be deployed on helicopter platforms.

VECSELs have several inherent advantages as an enabling technology when considering developing deployable quantum technologies. The laser architecture features a minimalistic number of elements and cavity design, while still meeting wavelength versatility and power scaling capabilities, avoiding the need for external amplifiers and doubling cavities. Similarly, as quantum computing transitions to data centers, VECSELs have the potential to offer a best-in-class size, weight, power, and cost metric needed for future at-scale quantum computing (Figure 5).

From these benefits and ongoing innovation, VECSELs have emerged as a powerful and versatile tool for a variety of quantum applications; their inherent flexibility makes them viable solutions for many types of systems while enhancing stability and efficiency. As advancements in design and performance continue, VECSELs' role in driving the future of quantum research and applications is set to expand, enabling future breakthroughs in fundamental science and real-world technologies.

Meet the authors

Philip Makotyn is president of Vexlum US, a subsidiary of Vexlum Ltd. He has more than 15 years of experience in quantum technologies and earned a Ph.D. in physics from the University of Colorado; email: philip.makotyn@vexlum.com.

Mircea Guina is chairman, chief science officer, and cofounder of Vexlum Ltd. He is also a professor of semiconductor technology at Tampere University, where he leads the Optoelectronics Research Centre; email: mg@vexlum.com.

Jussi-Pekka Penttinen is the chief executive officer, chief technical officer, and cofounder of Vexlum Ltd. He has more than 15 years of experience in optically pumped VECSELs and is a leader in the field; email: jp@vexlum.com.

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Expert Insights:

Laser Fusion

Bears Promising Opportunities for Photonics

Laser fusion has commanded significant interest from researchers and policymakers in recent years. Two world-leading laser and optics experts in Germany share their current perspectives on laser fusion and the potential benefits that they envision for the future.

Constantin Haefner.

Andreas Tünnermann.

BY ANDREAS THOSS
CONTRIBUTING EDITOR

With the demand of global electricity expected to double by 2045, fusion energy is gaining strategic importance as a sustainable, carbon-free power source. Among the various approaches, laser-driven inertial fusion has recently attracted increasing attention — not only in science, but also in politics and industry.

In Germany, this interest sparked action, with the release of the national funding program Fusion 2040 by the Federal Ministry of Education and Research (BMBF) in late 2023. This program is the result of a consultation process that commenced in 2022. In addition to expert panels and stakeholder workshops, this comprehensive process led to the formation of the BMBF commission on inertial fusion energy (IFE), chaired by Constantin Haefner.

Fusion 2040 marks a significant turning point in Germany's fusion strategy, supporting magnetic and laser-based fusion pathways for the first time. It enhances ongoing world-class basic science research with additional funding of more than €400 million that will be put toward technological developments needed for the first fusion power plant. This will bring Germany's investment to more than €1 billion over the next five years, which does not account for the funds brought in from Europe and the ITER project. Fusion 2040 draws on expertise from universities, industry, and key organizations such as the Fraunhofer-Gesellschaft, Max Planck Institutes, and Helmholtz Centers to cultivate a national innovation ecosystem that bridges research and industry. Importantly, the program is technology-agnostic, which is necessary to support IFE and magnetic fusion energy.

Today, Germany excels in basic research and essential technologies related to magnetic confinement, fusion materials, and the fuel cycle. What it currently lacks is foundational research in inertial confinement fusion, which is the basis for IFE.

But Germany's laser and optics industry, as well as German-led applied research in these areas, make it a world leader in the supply of enabling technologies for inertial fusion.

Two world-leading experts from Germany, Constantin Haefner and Andreas Tünnermann, are uniquely equipped to offer insights into this dynamic. Haefner, an internationally recognized expert in IFE and high-energy lasers, is an executive board member of Fraunhofer-Gesellschaft, responsible for research and transfer. He is former director of the Fraunhofer Institute for Laser Technology ILT, a world-leading institute for the development of laser technology and applications, and former program director at Lawrence Livermore National Laboratory. Tünnermann is director of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF (Fraunhofer IOF). The institute is acclaimed for its high-end optics R&D and high-power fiber laser systems.

Haefner and Tünnermann shared their insights with *Photonics Spectra* contributing editor Andreas Thoss.

Lasers playing a pivotal role in IFE and magnetic fusion energy

Thoss: As a leading expert in IFE and head of the German Expert Commission on IFE, can you share your insights on the current state of the field?

Haefner: IFE holds incredible promise for the future of energy production, a real transformative shift in power generation. With fusion energy, the cost of energy will be mostly determined by the cost of a power plant and its operations, while the fuel is cheap and abundant. The achievement of igniting a self-sustaining burning plasma at the National Ignition Facility in December 2022 marked a groundbreaking milestone, sparking excitement across the global scientific community. The National Ignition Facility — the only fusion ignition-capable infrastructure worldwide — has since repeated this experiment numerous times, consistently improving yield and energy gain, demonstrating a robust physics platform, and deepening our understanding of the fusion process. This success provides a first step on the long journey toward harnessing the immense energy produced by fusion, potentially offering a clean energy source.

Fusion ignition also initiated a global competition among nations. Beyond its green energy character, countries recognize that fusion can unlock market opportunities for technologies and redefine energy security and energy sovereignty for societies.

For Germany, fusion energy represents a unique opportunity to lead in the fusion landscape, particularly for its robust high-precision laser and optics industry. Many optical and laser components deployed in inertial confinement fusion/IFE research facilities today were produced or invented in Germany, and its industry is well positioned to furnish a significant part of the supply chain for a fusion demonstrator. Lasers also play a role in reactor designs, including those for magnetic fusion energy. Lasers and optical technologies provide important plasma diagnostic capabilities; laser-based processes enhance surface properties of fusion materials, improving resistance to erosion and damage or providing specific functions. Techniques such as laser welding and cutting enable the precise assembly of reactor components, while laser-based additive manufacturing allows for the creation of complex geometries, including the use of advanced materials.

Thoss: You recently joined the board of Fraunhofer and are responsible for research and technology transfer for the entire Fraunhofer society. What are the greatest challenges in bringing fusion to the grid? And what role will Fraunhofer play here?

Haefner: The leap from fusion experiments to commercially viable power plants demands significant breakthroughs in technological developments. Many are needed, from efficient, industrial-grade high-energy lasers to robust optics that survive the harsh conditions close to a fusion reactor, to closing the fuel cycle and harvesting the energy from the fusion reactions. The world is far from being able to build a power plant tomorrow, and this includes all technological approaches; many needed technologies and supply chains are at the conceptual level at best.

The mission of Germany's Fusion 2040 program is to develop these technologies, and Fraunhofer is integral to this effort. Our focus on applied research aims to close critical gaps while facilitating technology transfer to cultivate a competent and competitive industry. Fraunhofer is poised to establish robust supply chains for the high-quality components and materials that are vital for fusion reactors, leveraging our extensive competencies across 75 institutes and our strong network in industry.

The largest challenge toward realizing fusion energy is to get going, close science gaps, and build a robust supply chain. If the world is to achieve its first fusion power plant by 2050, we must advance R&D in parallel and foster international collaboration. This approach presents several challenges, such as the need to strategically align our efforts, prioritize low-risk approaches while phasing out less promising alternatives, focus our investments wisely, and establish international open research infrastructures for testing physics, innovative ideas, and components.

A significant gap in R&D exists in the moderate-scale demonstration of fuel breeding blankets, coupled with efficient tritium extraction while simultaneously generating energy for thermoelectric conversion. This shortfall poses a critical challenge for advancing fusion technology, as there is currently no testing facility worldwide — referred to as a volumetric neutron source — that can facilitate this essential research. This is just one example, but many other modern technologies have undergone similar challenges, and I am positive that these will be resolved with increasing speed.

Last, we must establish a collaborative [intellectual property] strategy among all contributors that effectively protects and leverages innovations for a strong return on investment. This strategy should also guarantee that all participants have equitable access to licensing opportunities, allowing them to benefit from the resulting innovations and providing collective impact for driving the advancement of fusion energy.

Thoss: Your Memorandum of IFE (2023) called for establishing an innovation ecosystem in fusion energy and provided recommendations for actions. How far have we come toward those achievements — and what effect will fusion energy have for Germany?

Haefner: Germany has made tremendous strides in advancing its fusion energy initiatives, establishing a comprehensive fusion strategy through the IFE Memorandum in 2022 and launching the public-private partnership program Fusion 2040 in 2023. The first call of Fusion 2040 was oversubscribed by 3×, highlighting the enormous interest from industry and its eagerness to invest in maintaining and enhancing its competitive edge in the fusion technology sector. In addition, Germany's Federal Agency for Disruptive Innovation (SPRIND) invested approximately $100 million in technology procurement and development to support its startups. And several State governments have launched supporting programs, ranging from substantial investments into education and training of next-generation talent, funding some experimental infrastructure, to supporting their startups with seed funding.

Germany has also launched a project aimed at evaluating and developing recommendations for a comprehensive regulatory framework for fusion research, ensuring a conducive environment for innovation and safety. This is of utmost importance to reassure industry in clear and sustained rules for engaging in fusion technology development and encouraging international investors in actively participating in building our fusion ecosystem. By its prompt actions, its competence and capabilities in plasma physics, tokamak and stellarator technologies, fuel cycle and materials science, and the swift launch of the Fusion 2040 program, the German government has propelled the country to the forefront of global fusion energy initiatives. These efforts not only position Germany as a leader in the development of sustainable energy solutions but also attract significant interest and investment from both domestic and international stakeholders.

Pushing optical frontiers for fusion

As director of the Fraunhofer IOF in Jena, Germany, Tünnermann holds a critical position, spearheading development of

the optical components and systems upon which laser fusion will depend. Funded by the German BMBF, the teams at Fraunhofer IOF work on several projects with partners from research institutes and industry to develop the necessary manufacturing technologies and components.

Tünnermann discusses Germany's optical heritage, the role of Fraunhofer in building a fusion ecosystem — and why working on fusion is like making shovels for a gold rush. The journey is uncertain, but the tools created will have a far-reaching influence.

Thoss: What do you think when you hear the term "laser fusion"?

Tünnermann: Big challenge, big chances. The promise of clean energy generation is one of the rare cases where the work of physicists makes it to the evening news. So, we have a chance to tell people what science can do to save our planet. That is really unique.

On the other hand, we have to explain how long it will take to fulfill such a promise. Laser fusion research has made exciting progress in recent years, but we are currently facing a typical research problem: An experiment that has worked well a few times in the lab is not a technical solution ready for continuous operation 24/7. It takes a lot of work by scientists, engineers, and many other experts to build a power plant that has never been built before.

Thoss: What is your part in making laser fusion happen?

Tünnermann: There is just one place in the world where laser fusion was successfully executed — the National Ignition Facility in California. That was a huge achievement, but it was made at a dedicated research facility. I think most experts agree that a fusion power plant that operates around the clock places much higher requirements on its optics.

This is a huge challenge that we are picking up. Here at Fraunhofer IOF, teams have been gathering know-how for decades to develop optical components, systems, and processes for 24/7 operation in industrial facilities. And this is what we bring in to develop optical components and processes for laser fusion. With the Fusion 2040 program from the German government, we are receiving funding for a number of projects to develop components and processes for future fusion systems.

Thoss: Can you provide some examples of what you are working on?

Tünnermann: One example is laser mirrors. You know, modern optics has long had a home here in Jena. The first dielectric antireflection coatings were introduced here by Schott almost 100 years ago. Even if optics is supposedly an old technology, there are always new, surprising challenges. This also applies to mirrors. Extreme-ultraviolet mirrors are a prominent example. But even seemingly simple laser mirrors are still challenging.

We are now working on the Scalable Highpower Reflectors for Petawatts (SHARP) project, which is funded by the German BMBF. Together with seven industrial partners and two other research institutes, we aim to develop a new generation of highly reflective laser mirrors that will meet the extreme requirements of future petawatt laser fusion reactors.

Thoss: How far will you go in this project?

Tünnermann: The project team is made up of various champions along the value chain, so we will investigate the scientific and technical fundamentals to develop novel manufacturing technologies for super-polished, curved, large-area optics, and move forward, step by step, along the precision optics value chain. It all starts with the substrate material and the manufacturing process. An important topic is a defect-free substrate surface. We are developing polishing process technologies minimizing subsurface defects, which have been identified to be critical concerning the laser damage. Optics for high average-power lasers will need cooling, so we must find solutions for thermal stabilization and active cooling, novel integrated cooling structures in glass substrates, and to balance thermomechanical effects.

This is a huge effort. In the end, we will be developing an entirely new generation of optics that can withstand the enormous loads over an extended period of time. Just imagine what it takes, going from one shot per day up to 15 shots per second.

Thoss: Isn't coatings considered a separate topic?

Tünnermann: Yes and no. Coatings are part of the system, so we have to think about it together with the project partners. But we also have a separate project where we are working on completely new coatings based on a combination of antireflective coatings and nanostructures. It is called nanoAR and we are one of nine collaborating partners working on this idea.

We are pursuing two different approaches here. One relies on nanostructured or nanoporous antireflective coatings based on high-bandgap materials to provide the required laser damage threshold. Another approach is to directly nanostructure the optical surface. There will be no coating, just nanostructures.

Thoss: It is obvious that such technologies have more potential than fusion. What do you have in mind?

Tünnermann: The general idea behind these projects is actually quite compelling: Take some excellent players in the field, let them work on a challenging technology for a distant project, and let them profit from the new technology right after the project finishes. It is a bit like making the shovels for a gold rush; we do not know yet who will benefit from fusion energy and when — but making better optics will have an immediate impact on many industries.

First and foremost, laser materials processing could benefit. We see an insatiable appetite for more power, leading to a steady demand for ever better optical coatings. In particular, the advent of ultrashort-pulse lasers will benefit from these coatings.

Other benefited areas could be laser systems for which maintenance is difficult, such as space applications or, again, extreme-ultraviolet generation. The combination of advanced substrates and more durable coatings could be attractive for this multibillion-dollar market.

th@thoss-media.de

A researcher holds a highly reflective mirror for laser applications. The technology is to be optimized for laser fusion.

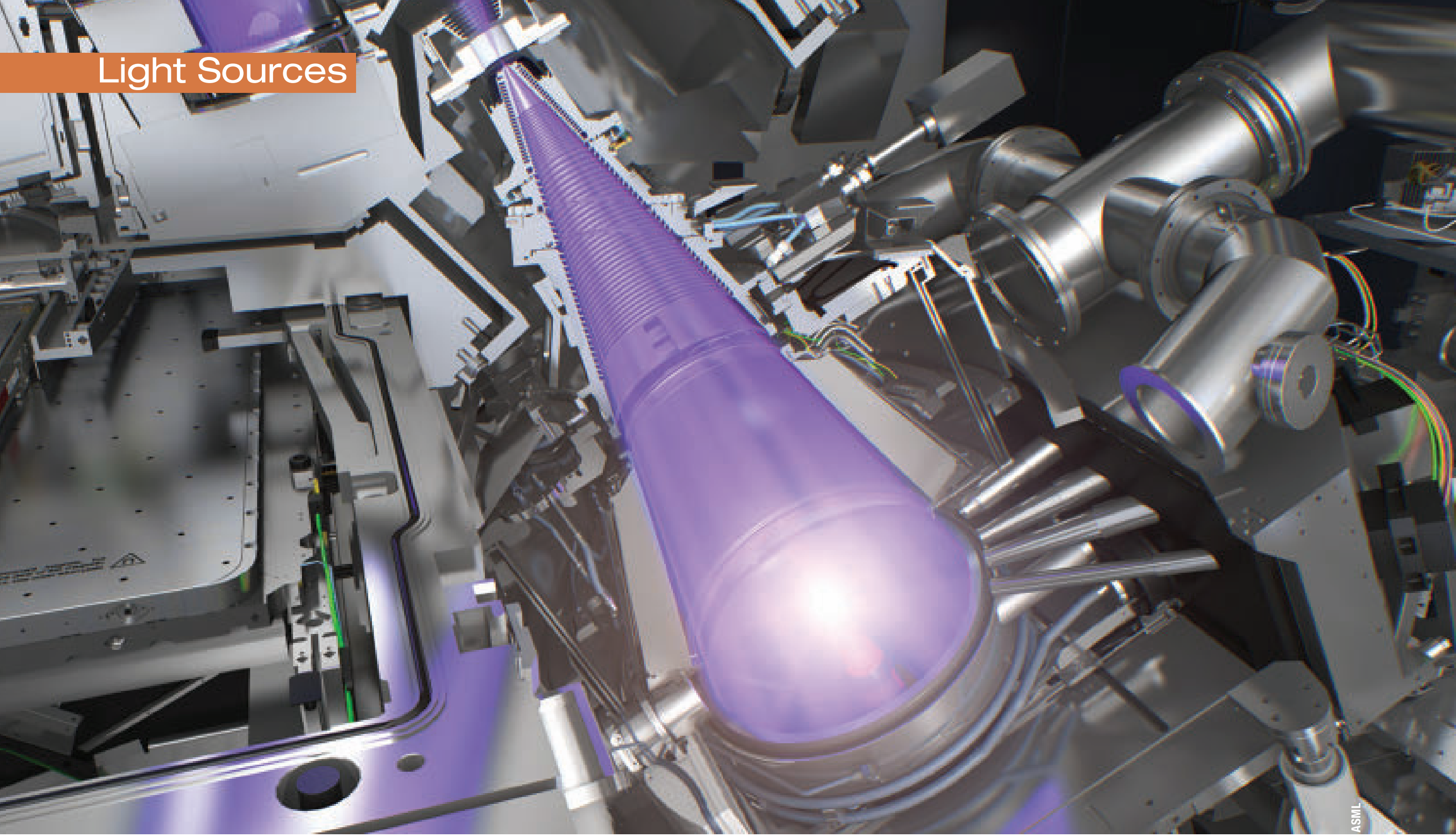
Meet the interviewees

Constantin Haefner has been a member of Fraunhofer's executive board, responsible for research and transfer, since February 2025. After more than 15 years in Silicon Valley, Haefner returned to Germany to take over as director of the Fraunhofer Institute for Laser Technology ILT, one of the world's leading institutes for the development of laser technology for industry, research, space applications, and medicine. Since 2019, he has been a full professor and holds the Chair for Laser Technology LLT in the Faculty of Mechanical Engineering at RWTH Aachen University.

Haefner earned his physics degree from the University of Konstanz in 1999 and his Ph.D. from Heidelberg University in 2003. He has received several awards for his achievements, including OSA (Optica) Fellow (2017), the Federal Laboratory Consortium Tech Transfer Award (2018), and the Fusion Power Associates Leadership Award (2024).

Andreas Tünnermann is a German physicist and university lecturer. From 1992 to 1998, he headed the development department of the Laser Zentrum Hannover and habilitated in 1997. In 1998, Tünnermann accepted a professorship at the Friedrich Schiller University Jena as a professor of applied physics and took over the management of the Institute for Applied Physics. Since 2003, he has also been director of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF in Jena, Germany.

Tünnermann has received numerous awards for outstanding achievements, including the Gottfried Wilhelm Leibniz Prize in 2005, the ERC Advanced Grant by the European Research Council in 2015, and the Cross of the Order of Merit of the Federal Republic of Germany in 2024.



In Semiconductor Manufacturing and Beyond, Extreme-Ultraviolet Extends Its Reach

In enabling users to manipulate materials at the atomic scale, extreme-ultraviolet lithography is paving the way for chip design, metrology, and a range of additional science applications.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

Though the concept of extreme-ultraviolet (EUV) lithography dates to the late 1980s, it is only now, in this contemporary era of semiconductor manufacturing, that EUV sources are firmly in the limelight. The company ASML, whose debut EUV lithography systems released in the 2010s quickly set a benchmark for the industry, is the dominant force in advanced chip fabrication technology. Today, the company stands as the only supplier of EUV lithography machines capable of producing the most advanced chips.

ASML's journey toward dominance in this technology space has not avoided challenges. Geopolitical pressures and export controls, both ever-present and highly consequential, are indicative of the direct link that chipmaking technology has to the economic competitiveness of global powers. Overcoming technical challenges have also shaped ASML's history.

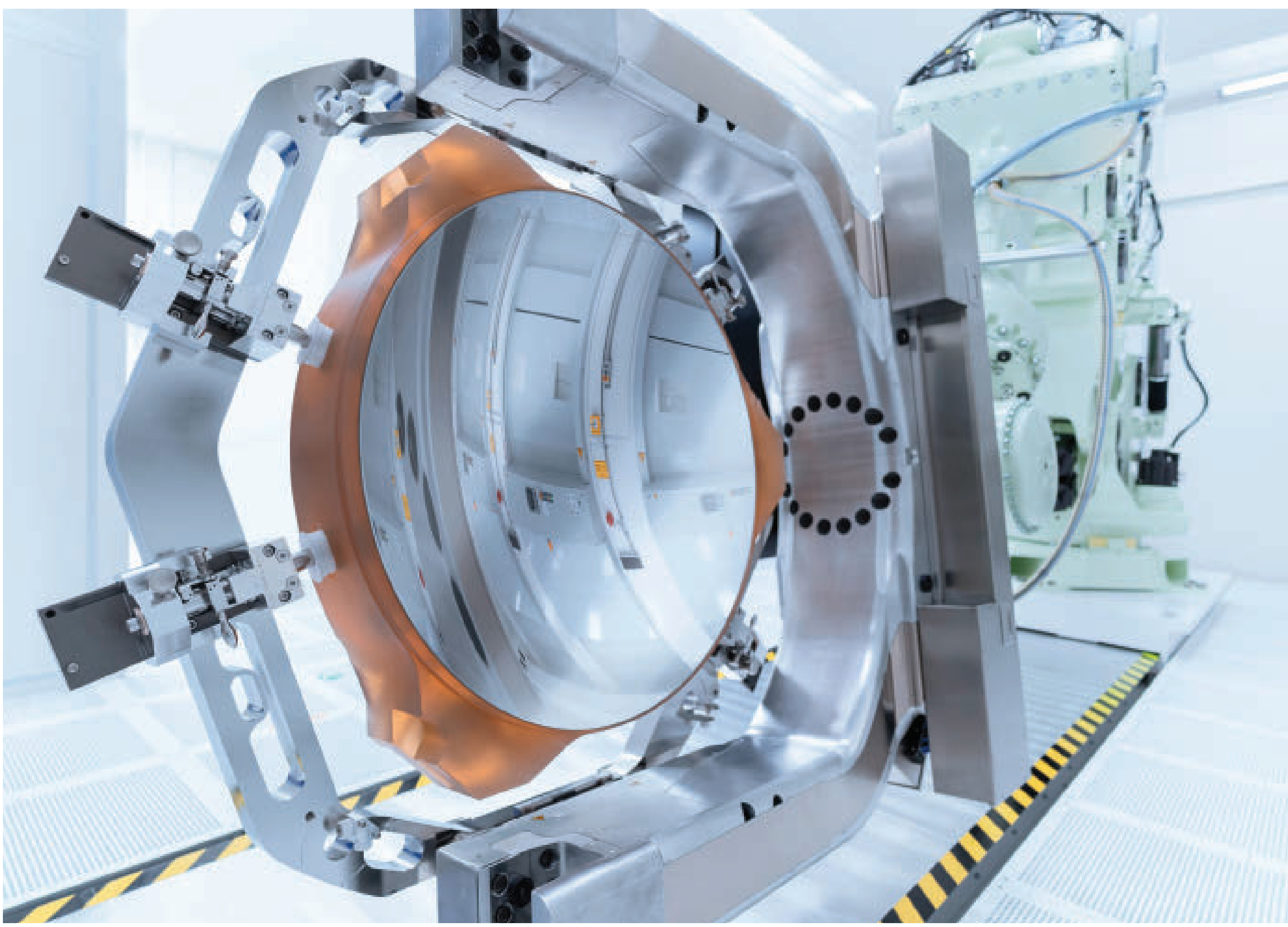
"The evolution [of EUV sources] was the result of targeted research and development. Achieving the required power was the biggest challenge," said Marc Assinck, media relations manager at ASML. "Achieving sufficient power at the EUV wavelength was a requirement by the semiconductor industry to make the tools economically viable."

At the core of this transformative technology is the use of the 13.5-nm wavelength, which enables the precise manipulation of materials at the atomic scale. This level of accuracy is driving the next generation of semiconductor devices.

Further downstream, advancements in EUV metrology are cementing EUV's role in quality control in semiconductor fabrication, enabling users to detect defects at resolutions that were impossible to achieve with conventional techniques.

The power of 13.5 nm

Semiconductor manufacturers have steadily pushed the boundaries of chip design by etching increasingly fine structures onto wafers. While many commercially available microchips rely on wavelengths between 193 and 365 nm, EUV lithography at the 13.5-nm wavelength



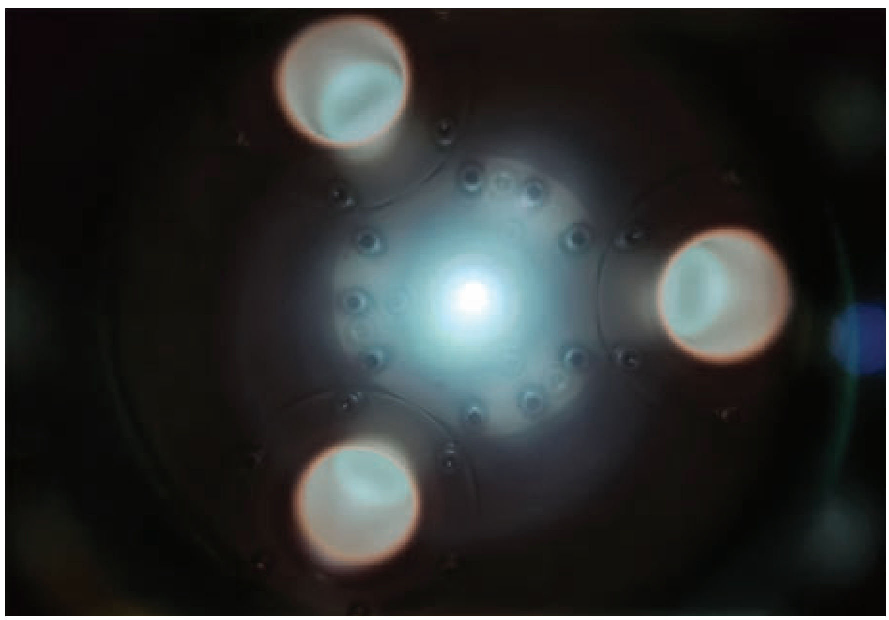
Precise mirrors are installed in the optical systems used for high-numerical aperture (NA) extreme-ultraviolet (EUV) technology.

ZEISS

ASML

A manufactured wafer is exposed in a high-numerical aperture (NA) extreme-ultraviolet (EUV) system (impression) **(left)**.

An electrodeless Z-Pinch discharge plasma source. The bright spot is the 13.5-nm emitting 'pinch.' Three plasma 'return loops' emit brightly in the visible region **(below)**.



Energetiq

enables conductor paths to be manufactured in the nanometer range. This is essential to producing the high-performance chips found in cutting-edge graphics cards and high-end smartphones, driving advancements in speed, efficiency, and functionality.

"EUV has followed a longstanding trend of using shorter and shorter wavelengths for lithography; shorter wavelengths result in higher resolution and smaller feature sizes," said Don McDaniel, vice president and general manager at Energetiq. The company is a developer and manufacturer of broadband and EUV sources, targeting semiconductor metrology applications.

"This increases transistor density and reduces power consumption, both of which are essential for the astounding improvements in computing power and memory density over the past 50 years," McDaniel said.

ASML's status as a technology pioneer in EUV lithography places it at the center of international trade policies. The company has faced mounting restrictions, particularly as the Dutch government, which is under pressure from the U.S. and others, imposed export controls to prevent the shipment of advanced chip-making technology to certain countries. Despite these restrictions, ASML continues to expand its partnerships and technological reach.

The near monopoly on EUV lithography for chip production that ASML holds has not precluded it from close collaboration with industry leaders. ZEISS, which supplies high-precision optics essential for EUV systems, has fostered a strategic partnership with ASML since 1997, according to Jeannine Rapp, head of communications and implementation of group initiatives at ZEISS SMT. "Together, we bear a significant responsibility: The machines we have codeveloped and built hold an 80% market share, and for the EUV systems — and in the future also for the latest high-numerical aperture (NA)-EUV technology — it is 100%," Rapp said.

Pushing the limits of chip design

Widespread adoption of EUV technology in 2019 marked a critical turning point for chip manufacturing and the industries — electronics, photonics, optoelectronics, among others — that enable it. Major semiconductor foundries such as TSMC and Samsung integrated EUV into high-volume production, initiating a shift that triggered massive investments in semiconductor manufacturing. Foundries and equipment suppliers began a shift to ramp up capacity to meet global demand that is still ongoing. Investments continue to reach new high dollar amounts.

With EUV lithography only recently entering high-volume manufacturing, McDaniel believes that the industry is about five years into a technology cycle that is likely to run for 20 years. Industry settled on 13.5 nm as the next key wavelength in chip design more than two decades ago, but it was the physics of the optics that determined the course of lithography rather than the physics of the lasers. The challenge was to find suitable sources at this wavelength where there is no laser line available.

"Every previous reduction in wavelength has been driven by the physics of available sources, particularly lasers," McDaniel said. "Below 193 nm, things significantly change as no transparent materials are available. Instead, optical systems have to use reflective optics, especially multilayer mirrors."

These multilayer mirrors are made from alternating layers of two elements, for which there are limited available choices. In turn, a limited number of wavelengths can make mirrors with sufficient reflectivity.

"The optical systems used in EUV lithography have been designed to operate in a vacuum and utilize mirrors instead of lenses, which are essential due to the absorption of EUV radiation by air and glass. This innovation allows for near-perfect imaging and high precision in chip manufacturing," Rapp said. "The mirrors are crafted with extreme precision, allowing for minimal loss of EUV light."

According to Rapp, this necessary precision is achieved via a complex layering system — creating a Bragg mirror. This element consists of more than 100 atomically precise layers.

The best solution for the source was laser-produced plasma, which was developed to achieve the necessary power and brightness at the crucial 13.5-nm wavelength.

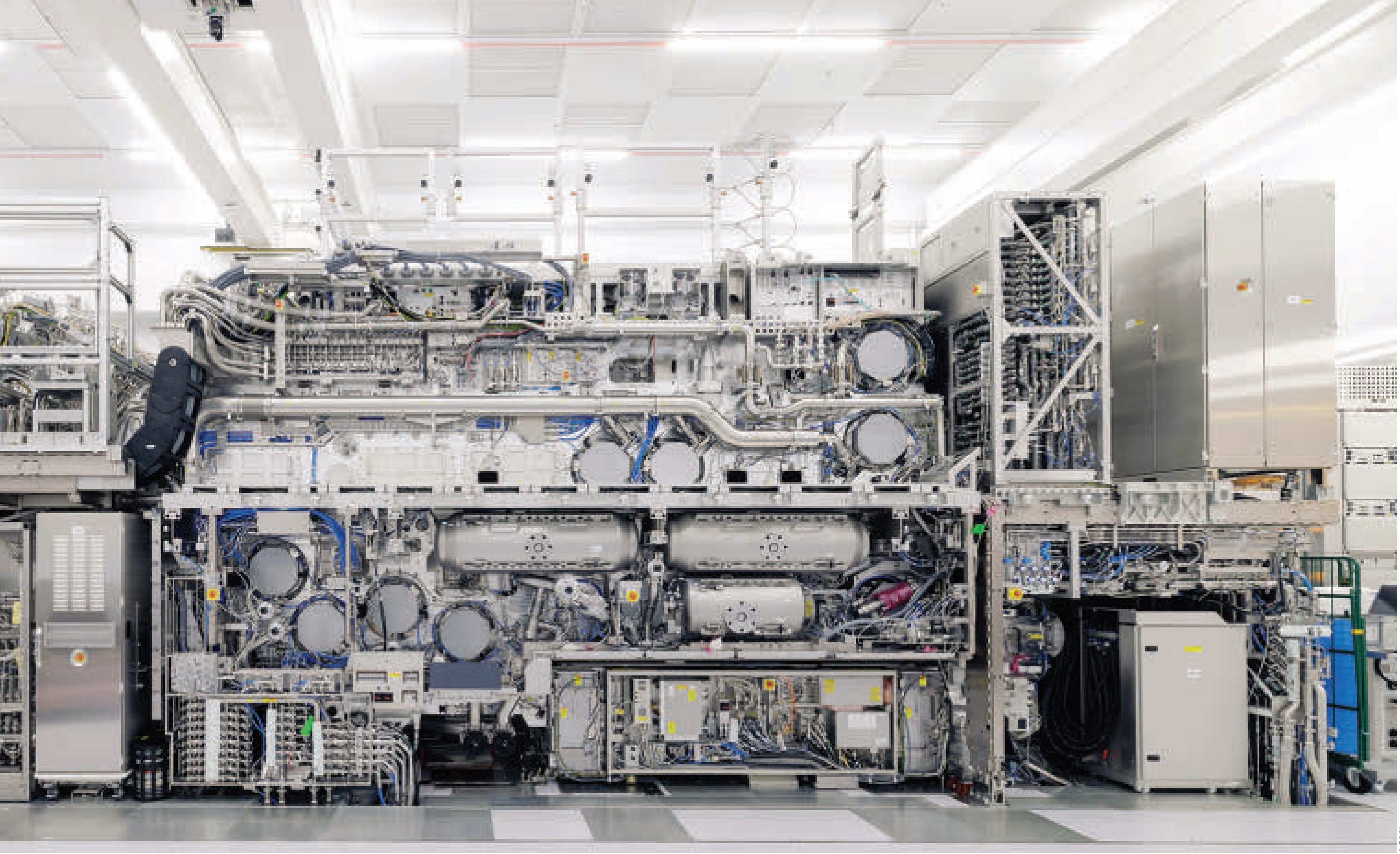
"The development of a unique light source that generates EUV light by creating a plasma from tin droplets has revolutionized the lithography process," said Matthias Wissert, head of the department in development at TRUMPF Lasersystems for Semiconductor Manufacturing. "This source operates at extremely high temperatures and can produce EUV radiation at a rate of 50,000 times per second."

ASML's high-numerical aperture (NA) extreme-ultraviolet (EUV) system represents the chipmaking industry's gateway to the invaluable 13.5-nm wavelength.

McDaniel attributes the race to develop an EUV lithography source to the commercialization of several other source architectures. These include tin sources other than droplet; discharge plasma sources (electrode and electrodeless); hybrid discharge/laser sources; and high-harmonic conversion of pulsed laser sources. "These architectures are now vying for market share with regard to the many inspection metrology needs supporting EUV lithography," McDaniel said.

The EUV metrology challenge

The need to innovate for EUV metrology and defect inspection goes hand-in-hand with the incredible levels of precision that are achieved in advanced chipmaking. Companies such as EUV Tech and Energetiq are leaders in this space. EUV Tech, an EUV metrology tools developer based in California's Bay Area, offers at-wavelength EUV metrology solutions, ensuring that manufacturers can detect defects at the nanoscale. In addition to its EUV sources, Energetiq also provides compact, high-brightness x-ray sources.



ASML

"Chip production as a whole needs a wide variety of metrology tools, and in order to be effective, many of these metrology tools should use the exact same wavelength as used in the lithography tool, providing another important opportunity for EUV sources," said Patrick Naulleau, CEO of EUV Tech.

"Additionally, the requirements for metrology tool light sources are quite different than those for lithography, so different light sources are required."

Mirrors and mask blanks must be inspected for defects "at wavelength" because buried phase defects cannot be detected by any other method. Until it is possible to produce large, defect-free multilayers, these components will require complete inspection. Today's mask blanks are delivered with full defect maps. These maps are used to orient the mask pattern so that the defects are not printed.

Accordingly, McDaniel said, the inspection of patterned masks is becoming an important application for EUV source developers. But other technologies may have a role to play here as well.

"There are a number of competitors to EUV, as [electron beam] and deep-ultraviolet (DUV) technologies are both effective to some degree. All three technologies are likely to gain some traction with cost, relative capability, and throughput, ultimately determining the market share of each," McDaniel said.

The next frontier

ASML's pursuit of industry-best imaging resolution led to the development of what is widely considered the next generation of EUV lithography systems. In collaboration with ZEISS and TRUMPF, ASML shipped the first high-NA EUV system to Intel in December 2023. Series production with an optical resolution of <10 nm (on-chip) will be possible beginning in 2026.

Meanwhile, ASML, ZEISS, and an ecosystem of more than 1200 partners continue to work. So-called hyper-NA is one area currently under study.

To support this, EUV source manufacturers are challenged with increasing EUV power to 2 kW — double the best-known lab performance and ~5× the power in currently deployed scanners. The mask industry is challenged, too; it is tasked with doubling mask size to preserve field size as NA increases. Further improvements in photoresist performance are also in development.

The same core principles that make EUV effective for patterning nanometer-scale features on silicon wafers also lend themselves to a range of nonlithographic applications. Other industries are capitalizing on EUV's high-energy, short-wavelength light for advanced imaging, metrology, materials science, and biomedical research. In advanced materials analysis, for example, EUV-based techniques facilitate nondestructive testing of aerospace and automotive components, revealing structural weaknesses at microscopic levels. EUV-based spectroscopy provides critical insights into material properties, supporting the development of next-generation energy solutions, including more efficient solar cells.

And with the post-COVID-19 era accelerating demand for advanced imaging and diagnostic tools, EUV microscopy provides ultrahigh-resolution images of biological specimens. The approach enables researchers to study viruses, bacteria, and cellular structures with unprecedented clarity. This technology opens doors for breakthroughs in drug discovery, vaccine development, and medical diagnostics.

For McPherson Instruments' Erik Schoeffel, scaling up existing capabilities is much less exciting than discovering new ones. McPherson Instruments develops purpose-built spectroscopy systems as well as components and services for the soft x-ray and vacuum ultraviolet region.

Schoeffel also cites solar — both physics and space weather applications — as an area for which EUV has utility. EUV light derived from novel sources, he said, or test and calibration services requiring EUV light (such as for space projects), belong in a conversation on the prospects for EUV light and EUV sources.

Other applications are already in practice, and potential applications hold significant promise, though challenges remain. The cost of EUV systems is an obvious barrier to increased adoption.

"Typical challenges that are often overlooked with respect to producing commercially viable EUV light sources include thermal and debris management," EUV Tech's Naulleau said. "But as costs come down, it will become viable across a much broader application space."

The need for specialized infrastructure is a further roadblock, as is technical complexity.

"It is important to remember that almost everything absorbs EUV, necessitating vacuum sample handling and beamlines. This introduces a level of complexity and cost that is only overcome by a dramatic performance value proposition," McDaniel said.

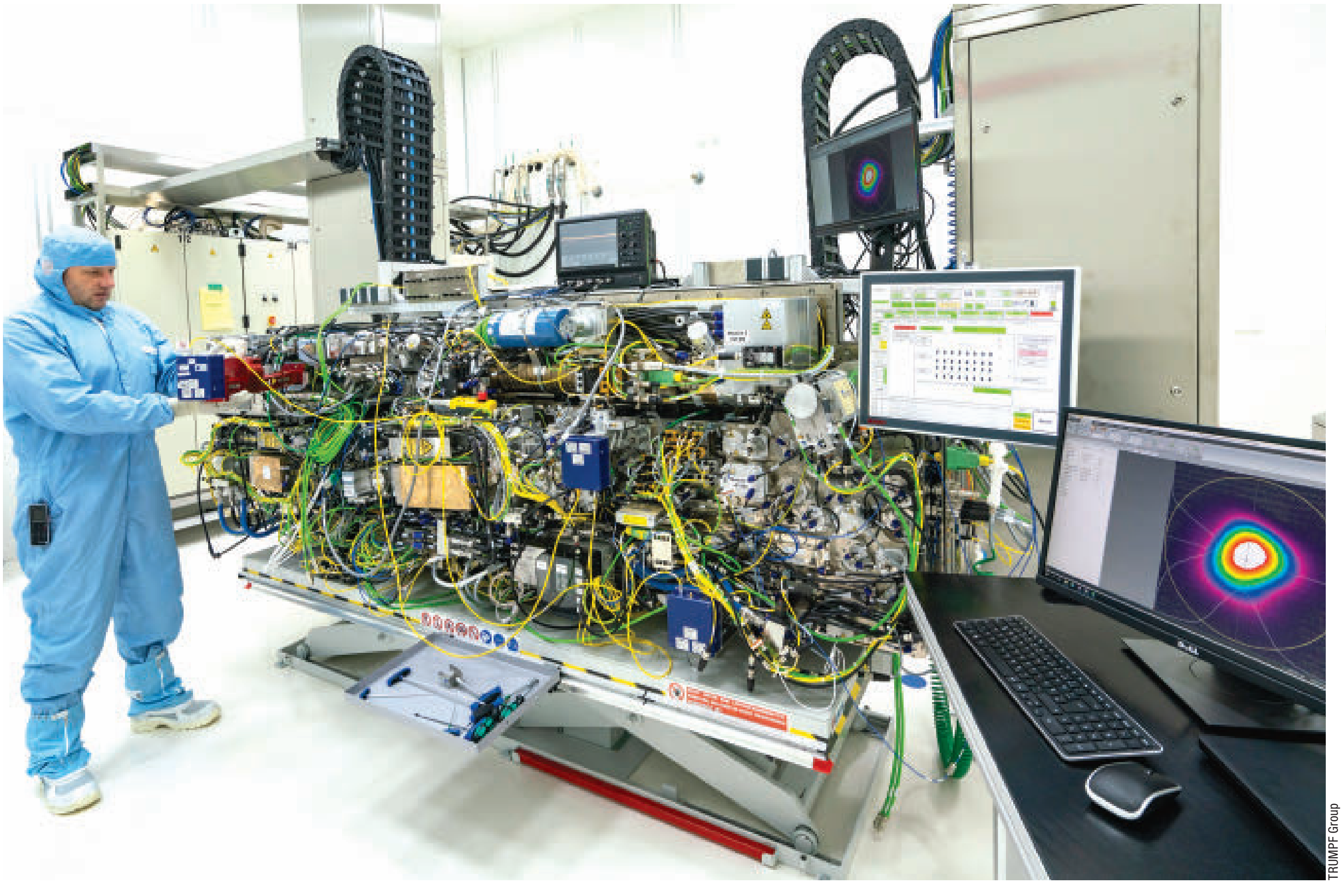
"Consequently, the majority of potential applications outside of semiconductor manufacturing tend to be scientific applications, which have traditionally been performed in national lab facilities using synchrotron sources," he said. "These sources are tremendously flexible but offer limited availability. A few standalone EUV sources have been installed to supplement synchrotrons, but it would be a bit of a stretch to call this a market at this time."

Industry continues to invest despite these barriers to adoption. Though it will not occur immediately, this will result in more efficient EUV sources, improved optics, more effective contamination control, and, ultimately, new applications and markets. For example, according to Schoeffel, reliable 13.5-nm coherent light sources, and the optical systems capable of delivering them, open the door to exploring fundamental high-harmonic laser technology and attosecond and thermonuclear fusion. "Generally, growth in high-harmonic generation lasers, CMOS detectors, and related technologies enable better experiments throughout the EUV region," Schoeffel said. "Some applications are enabled by the advancements such as water window physics and attosecond movies."

As EUV applications expand further into metrology, defect inspection, energy, and biomedical research, industry must continue to innovate to overcome challenges. With ongoing advancements in high-NA EUV and research into novel use cases, EUV sources will undoubtedly play an even greater role in shaping future technology landscapes.

mariefreebody@physics.org

Assembly and commissioning of an extreme-ultraviolet (EUV) system in a cleanroom.



TRUMPF Group

AI Requires More from Moore's Law

BY JOHN T.C. LEE
MKS

As an enabling technology, photonics has always proved to be capable of supporting next-generation solutions. This trend is poised to continue in the current technological environment, in which photonics will enable the improvements in computing power that are necessary to support the ongoing revolution in artificial intelligence.

As evidence for this assertion, it is helpful to review how computing power has advanced since the invention of the microprocessor. Figure 1 illustrates Moore's law, which states that the number of transistors on a microchip doubles about every two years. The figure includes data from 1970 to the present and projects potential future trends through 2040.

Starting around 1970, manufacturers steadily increased processor performance by leveraging Dennard scaling, also called MOSFET scaling. According to this principle, as transistors shrink, their power density remains constant because their voltage and current scale down proportionally. As a result, processors could be made smaller and faster without excessive power consumption or overheating.

Dennard scaling served as a viable principle for manufacturers until around 2005. It ultimately broke because the leakage current does not scale down with size, which leads to heat dissipation issues. Simply increasing clock speed (frequency) was no longer a way to improve the performance of single-core processors or central processing units (CPUs).

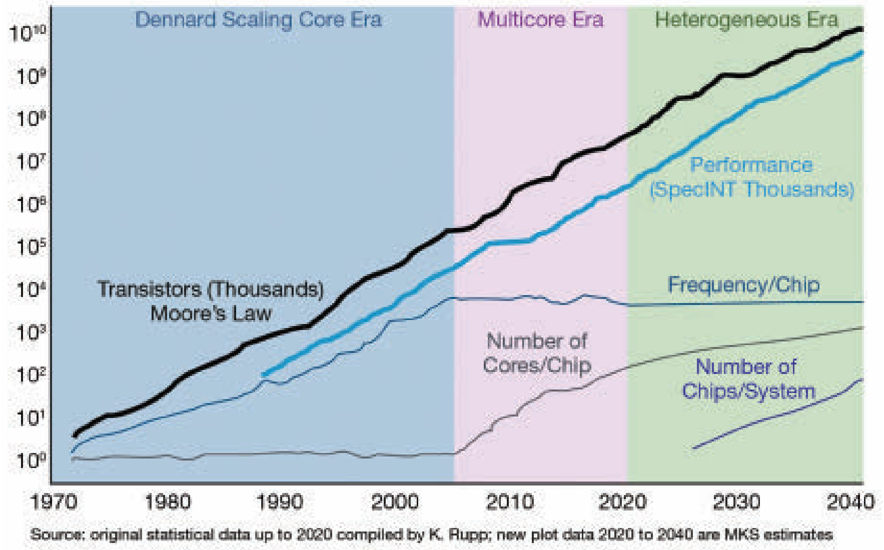
Next, manufacturers turned to multicore architectures. Instead of making a single core faster, they integrated multiple cores on a single chip, allowing workloads to be distributed across them. This increased overall processing power while keeping both power consumption and heat dissipation within manageable limits.

The multicore approach was effective for about 15 years. But power consumption still increased as more cores were added. Again, thermal and power dissipation constraints became limiting factors, preventing further performance scaling using multicore CPUs alone.

Heterogeneous packaging is the next technological evolution that has been introduced to overcome this limitation. This concept integrates multiple specialized chips into a single package in a way that allows them to act like a single chip. Heterogeneous packaging enables continued performance gains for the overall package despite the slowdown of traditional transistor scaling.

This key innovation is often referred to as More than Moore, and it is helping to maintain the trajectory originally predicted by Moore's law.

Figure 1. The chart shows historic trends in microprocessor transistor density, performance, and architecture from 1970 to the present, and projected through 2040.



Heterogeneous computing: The benefits

The move to heterogeneous computing is especially crucial for AI applications because they benefit significantly from parallel processing. As a result, an AI package might integrate CPUs, graphics processing units (GPUs), and multiple high-speed memory chips to boost overall performance.

However, heterogeneous computing is only beneficial if all the integrated circuits in a package function essentially as a single chip.

Figure 2 shows a typical heterogeneous

 All images courtesy of MKS.

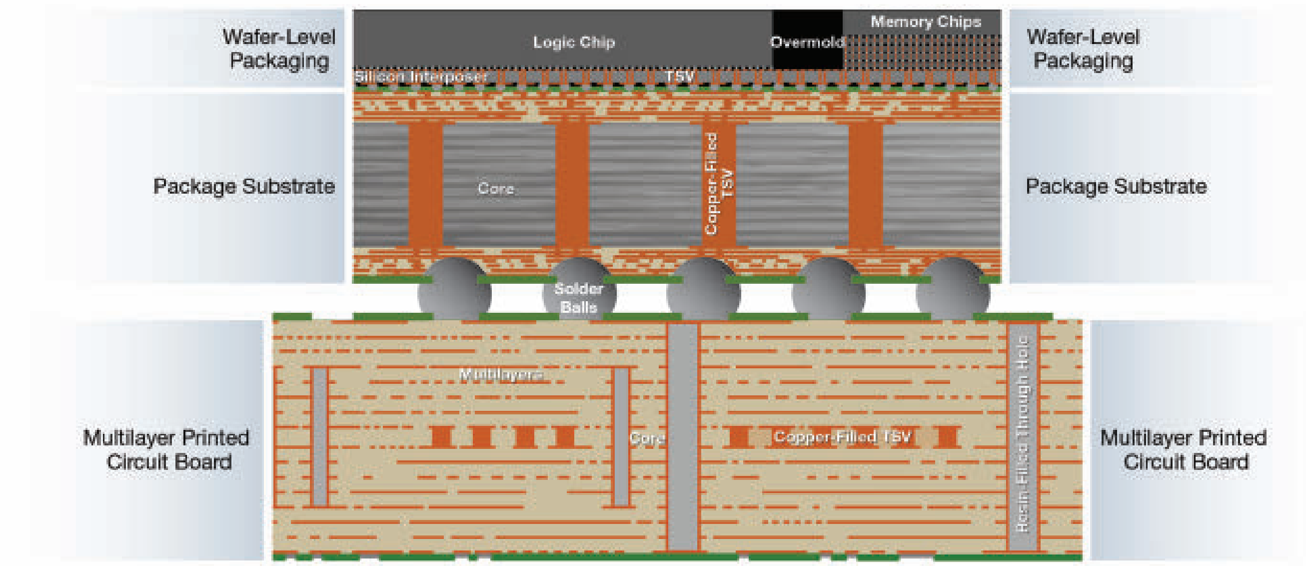


Figure 2. A simplified schematic of the cross section of advanced packages typical of AI applications. TSV: through-silicon via.

package configuration, such as one that might be used for AI. A logic chip(s), such as a CPU(s) or GPU(s), is at the top, along with a high-bandwidth memory module. The high-bandwidth module consists of multiple stacked dynamic random-access memory dies, connected vertically using copper-filled through-silicon vias to enable high-speed, low-power memory access. All of these components are electrically connected through a silicon interposer.

This entire assembly is mounted on a package substrate — a high-density interconnect structure that serves as the bridge between the chips and the multilayer printed circuit board (PCB). Unlike traditional PCBs, package substrates are specifically engineered for the fine-pitch, high-performance interconnects required in advanced semiconductor packaging. Several package substrates can be placed on a multilayer PCB and interconnected to behave as one chip.

By physically bringing these components closer together, heterogeneous packaging reduces latency, improves power efficiency, and enhances scalability. Additionally, the large number of interconnects used in advanced packaging is key to its performance.

Photonics keys heterogeneous packaging

A major challenge in manufacturing advanced packages is forming all of the necessary vias (holes) that connect each of the individual layers. This must be accomplished with increasingly challenging positional accuracy, hole shape quality, and at market-enabling speeds.

Photonics and laser drilling provide the best solution to many of the most demanding interconnect fabrication issues. Laser drilling is not new. For example, Electro Scientific Industries Inc., which MKS acquired in 2019, has supplied laser drilling systems to the electronics industry for more than 40 years. Still, steady increases in speed, accuracy, and hole quality have been necessary to keep pace with the demands for advanced packaging applications. The earliest via drilling systems simply moved the part relative to the laser beam using stepper motors. This allowed for speeds of ~100 holes/s. The next evolution was to add galvanometer scanners in combination with stage motion. This brought speeds up to ~1000 holes/s. But that value, too, was not fast enough for current advanced packaging production lines.

While photonics plays a critical role in achieving the precision and quality required for advanced semiconductor manufacturing, it does not operate in isolation.

To meet the needs of the highest throughput applications, MKS added an acousto-optic deflector into the system. The acousto-optic deflector element makes small, highly precise beam deflections at high speeds to improve both throughput and accuracy. The advanced packaging systems that use this technology can achieve drilling speeds of >10,000 holes/s.

Another important technology for advanced packaging production is precision motion. Typically, this involves high-precision positioning of components or test probes, often guided by machine vision, to accurately place and align them during assembly and testing.

Newport Corporation, which MKS acquired in 2016, is a leader in this area and continues to innovate in precision motion. Again, the present technology environment necessitates continuous improvements to the speed, accuracy, and stability of motion systems to support the most demanding advanced packaging production applications.

Accelerating the road map

Photonics will continue to drive innovation in semiconductor manufacturing — not only as a stand-alone technology but as an integral part of a broader, more interconnected ecosystem. By addressing markets for wafer fabrication equipment, package substrates, and PCB manufacturing, MKS aims to continue expanding its capabilities to ensure that as the industry evolves, the company is positioned to help shape its future.

Individual capabilities are key to meeting this goal; these include laser development and manufacturing as well as the supply of precision motion equipment.

However, this only addresses some reaches of the value chain. MKS acquired Atotech, a specialist in chemistry plating solutions, in 2022. The company supplies advanced plating equipment for the PCB industry and associated chemistry.

While photonics plays a critical role in achieving the precision and quality required for advanced semiconductor manufacturing, it does not operate in isolation. Broader technological capabilities such as via plating chemistry and equipment enable the development of solutions with greater efficiency, ultimately helping customers to achieve a faster time-to-market.

john.tc.lee@mks.com


Berthold Leibinger Foundation

Leibinger Awards 2025:

A Celebration of Laser Science and Time Itself

Precision meets purpose in the global photonics community during the Berthold Leibinger Awards ceremony. Breakthroughs spanning quantum clocks and ultrafast laser applications are honored.

BY ANDREAS THOSS
CONTRIBUTING EDITOR

On June 20, just days before the LASER World of PHOTONICS show opens its doors in Munich, the global laser community will gather once again in Ditzingen, Germany, for one of the most prestigious events in the field: the Berthold Leibinger Awards ceremony. Every other year on the grounds of TRUMPF headquarters, Nobel laureates, laser industry leaders, and pioneering scientists convene in a celebration of both applied innovation and fundamental research in laser technology.

The Leibinger Awards, presented by the Berthold Leibinger Stiftung, honor outstanding achievements with the Innovationspreis (Innovation Award) and the Zukunftspreis (Future Award). This year, the Berthold Leibinger Zukunftspreis was awarded to professor Jun Ye of JILA, the National Institute of Standards and Technology, and the University of Colorado Boulder for his revolutionary work in optical clocks. Three other teams will be recognized with the Berthold Leibinger Innovationspreis for innovations in laser applications.

Where precision meets purpose

If the idea of a clock that will remain within 1-s accuracy in the entire 13.8-billion-year lifespan of the universe sounds like science fiction, Ye is here to prove otherwise. His work on optical clocks pushes the boundaries of precision metrology to previously unimaginable levels of accuracy.

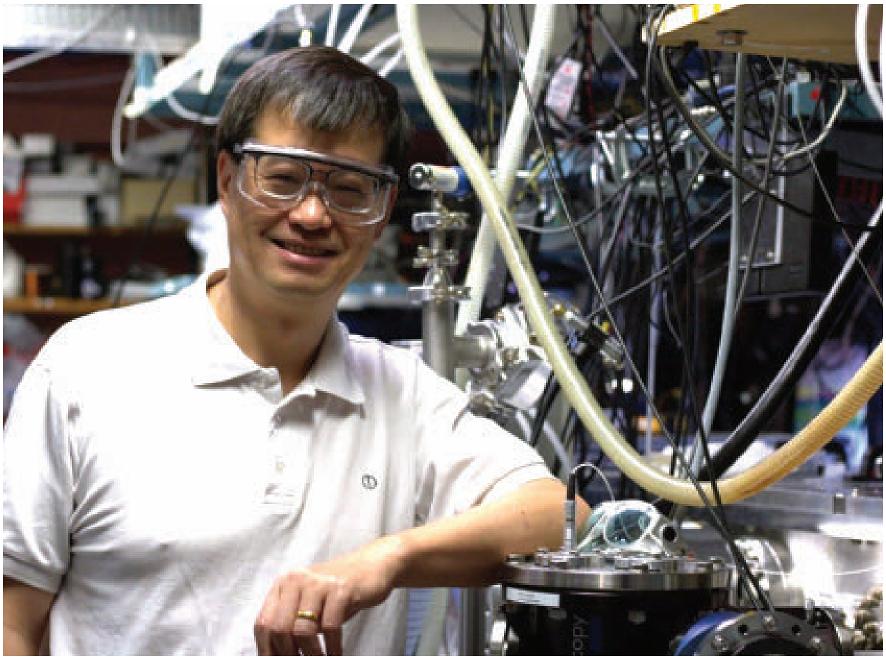
Traditional atomic clocks use transitions in atoms' electron shells. By stabilizing laser light to these transitions, Ye's team built clocks with a precision of 10^{-18}. But the team went further. It introduced transitions within the atomic nucleus itself — which "tick" even more precisely.

"Such an honor clearly reflects the scientific spirit of all the amazing people I have had the privilege of working with over the years," Ye said, reflecting on the collaborative nature of his lab at JILA. Ye's work not only enables more accurate GPS systems and time stamping for the internet, but also provides a foundation for new tools to test fundamental physics. Ultraprecise clocks can detect minute variations in gravity and search for potential interactions with dark matter.

Ye is part of a celebrated group of previous Zukunftspreis recipients, including Anne L'Huillier and Gérard Mourou, who received the Nobel Prize not long after they were honored in Ditzingen. The Zukunftspreis underscores the Leibinger Stiftung's commitment to advancing basic research with real-world implications.

The spirit of technology transfer

The Innovationspreis, established in 2000 by Berthold Leibinger, celebrates the successful transfer of laser research into



JILA

The winner of the 2025 Berthold Leibinger Zukunftspreis, professor Jun Ye, uses complex laser systems to measure time with ultraprecision.

practical applications. This year's eight finalist teams were selected from more than two dozen entries. Projects span a remarkable range of topics and technology readiness levels, reflecting both the breadth and dynamism of the field.

Three winners will be announced and honored in Ditzingen. Among the finalists is a team from Carl Zeiss Meditec. Its work on SMILE, a femtosecond laser-based procedure for minimally invasive eye surgery, has restored vision for millions. A team from 4JET Microtech uses laser-textured surfaces mimicking shark skin to reduce aerodynamic drag and CO_2 emissions. A third project applies laser-driven radiation sources to the inspection of nuclear waste containers — an application derived from fusion technology.

"The projects presented by all finalists were absolutely fascinating," said jury member Martin van den Brink, former president and CTO of ASML. Beyond exceptional engineering, the Innovationspreis often highlights paths to market that require exceptional persistence and creativity.

A family legacy of photonics

The Leibinger awards reflect the enduring influence of Leibinger, who transformed TRUMPF from a Swabian machine tool builder into a global technology leader. As a passionate advocate for the interplay between science and industry, he strongly believed in the importance of rewarding scientific curiosity alongside technical application.

Since his death in 2018, the foundation has been led by his children, Nicola Leibinger-Kammüller, CEO of TRUMPF, and Peter Leibinger, who chairs the company's supervisory board. Peter Leibinger will once again host the ceremony. This year's keynote will be delivered by James Kafka, president of Optica.

A night for the global laser community

The ceremony in Ditzingen has become more than a prize event — it is a forum for global exchange. With up to 600 attendees, including scientific luminaries, industry executives, and representatives from leading institutions, the evening is a celebration of shared enthusiasm for laser science and technology.

As in previous years, attendance is by invitation only, and the list fills quickly. Those interested in attending can apply via the foundation's website, www.leibinger-stiftung.de. Submissions for the next round of the Innovationspreis open on June 20, 2025, and will be accepted through Sept. 1, 2026.

Whether in the lab probing the nature of time or in factories optimizing laser processes for industry, the Berthold Leibinger Awards shine a light on the people and ideas driving photonics.

th@thoss-media.de

With Ongoing Advancements, Ultrafast Laser Technology Is Breaking Boundaries

BY ANTONIO CASTELO
EUROPEAN PHOTONICS INDUSTRY CONSORTIUM (EPIC)

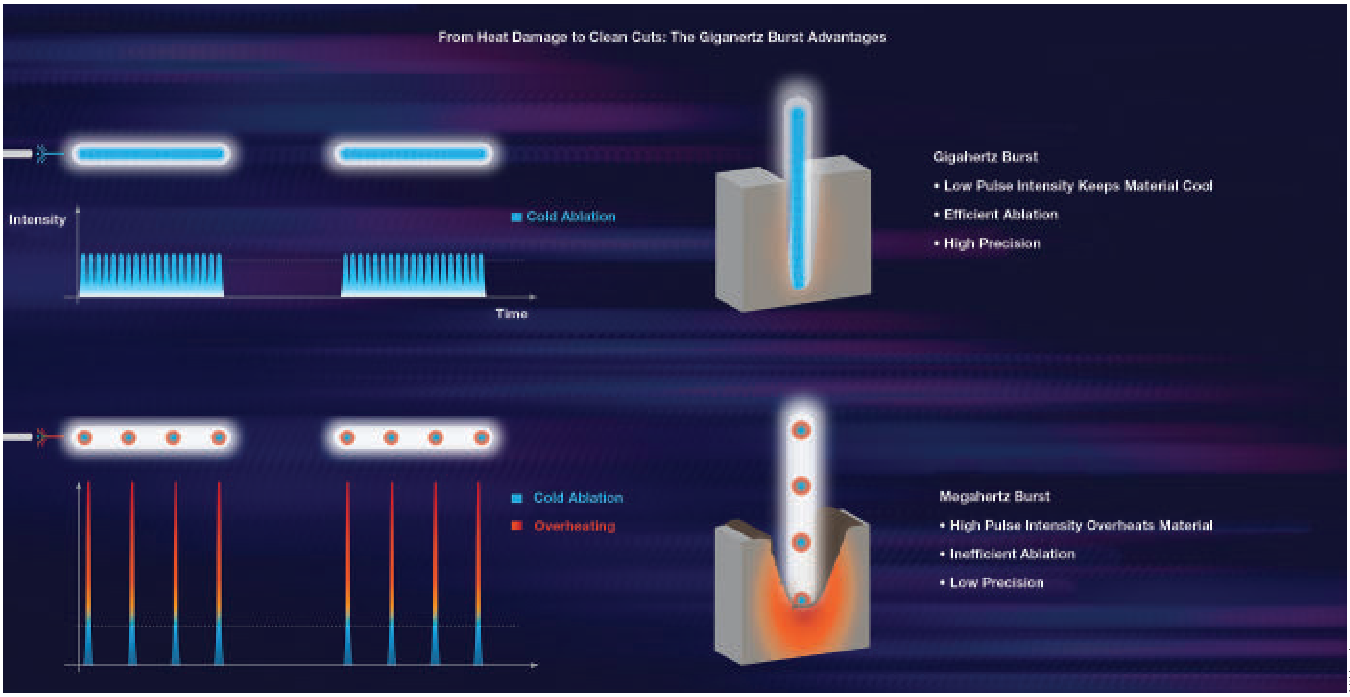
The market for ultrafast lasers has experienced significant, sustained growth in recent years. Buoyed by the strong adoption of these lasers for materials processing, medical diagnostics, bio-imaging, telecommunications, defense, and security, experts expect the market to continue to expand as demand increases for precision solutions.

Other developments, meanwhile, have advanced the performance of the laser sources. The possibility of manufacturing increasingly compact and reliable ultrafast lasers, in particular, has a direct tie to more accessible and versatile technologies, creating new opportunities for industry.

According to recent estimates, the global ultrafast laser market is forecasted to grow at a compound annual growth rate of roughly 10% to 15% during the next few years. Following the Ultrafast Lasers Market Analysis: Industry Growth & Forecast 2023-2033 by Future Market Insights Inc., the global ultrafast lasers market size was valued at $1.5 billion in 2023 and is projected to reach $3.8 billion by 2033.

Analysts have identified some hinderances to future growth, including adoption and integration costs, plus the related need for user-specialized expertise as well as the potential for market fragmen-

Figure 1. Application advantages of gigahertz burst(s) versus megahertz burst(s): Unlike conventional megahertz lasers, which deliver pulses at lower repetition rates and can lead to excessive heat accumulation, Lithium Lasers' technology emits a sequence of femtosecond pulses within a gigahertz burst. The gigahertz-burst technology minimizes thermal damage and enhances ablation efficiency, while allowing for precise control over thermal load.



Lithium Lasers

tation. But they have also signaled some compelling opportunities and trends. These include the manufacture of specific components, the miniaturization of ultrafast lasers (for integration into compact devices), the exploration of new materials to expand the range of applications, and progress in beam shaping and control technologies to further enhance precision.

Spotlight on applications

High-accuracy processing operations such as micromachining and surface treatment/functionalization currently make up one of the largest fields of application for ultrafast lasers. Especially in high-growth sectors, including automotive, semiconductor, consumer electronics, and consumer goods, these processes must be performed repeatedly at high levels of accuracy. In response, manufacturers continue to pioneer exciting developments both in sources and components to improve performance on microprocessing tasks. Many of the latest developments are now pushing the boundaries of precision and versatility across a range of applications.

Of course, improving the power, stability, and tunability of ultrafast lasers is critical to obtain higher energy pulses while maintaining exceptional temporal precision. Burst-mode techniques, for example, offer flexibility in pulse duration and timing, allowing users to harness laser energy in the most efficient way possible and adapt the laser parameters to the specific characteristics of a given task[1]. As it translates into application, developing commercial solutions with different emission wavelengths could unlock opportunities to use cutting-edge ultrafast sources to process new and alternative materials — a trend that is commonly cited in market reports. These trends are active alongside enhanced capabilities in beam shaping, which, as mentioned, is ensuring improved accuracy and faster processing times for a range of demanding functions, such as precision cutting, drilling, micromachining, and ablation. In the automotive and semiconductor industries, for example, these high-precision tasks are necessary to ensure accurate microstructures.

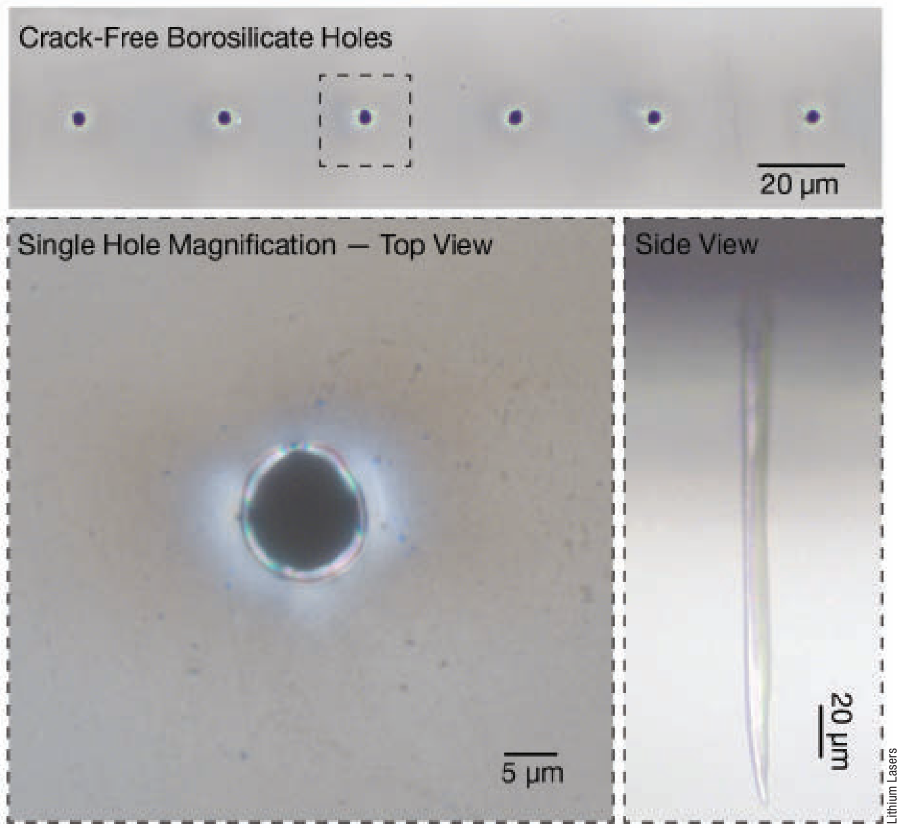


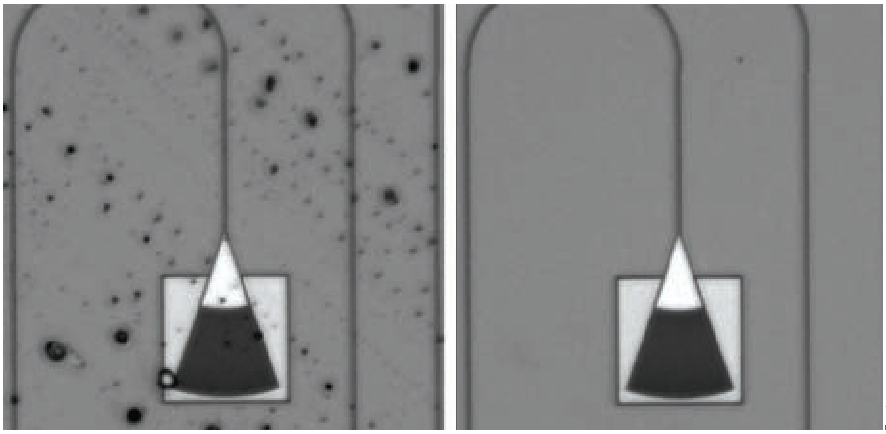
Figure 2. Lithium Lasers' ultrafast technology, enabling an end user to realize holes in a glass material.

Pulse trains for materials processing

The ability to produce fine features in materials such as ceramics, polymers, and glasses has enabled new applications in industries with critical requirements and regulations, such as the aerospace and medical fields. The versatility of current ultrafast laser technology also extends to modifying surface properties, functionalizing them and even enabling advanced 3D-printing techniques.

This growing area of application stems from improvements that address the low speeds at which ultrafast lasers can process materials — a common limitation to the use of these lasers in industry. The first attempts to solve this bottleneck focused on using more powerful lasers to increase the ablation rate. These trials showed certain unwanted effects, such as shielding, saturation, and collateral damage stemming from the heat accumulation.

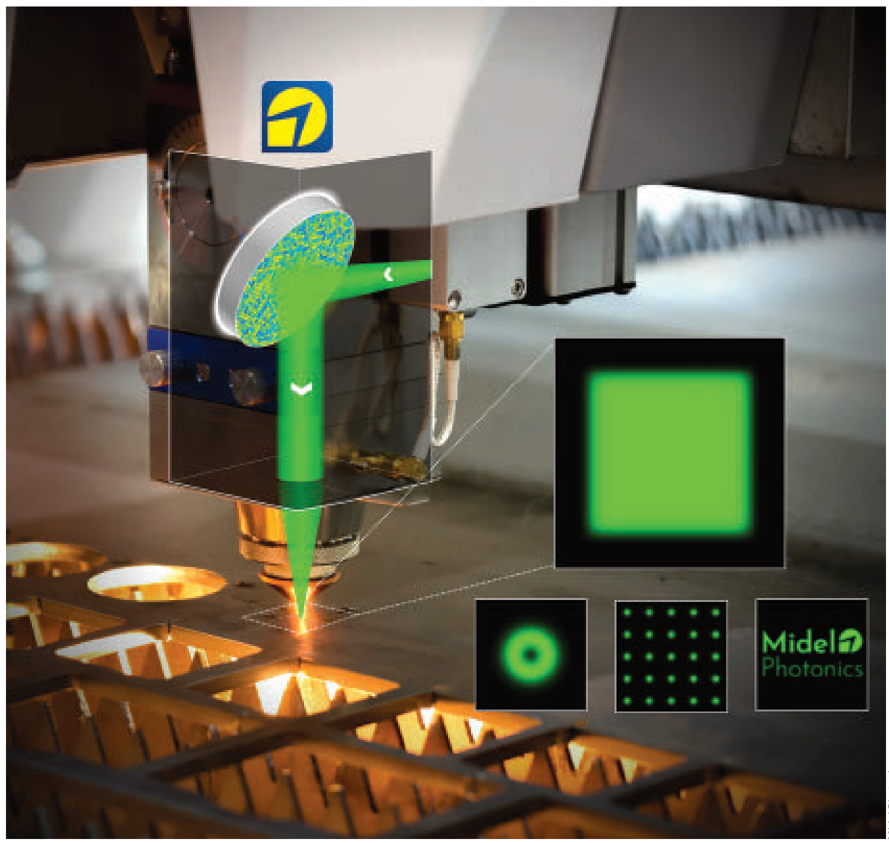
Laser technology developers have explored the use of successions of laser pulses (bursts) in recent years to overcome these effects. The goal is to process the target material before the residual heat deposited by previous pulses diffuses from the processing region. This technique can reduce the laser pulse energies



Femtum

Figure 3. Dry laser cleaning, a critical application for the semiconductor industry, shown via a laser emitting at 2.8 µm **(left)**. An example of selective residue removal in a grating coupler before cleaning **(far left)**, compared with after the cleaning.

Figure 4. Midel Photonics' reflective beam-shaping technology for ultrafast lasers offers a potential solution for processes in semiconductor manufacturing, high-speed lithography, and precision cutting and/or welding **(below)**. Ultrashort-pulse integrity across all wavelengths is enabled by dispersion-free beam control, without chromatic dispersion and nonlinear effects.



Midel Photonics

needed and increase the efficiency of the process without any thermal damage to the material.

The company Lithium Lasers is active in this area — namely, with its FEMTOFLASH source, which uses gigahertz-burst technology. With average powers up to 20 W at 1030 nm and 6 W at 515 nm, this femtosecond laser offers burst energies of up to 1 mJ at 1030 nm and 0.3 mJ at 515 nm.

Unlike conventional megahertz lasers, which deliver pulses at lower repetition rates and can generate excessive heat accumulation, FEMTOFLASH emits a sequence of finely controlled femtosecond pulses within a gigahertz burst (Figure 1). This ensures highly efficient energy deposition, where each pulse vaporizes the material before significant heat diffusion occurs. As a result, the gigahertz-burst technology minimizes thermal damage, enhancing ablation efficiency and allowing for precise control of the thermal load.

Lithium Lasers' source also offers high flexibility in pulse control, with an adjustable number of pulses per burst (from 25 to >1000). Configurable burst repetition rates optimize processing speeds and thermal dynamics, as well as arbitrary energy distribution of the individual pulses within a burst. These combined qualities serve to further refine material interaction. This level of overall control and performance makes the source ideal for applications in semiconductor manufacturing, printed circuit board processing, and advanced micromachining of glass and metal materials (Figure 2).

New wavelengths

Ultrafast lasers emitting at different wavelengths in the IR have garnered significant interest in recent years due to their distinctive properties and use potential for advanced materials processing applications. These lasers provide necessary specifications to achieve highly precise and controlled material interactions.

The 3-µm wavelength is particularly advantageous: It lies within an optimal absorption range for many materials, including polymers and glasses, and it also falls within the transparency range for most of the semiconductors. It therefore enables efficient cutting, drilling, and micromachining processes with minimal thermal damage and reduced heat-affected zones.

Femtum, a Canadian developer and manufacturer of mid-infrared (MIR) pulsed fiber lasers, has attracted widespread interest for its exploration of uses for its ultrafast 3-µm pulsed fiber laser. Supercontinuum generation, femtochemistry, and silicon photonics are some of the applications that the company has evaluated with this source.

But Femtum's MIR lasers can also emit short nanosecond pulses, and the company recently presented a use case for the semiconductor industry, in which the MIR source enables a dry laser cleaning solution (Figure 3). This approach aims to establish an alternative to manual cleaning for eliminating the dust particles and organic residues of different sizes generated during the manufacture of microelectronic and/or optical circuits. Current cleaning methods, such as brushing or ultrasonic baths, may not always remove all residues, leading to quality assurance inspection rejections. Moreover, these manual processes increase the risk of wafer or die damage and result in efficiency losses. Femtum's pulsed lasers, with emission at 2.8 µm, enable selective removal of organic residues while ensuring preservation of the substrate.

Further, the possibility to integrate the solution into existing assembly and test machines allows for the reduction of both manipulation and part handling to minimize rejections at mid- and late-stage production stages.

RayVen Laser, a Ruhr University Bochum spinout, is also active in the development of ultrafast lasers with new IR wavelengths. The company has detected a gap of sources between 1 and 3 µm for advanced materials processing. To bridge it, RayVen developed high-power ultrafast laser systems with emissions at 2 µm. In this region of the spectrum, the energy of the laser is efficiently absorbed and less affected by scattering in certain materials.

RayVen's lasers provide high repetition rates, high energy, and exceptional stability in two main configurations: the model RayVen-S, tailored for 1-W average power at a 50 to 70 MHz repetition rate, with 120-fs pulse durations across wavelengths from 2090 to 2120 nm; and the model RayVen-L, which is tailored for high-energy tasks. The RayVen-L delivers 10 W of average power and up to 1 mJ of pulse energy with 800-fs pulse durations. With its technology, RayVen aims to support the next-generation of semiconductor processing, including silicon modification, defect-free structuring, and laser-assisted bonding and debonding. Each of these process steps can be essential to the development of AI accelerators and photonic chips.

Reflective beam shaping

Ultrafast laser beam shaping refers to the process of manipulating the spatial and/or temporal properties of an ultrafast laser beam to achieve a desired intensity distribution or focus pattern. This is particularly important in materials processing applications, where it is apt to influence precision and control over the laser's interaction with materials. Beam shaping, in any context, is an excellent solution to meet industry's high demands in damage resistance, efficiency, and long-term stability. In laser processes using ultraviolet and deep-ultraviolet wavelengths, beam-shaping considerations often hold the key to tighter feature sizes.

Midel Photonics developed an innovative beam-shaping technology for ultrafast ultraviolet to IR lasers. The company specializes in customized, ultra-precise optics for reflective beam shaping, a technique to modify the spatial profile and characteristics of the beam using reflective optical elements rather than transmissive ones, such as lenses (Figure 4). This approach is especially advantageous in applications in which it is crucial to maintain beam quality, minimize losses, and achieve specific geometries.

Custom beam profiles for multiple distinct laser processes can be obtained using Midel Photonics' technology, and the tailoring of energy distribution could offer a potential solution for processes in semiconductor manufacturing, high-speed lithography, and precision cutting and/or welding.

Midel Photonics' components also exhibit strong damage thresholds and outperform transmissive optics, especially in ultraviolet/deep-ultraviolet applications. The company's use of high-reflectivity coatings makes it possible for the solution components to withstand extreme intensities. Additionally, Midel's approach can ensure dispersion-free beam control, with no chromatic dispersion or nonlinear effects. This quality is crucial to ensure ultrashort-pulse integrity across all wavelengths.

Understanding ultrafast dynamics

Apart from materials processing, research is another important field of growth for ultrafast lasers. One critical topic for researchers is understanding how materials respond to short laser pulses. Such understanding is paramount to improving future solutions and systems and the outcomes that they enable.

Research on ultrafast dynamics in materials has evolved rapidly in the last 5 to 10 years, characterized by breakthroughs in materials science, quantum technologies, and other disciplines. Generally, the goal of these research efforts is to study processes that occur on extremely short timescales. These processes offer insight into controlling the fundamental behavior of electrons, atoms, and molecules, and how the investigated material(s) absorbs, transmits, or heats with these ultrafast pulses.

In photonics R&D, laser-based pump-probe experiments via attosecond magnetic circular dichroism (MCD) detection has emerged as an interesting example of this type of research. These experiments have established this method as a cutting-edge approach to studying ultrafast dynamics in materials, particularly those involving magnetic properties and spin interactions. This method combines the power of attosecond pulses with the sensitivity of MCD, which enables the study of magnetization and spin dynamics on ultrafast timescales.

Applied research in this area has extended to industry. To add spin sensitivity to the conventional laser-based pump-probe experiments, the German company UltraFast Innovations has developed the AURORA XUV phase retarder. This solution is geared to be joined with ultrafast high-harmonic extreme-ultraviolet (EUV) sources, and will function as a quarter waveplate to turn linearly polarized EUV light into circularly polarized light without introducing noticeable dispersion. The phase retarder achieves close-to-circular polarization of $P_c = 0.75$ and obtains >25% transmission around 66-eV photon energy, where the Ni M2/M3 edge is located. A broad spectral range from 40 to 85 eV is supported to cover the M2/M3 edge of the transition metals iron, cobalt, and nickel.

The retarder uses a transmission-optimized, four-mirror grazing incidence reflection geometry that induces a quarter wave phase offset between the *s*- and *p*-polarization components of a linearly polarized input EUV beam. A clear aperture of 3 mm allows the low divergent EUV light to pass through without clipping. These characteristics make the solution an ideal component for attosecond applications.

antonio.castelo@epic-photonics.com

Reference

1. A. Žemaitis et al. (2025). The ultrafast burst laser ablation of metals: speed and quality come together. *Opt Laser Technol*, Vol. 180, 111458.

The 2025 *Vision Spectra* Conference Spotlights Innovation Across Machine Vision

Tracks cover AI, robotics, 3D imaging, cameras, sensors, hyperspectral and SWIR imaging, optics, and illumination.

A series of must-see webcasts on topics ranging from sensors to vision-guided robotics will headline the fifth annual *Vision Spectra* Conference (VSC). Taking place July 15 to 17, the virtual event features six technology tracks for end users and systems integrators, from industry titans to up-and-coming startups.

Attendees can expect more than 30 presentations in the following tracks: Optics, Filters, and Illumination; Hyperspectral and SWIR Imaging; Cameras, Systems, and Sensors; Vision-Guided Robotics and Logistics; Deep Learning, AI, and Inspection; and 3D Imaging.

VSC 2025 will also feature three keynote speeches from experts in the field. Mathew Pelletier from the U.S. Department of Agriculture will discuss the path to commercializing the Plastic Inspection, Detection, and Ejection system (PIDES) and how it evolved through AI. Vision Markets' Ronald Mueller will present on the value of compression in vision applications, and Yole Group will deliver a market analysis of the industry.

The Optics, Filters, and Illumination track will include presentations from Toshiba Teli, CCS, Midwest Optical, and Smart Vision Lights on topics ranging from capturing micro-defects to machine vision lighting. Hamamatsu, an addition to the track for 2025, will present "Translating Infrared Component Performance into Detection and Imaging success."

Within the Vision-Guided Robotics and Logistics track, discussions will include a presentation from FANUC America on "Robotic Systems in Logistics."

In this year's Camera, Systems, and Sensors technology track, companies such as Balluff, Ansys, and LUCID Vision Labs will return to examine IO-Links, RGB-IR sensor exporters, and 10-GigE cameras. Additionally, newcomers such as Northrop Grumman, Pleora, and Teledyne FLIR OEM will cover CMOS sensors, boosting bandwidth, and automatic emergency braking.

The 3D Imaging track is returning this year. Optical Metrology Solutions will cover "Advancements in Methods for 3D Vision Inspection." The Machine Vision Source and the National Chung-Shan Institute of Science and Technology in Taiwan will share advice on practical machine vision as well as hybrid dual-fisheye and depth cameras.

In the conference's largest section — Hyperspectral and SWIR — Léa Butruille from Headwall Photonics will present a talk on "Multi-Camera Acquisition." Specim's Mathieu Marmion, Edmund Optics' Christopher Razze, and HySpex's Trond Løke, among others, will also discuss topics within the track, including nondestructive coating inspection, SWIR imaging lenses, and hyperspectral processing in UAVs.

Lastly, the Deep Learning, AI, and Inspection track will focus on topics such as creating platforms for AI and shop floor autonomy. Matthias Kerschhaggl from EVK will speak on "Quantitative Chemical Imaging: How to Bring Your Lab Analysis to the Production Line," along with MVTec's Thomas Binder, who

Register today at
www.photonics.com/vsc2025.

will present “Bin Picking with a Combination of Deep Learning and Rules-Based Algorithms.”

Register now

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Presentations will include:

Translating Infrared Component Performance into Detection and Imaging Success
Albert Tu and Gary Spingarn, Hamamatsu

Ruggedized Lens & Camera Selection
Ethan Ide, Kowa American Corp.

Photonics Wireless CMOS Image Sensors
James Pan, Northrop Grumman

Open-Source Resources for Hyperspectral Imaging
Yingyun Liu, Brimrose Technology Corp.

Practical Machine Vision — System Integration that Drives Application Success
David Dechow, The Machine Vision Source

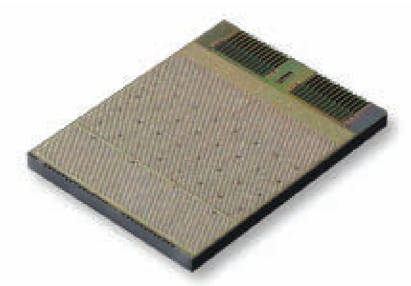
Semiautomated Training of AI Vision Models
Mathew Pelletier, USDA

Quantitative Chemical Imaging: How to Bring Your Lab Analysis to the Production Line
Matthias Kerschhaggl, EVK

Real-Time Video Applications for Snapshot HIS with NVIDIA Edge Computing
Nikhil Jawade, Living Optics

Hybrid Dual-Fisheye and Depth Cameras for 3D Camera System
Yung-Hsiang Chen, NCSIST

Saving Lives with Pedestrian Automatic Emergency Braking Driven by Sensor Performance
Mike Walters, Teledyne FLIR OEM

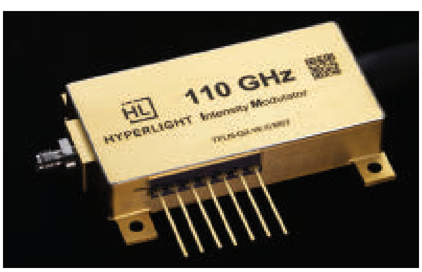


Optical Chiplet

The TeraPHY from **Ayar Labs** is an optical interconnect chiplet designed for AI infrastructure. Capable of achieving 8 Tbps bandwidth, the chiplet is powered by the company's 16-wavelength SuperNovalight source.
info@ayarlabs.com

Photometric Detector

The VL-3708 from **Gigahertz-Optik** is a class L photometric detector for illuminance measurements such as pulsed light measurements. The detector can be used in combination with the company's filter radiometer/photometer or amplifier and features low-end sensitivity of 0.5 nA/lx, a response time of 2 µs, and the ability to make low-level light measurements as low as 2 mlx.
info-us@gigahertz-optik.com



Intensity Modulator

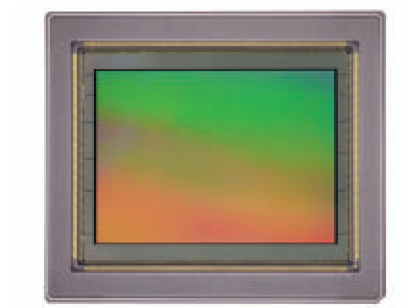
HyperLight's 110-GHz low half-wave voltage ($V\pi$) intensity modulator can be used for electro-optic modulation capabilities in applications including 400-Gbps-per-lane testing, 100 GHz+ photodiode calibration, and high-frequency radio-over-fiber systems. Using the company's TFLN (thin-film lithium niobate) Chiplet platform, the modulator achieves a $V\pi$ of just 1.4 V with bandwidth performance >110 GHz as well as a wavelength coverage across optical O-, C-, and L-bands.
sales@hyperlightcorp.com

Optical Spectrum Analyzer

The WaveAnalyzer 1500B from **Coherent** is a high-resolution optical spectrum analyzer for testing optical transceivers. Able to integrate with existing setups via graphical user interface and a backward-compatible application programming interface, the analyzer features a 180-MHz resolution bandwidth, 10 sweeps/s, and 100-MHz frequency accuracy.
info@coherent.com

Six-Axis Piezo Stage

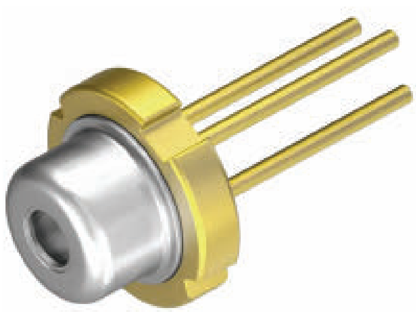
The P-562.6CD from **PI** (**Physik Instrumente**) is a six-axis nanopositioning stage for applications in photonics, semiconductor metrology, super-resolution microscopy, and nanomanufacturing. The operating principle of the stage is based on a parallel-kinematic design with only one moving platform for all six axes and is programmed with the company's E-712 digital servo piezo controller. The P-562.6CD includes interfaces such as Ethernet, USB, SPI, RS-232, and analog, as well as supported functions, including wave generating, data recording, auto zeroing, and trigger input/output.
info@pi-usa.us



BSI CMOS Image Sensor

The GMAX15271 BSI from **Gpixel** is a rolling-shutter CMOS image sensor designed for high-end industrial and scientific applications such as display inspection, semiconductor and printed circuit board defect detection, pathol-

ogy, and genomics, among others. Leveraging 1.5-µm backside-illuminated pixel technology, the sensor supports dual analog-to-digital converter modes, including a 14-bit mode with 0.75 e^- readout noise, a dynamic range of 73.9 dB, a frame rate of 4.8 fps, and a 12-bit mode with a frame rate of 8.5 fps. The GMAX15271BSI also features 2 × 2 binning for both modes as well as both color and monochrome variants packaged in 161-pin ceramic micro pin-grid array packaging.
info@gpixel.com

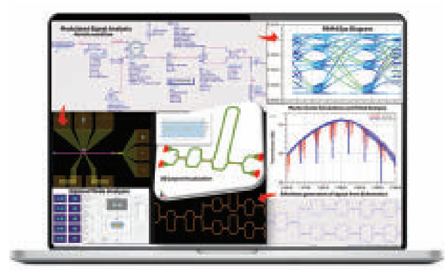


Blue Laser Diode

The PLPT9 450LC_E from **ams OSRAM** is a high-power blue laser diode for applications such as specialty lighting, medical, and industrial. Engineered with a wall-plug efficiency of 43%, the laser diode is available in a TO90 Metal Can package featuring low thermal resistance. The PLPT9 450LC_E can deliver an optical power of 5.5 W at a 455-nm wavelength that includes 2-nm step binning.
sensors@ams.com

3D Laser Profilers

The Gocator 6300 Series from **LMI Technologies** features smart 3D laser line profile sensors designed for use in measurement and inspection applications in manufacturing processes such as semiconductor, electric vehicle battery, and consumer electronics, among others. The profilers deliver a combination of fast scan rates up to >1800-Hz full-frame to meet inline production cycle times, with high x profile data intervals down to <2.1 µm at 13.4-mm field of view. The Gocator 6300 Series also features z-repeatability down to 0.15 µm, a field of view up to 31 mm at <4.3-µm x profile data interval, on-sensor measurement tools, input/output connectivity, and onboard multisensor alignment.
contact@lmi3d.com



Photonic Design Automation Software

The Photonic Designer from **Keysight Technologies** is a photonic design automation software solution for photonic design validation. The software integrates real-world measurement data directly into the simulation workflow and allows engineers to verify designs against industry modulation standards before fabrication with compatibility with foundry process design kits.
usa_orders@keysight.com

Digital LED Control Units

The PD4-A Series from **CCS Inc.** features image processing LED lighting digital control units for machine vision lighting that manage multiple LED lighting arrangements. The series is available in 30-W output with a two-channel model and a four-channel model, as well as a 120-W model with eight channels. The PD4-A Series supports trigger/parallel input signal voltages from 5 V and the products' pulse-width modulation frequency can be set at 500 kHz.
sales@ccs-inc.co.jp

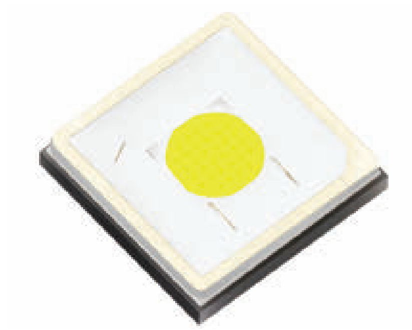
Laser Weld Monitor

The MM-L400A from **AMADA WELD TECH** is a laser weld monitor that provides in situ judgment of weld quality by monitoring workpiece gaps, surface conditions, and focus accuracy. Able to detect IR, reflective, and visible light, the monitor can differentiate between good and

bad welds through a comparison of data and uses the company's MS-Viewer software for interfacing. The MM-L400A's light-receiving unit can be integrated with the company's focusing units or scanner heads and features a compact design and support for high-speed resolution with dedicated sensors.
info@amadaweldtech.com

3D Time-of-Flight Camera

The Helios2 Narrow from LUCID Vision Labs Inc. is a 3D time-of-flight camera for industrial applications. Equipped with Sony's IMX556 DepthSense sensor, the camera generates real-time 3D point cloud data with reduced multipath interference and can deliver precision in limited workspaces due to a 31° × 24° field of view. The Helios2 Narrow is optimized for target distances between 75 and 150 cm and features an IP67-rated design as well as the company's Arena software development kit.
sales@thinklucid.com

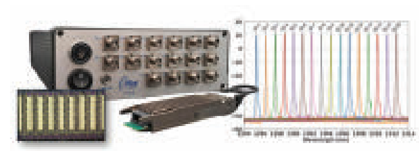


Round LEDs

The SFT-12R (shown) and SFT-25R from **Luminus Devices** are round LED technologies. The LEDs feature round light emitting surfaces in a flat-top package and deliver optical efficiency that requires up to 2.5× less fixture flux compared with conventional LED solutions. The SFT-12R and -25R also feature phosphor-on-chip technology, vertical chip architectures, and a small LED emitter design.
sales@luminus.com

Laser Distance Sensor

The optoNCDT ILR104x series from **Micro-Epsilon** features laser distance sensors designed for distance measurements of 10 m without reflector film and 60 m with reflector film. The ILR104x sensors can be put into operation quickly via the IO-Link interface, and feature linearity ±20 mm, resolution of 1 mm, and resistance to ambient light up to 50,000 lx.
me-usa@micro-epsilon.com



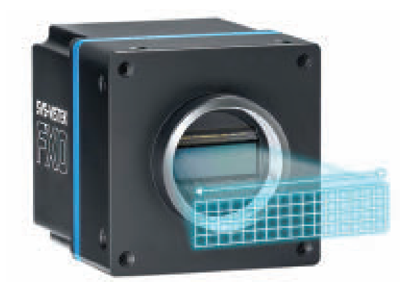
O-Band Laser Products

Pilot Photonics' 16-channel O-band laser array chip and laser instrument are designed to support scalable, parallel optics in data centers and AI systems. The 200-GHz spaced laser products enable prototyping and system development for

continuous-wave wavelength division multiplexing architectures as well as for high-density optical interconnects.
sales@pilotphotonics.com

Spectrophotometer

The Helium 1 µL Spectrophotometer from **DeNovix** is a helium nanovolume spectrophotometer for delivering quantifications of 1-µL nucleic acids and protein samples. The device features a 7-in. HD touchscreen and can rapidly assess double-stranded DNA between 2 ng/µL and 1600 ng/µL double-stranded DNA while also reporting key 260/230 and 260/280 purity ratio results for sample quality control.
info@denovix.com

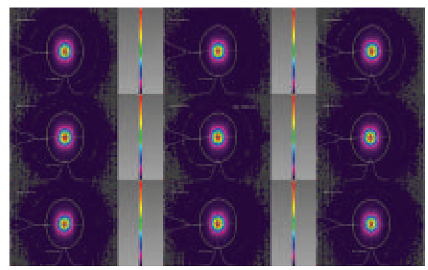


Wide-Angle Camera

The fxo901CXGE from **SVS-Vistek** is a wide-angle 10-GigE color camera for conveyer belt and logistics applications. Built with the Sony IMX901-AQR wide-aspect global shutter 16.4-MP CMOS sensor, the camera captures targets in a wide field of view while maintaining resolutions as high as 8016 × 2048 pixels at 73 fps and a 4:1 horizontal aspect. The fxo901CXGE's 10-GigE interface supports 10 Gbit/s and power over Ethernet over cable lengths of 100 m without repeaters or optical extensions. It features an integrated four-channel LED strobe controller, binning with frame-rate boost, SafeTrigger, programmable logic controller functions, and an IP30 industrial-grade metal housing with an operating temperature range of −10 to 60 °C.
info@svs-vistek.com

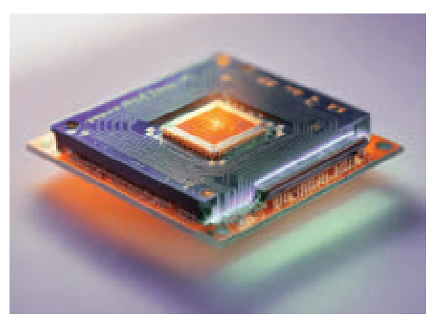
Laser Marking Scan System

The SCANcube IV 7 from **SCANLAB** is a compact scan head for laser marking applications. The scan head has an integrated read-back function for status values and features a 7-mm aperture, write speeds of up to 1840 cps (characters/s), and power compatibility up to 300 W.
info@scanlab.de



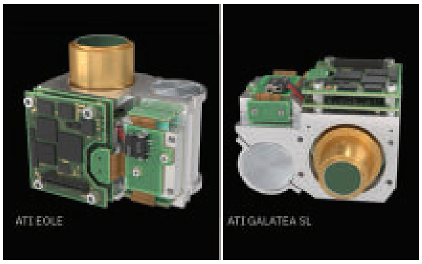
Transceiver Continuous Wave Lasers

HieFo's uncooled O-band continuous wave laser family for silicon photonics transceivers supports the CWDM4 wavelength plan over an operating temperature of −5 to 75 °C, while maintaining 70-mW minimum optical output power. The indium phosphide laser has a 1-mm cavity length that can produce >200-mW typical optical output power while achieving <300-kHz spectral linewidth performance.
info@hiefo.com



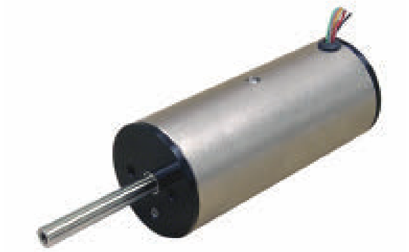
Hybrid Laser Design Module

Epiphany's hybrid laser design module is a plug-and-play solution for developing hybrid lasers for PICs. The module supports a range of wavelengths, power levels, and tunability ranges, and is fully tested and packaged using assembly design kits.
info@epiphany-design.com



Thermal Imaging Modules

The ATI EOLE and ATI GALATEA SL from **Lynred** are advanced thermal imaging modules for integration into infrared sensing vision systems such as gas detection and UAVs, respectively. Both modules come with an additional processing board stacked onto the proximity board, while the ATI EOLE operates in the 3.2- to 3.55-µm spectral band and the ATI GALATEA SL operates in the 3.6- to 4.2-µm spectral band.
info@lynred.com



Linear Servo Actuator

The SDLM-038-070-01-01M from **Moticont** is a linear voice coil actuator for medical, semiconductor handling, assembly, laser machining and drilling, packaging, scanning, laser beam steering, and filtering applications. The actuator uses an internal quadrature encoder for closed servo loop operation with 1.25-µm resolution and high repeatability. The SDLM-038-070-01-01M also features a 38.1-mm diameter, 25.4-mm stroke, 16.8-N continuous force, 52.9-N peak force, and a HOME sensor for initial positioning.
moticont@moticont.com

Modular Bar Lights

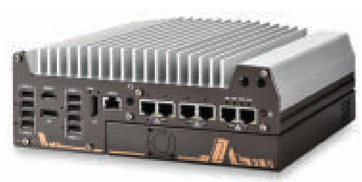
The AL325 Series from **Advanced Illumination** features modular bar lights for machine vision applications. The modular lights are built around field-swappable lenses and light conditioning materials that allow for configuration in the field and include embedded control capabilities for continuous or overdrive strobe operation without external controllers. The AL325 Series can adapt to multiple size requirements, ranging from 150 mm to 2.1 m in length, and comes in 16 different wavelengths. It also provides beam spreads ranging from 10° to 56°.
info@advancedillumination.com

Industrial Microscopes

The ECLIPSE LV100NDA LED, LV100ND LED, and LV100N POL LED from **Nikon** are industrial microscopes that have adopted high color-rendering LED light sources for natural observation. The ECLIPSE LV100NDA LED and LV100ND LED are modular upright microscopes designed for episcopic and diascopic optical contrast techniques. The ECLIPSE LV100N POL LED is specifically designed for polarizing observation, featuring episcopic and diascopic illumination for metal materials analysis.
sales.nm-us@nikon.com

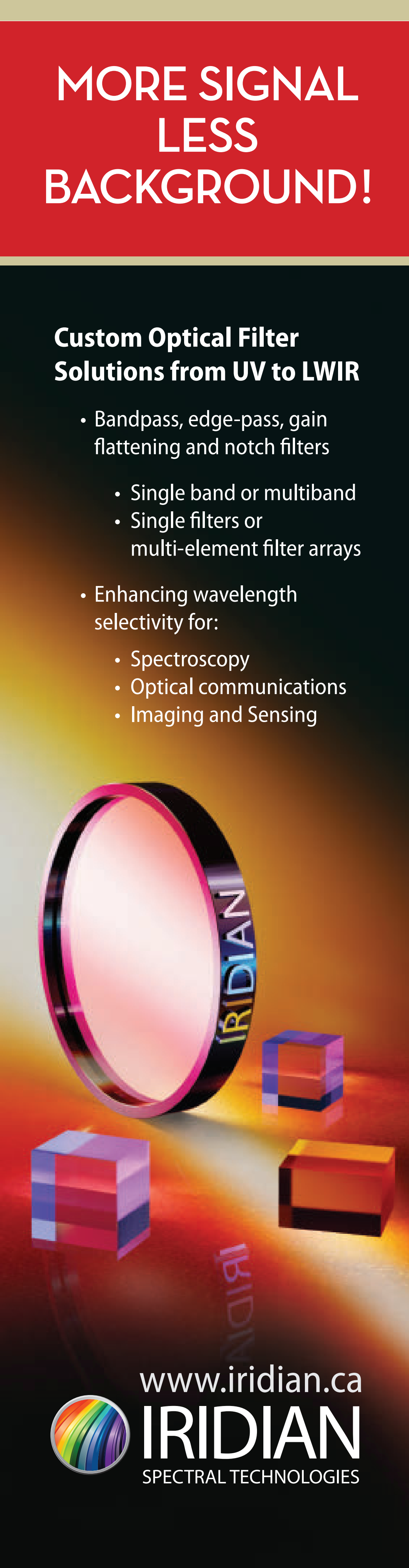
Piezo Objective Positioner

The OP200 from **Queensgate** is a piezo objective positioner designed for applications in the 200-µm range, such as semiconductor inspection, autofocus systems for time-lapse imaging, high-content screening, and surface analysis. The OP200 features a stiffness of 1.3 N/µm, a 20-µm step at sub-8 ms with a 150-g load, and stainless-steel construction.
inquiries@prior.com

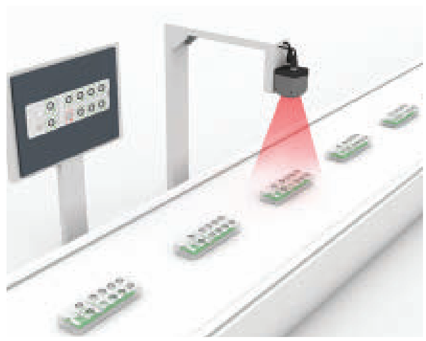


Fanless Embedded Computers

The Nuvo-11000 Series from **Neousys Technologies** features fanless embedded computers for industrial applications. Powered by Intel Core Ultra 200S processors and a built-in AI neural processing unit, the series delivers AI

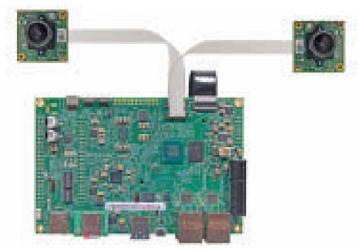


computing capabilities of up to 36 TOPS (tera operations per second) and supports DDR5-6400 memory and PCI express Gen5. The Nuvo-11000 series has a direct current input of 8 to 48 V, three 4K video outputs, and six 2.5 GbE/GbE Ethernet ports with power over Ethernet+ capability. It also achieves read/write speeds of >11,000 MB/s and up to 96 GB of non-ECC DDR5-6400 synchronous DRAM.
sales@neousys-tech.com



Identification and Vision Sensors

Balluff's identification and vision sensors are meant for optical code reading and image processing applications. The identification sensor can read barcodes, 2D codes, and data matrix codes for fast and precise product identification in industrial environments, while the vision sensor supports an edge analysis function and scan trigger mode for continuous image capture. Both sensors feature an L-coded M12 connector and Industrial Internet of Things interfaces.
balluff@balluff.com



AI Vision Cameras

The e-CAM22_CURZH (shown) and e-CAM25_CURZH from **e-con Systems** are AI vision cameras designed for integration into Renesas' RZ/V2N development kit. The e-CAM22_CURZH is a full HD ultralow-light color camera based on Sony's Starvis IMX462 CMOS image sensor that can capture images in the near-infrared. Based on onsemi AR0234CS, the e-CAM25_CURZH is a full HD global shutter camera that minimizes frame-to-frame distortion while imaging fast-moving objects.
sales@e-consystems.com

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(June 10-12) Detroit.
Contact AutoSens, +44 (0)208-133-5116, **info@sense-media.com**; www.auto-sens.com/usa.

Optica Design and Fabrication Congress
(June 15-19) Denver.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/optical_design_and_fabrication_congress.

European Conferences on Biomedical Optics
(June 22-26) Munich.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/topical_meetings/european_conferences_biomedical_optics.

Strategic Materials Conference — SMC 2025
(June 23-25) San Jose, Calif.
Contact Shane Poblete, +1 202-847-5983, **spoblete@semi.org**; www.semi.org/en/connect/events/strategic-materials-conference-smc.

● **Sensors Converge**
(June 24-26) Santa Clara, Calif.
Contact Questex, **info@sensorsconverge.com**; www.sensorsconverge.com.

automatica 2025
(June 24-27) Munich.
Contact Messe München GmbH, +49 89-949-11538, **info@automatica-munich.com**; www.automatica-munich.com/en/trade-fair.

● **LASER World of PHOTONICS Munich**
(June 24-27) Munich.
Contact Messe München GmbH, **info@world-of-photonics.com**; www.world-of-photonics.com/en/trade-fair.

JULY

Optica Advanced Photonics Congress
(July 13-17) Marseille, France.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/advanced_photonics_congress.

Optica Sensing Congress
(July 20-24) Long Beach, Calif.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/optical_sensors_and_sensing_congress.

● **Microscopy & Microanalysis**
(July 27-31) Salt Lake City.
Contact the Microscopy Society of America, +1 703-234-4115, **AssociationManagement@microscopy.org**; www.microscopy.org/events.

AUGUST

● **SPIE Optics + Photonics**
(Aug. 3-7) San Diego.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/optics-and-photonics/attend/invitation.

Optica Nonlinear Optics
(Aug. 4-7) Honolulu, Hawaii.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/topical_meetings/nonlinear_optics.

Optica Imaging Congress
(Aug. 18-21) Seattle.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/imaging_and_applied_optics_congress.

European Optical Society Annual Meeting (EOSAM) 2025
(Aug. 24-28) Delft, Netherlands.
Contact Boglárka Selényi, **eosam@europeanoptics.org**; www.europeanoptics.org/events/eos/eosam2025.html.

SEPTEMBER

FABTECH
(Sept. 8-11) Chicago.
Contact FABTECH, +1 888-394-4362, **information@fabtechexpo.com**; www.fabtechexpo.com.

● **CIOE**
(Sept. 10-12) Shenzhen, China.

PAPERS

Neuroscience 2025
(Nov. 15-19) San Diego.
Deadline: Abstracts, June 4
Contact Society for Neuroscience, +1 202-962-4000, **meetings@sfn.org**; www.sfn.org/meetings/neuroscience-2025.

Frontiers in Optics + Laser Science Conference and Exhibition
(Oct. 26-30) Denver.
Deadline: Abstracts, June 24
Contact Optica, +1 202-416-1907, **info@optica.org**; www.frontiersinoptics.com/home.

SCIX
(Oct. 5-10) Covington, Ky.
Deadline: Poster, June 30
Contact FACSS, +1 856-224-4266, **scix@scixconference.org**; www.scixconference.org.

SPIE Photonics West 2026
(Jan. 17-22) San Francisco.
Deadline: Abstracts, July 9
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/photonics-west/attend.

Cell Bio
(Dec. 6-10) Philadelphia.
Deadline: Abstracts, Sept. 3
Contact ASCB, +1 301-347-9300, **info@ascb.org**; www.ascb.org/cellbio2025.

● Indicates shows **Photonics Media** will be attending.
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Contact China International Optoelectronic Exposition, 0755-8629-0901, **cioe@cioe.cn**; www.cioe.cn/en.

MEMS & Sensors NextGen 2025
(Sept. 16-18) Milpitas, Calif.
Contact Michelle Fabiano, **mfabiano@semi.org**; www.semi.org/en/event/mems-sensors-nextgen.

ECOC
(Sept. 28-Oct. 2) Copenhagen, Denmark.
Contact +45 70-20-03-05, **info@cap-partner.eu**; www.ecoc2025.org.

World Molecular Imaging Congress
(Sept. 29-Oct. 3) Anchorage, Alaska.
Contact the World Molecular Imaging Society, +1 310-215-9730, **wmis@wmis.org**; www.wmis.org/wmic-2025.

MEDevice
(Sept. 30-Oct. 1) Boston.
Contact Informa Markets, +1 310-445-4273, **registration.ime@informa.com**; www.medeviceboston.com/en/home.html.

OCTOBER

SCIX
(Oct. 5-10) Covington, Ky.
Contact FACSS, +1 856-224-4266, **scix@scixconference.org**; www.scixconference.org.

AutoSens Europe
(Oct. 7-9) Barcelona, Spain.
Contact Sens Media, +44 (0)208-133-5116, **info@sens-media.com**; www.auto-sens.com/europe.

Manufacturing Technology Series WEST
(Oct. 7-9) Anaheim, Calif.
Contact SME, +1 800-733-4763, **westec@sme.org**; https://west.mtseries.com.

SEMICON West & FLEX
(Oct. 7-9) Phoenix.
Contact SEMI, +1 408-943-6900, **semiconwest@semi.org**; www.semiconwest.org/special-features/FLEX-Conference-and-Exhibition.

ICALEO
(Oct. 13-16) Orlando, Fla.
Contact the Laser Institute, +1 407-380-1553; www.icaleo.org.

European Machine Vision Forum 2025
(Oct. 16-17) Fürth, Germany.
Contact European Machine Vision Association, +34 931-80-70-60, **info@emva.org**; www.emva.org/events/more/european-machine-vision-forum-2025.

Optica Laser Applications Conference
(Oct. 19-23) Prague.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/laser_congress/program/laser_applications_conference.

SPIE Optifab
(Oct. 20-23) Rochester, N.Y.
Contact SPIE, +1 360 676 3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/optifab.

Manufacturing Technology Series SOUTHEAST
(Oct. 21-23) Greenville, S.C.
Contact SME, +1 800-733-4763, **southtec@sme.org**; https://southeast.mtseries.com.

Frontiers in Optics + Laser Science Conference and Exhibition
(Oct. 26-30) Denver.
Contact Optica, +1 202-416-1907, **info@optica.org**; www.frontiersinoptics.com/home.

NOVEMBER

Neuroscience
(Nov. 15-19) San Diego.
Contact Society for Neuroscience, +1 202-962-4000, **meetings@sfn.org**; www.sfn.org/meetings/neuroscience-2025.

AutoSens and InCabin China 2025
(Nov. 18-20) Hefei, China.
Contact Sense Media Group, +44 208-133-5116, **info@sense-media.com**; www.auto-sens.com/china.

SEMICON Europa 2025
(Nov. 18-21) Munich.
Contact SEMI Europe, +49 30-3030-8077-0, **semiconeuopa@semi.org**; www.semiconeuropa.org.

DECEMBER

Cell Bio
(Dec. 6-10) Philadelphia.
Contact ASCB, +1 301-347-9300, **info@ascb.org**; www.ascb.org/cellbio2025.

SEMICON Japan
(Dec. 17-19) Tokyo.
Contact SEMI, **jcustomer@semi.org**; www.semiconjapan.org/en.

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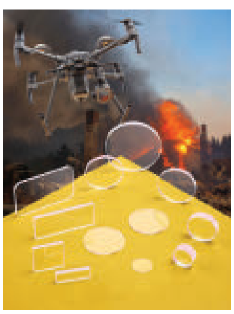
Protecting Drone Vision Systems



Sapphire Windows for drones combine optical clarity and toughness for protecting sensitive vision systems when flying in harsh environments. Featuring Mohs 9 hardness which is second only to diamond, sapphire resists fast moving dirt, chemicals, high heat and transmits 85% from the UV to IR uncoated and offers better than 99% transmission with A/R coatings. Meller Sapphire Windows for drones are available in sizes from 1/4" to 10" diameter.

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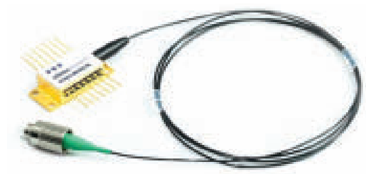
A Light Source for the Quantum Age



The future of quantum is photonics. From enabling secure global communications to building the next generation of sensors and processors, Eblana Photonics powers the quantum frontier with reliable, high-precision lasers and gain chips built for real-world deployment. At Eblana, we work alongside innovators to tailor optical solutions for complex quantum architectures, spanning research to scalable product development.

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info@wdidevice.com
www.wdidevice.com

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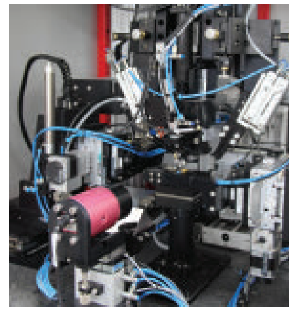

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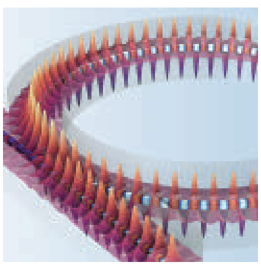

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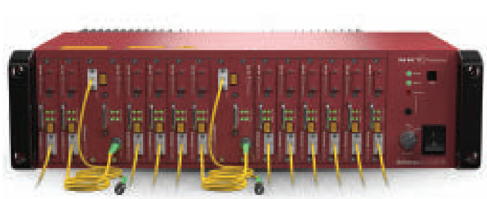
Modular Laser Systems for Quantum



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Advancing Quantum Computing: The ALS 1762 nm High-Power Amplifier for Barium Ions The field of quantum computing is progressing rapidly, with spectacular improvements in qubit fidelity and scaling. For systems based on barium ions, TOPTICA recently released the fiber amplifier ALS-1762-3. It is optimized for the 6S1/2 to 5D5/2 transition in Ba+ at 1762 nm and offers an unprecedented 3 W of power.

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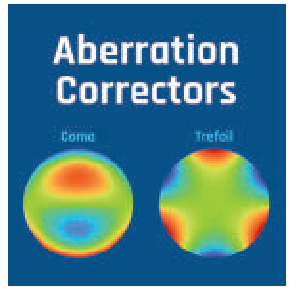
Freeform Aberration Corrector



PowerPhotonic freeform aberration compensators are a cost-effective solution for correcting aberrations in laser systems – pointing, defocus, astigmatism, coma etc. Manufactured in fused silica, our compensators have an extremely low scatter and low loss. They can be used in high power applications such as laser inertial fusion or low light applications such as fluorescence microscopy and cytometry.

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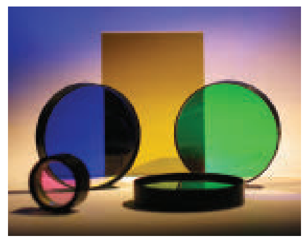
More Signal, Less Background



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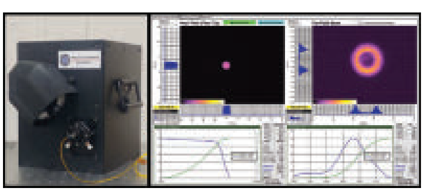

USB3.1 real-time high-power (up to 500W) camera-based divergent beam metrology tool. Continuously analyzes both the near-field and far-field images for small (<1mm diameter) divergent sources (up to NA = 0.30) such as fiber coupled lasers, single emitters, and TO-Cans. Measurements/Applications: •Near-field and far-field measurement •High-intensity source inspection and characterization •Real-time optical assembly optimization

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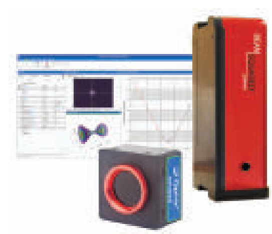

To understand beam quality, focusability, you need Ophir® BeamSquared® SP204S-PRO, the M2 beam propagation analyzer for high-precision, advanced laser manufacturing. This compact, automated system quickly and accurately measures propagation characteristics of standard and large diameter CW and pulsed lasers with Rayleigh lengths to 40 meters. Measures M2, waist position, beam symmetry, more. Industry-leading 3% laser astigmatism. ISO-compliant.

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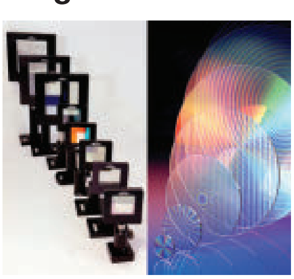

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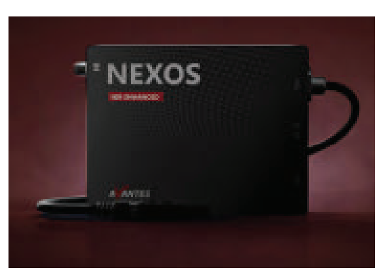

NIR-enhanced Spectrometers unlock the full potential of near-infrared spectroscopy with: • Up to 100% increased NIR sensitivity • Ultrafast data transfer – just 0.38 ms/scan • Compact, modular design, built on our NEXOS™ and VARIUS™ platforms A perfect fit for: • Fruit sorting • Raman • VCSEL • System Integration Discover the product live at LASER World of Photonics, booth 218 Or visit www.avantes.com for more information.

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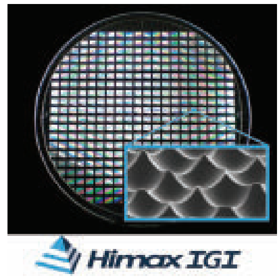

Wafer-level optics solutions from origination and nano-imprinting to assembly. Using advanced lithography and other manufacturing processes, a wide variety of micro/nano structures are created according to customers' desires in applications including refractive/diffractive optics, imaging optics, freeform optics, and many more. Break through current design rules using Himax IGI's design, mastering, and fabrication services.

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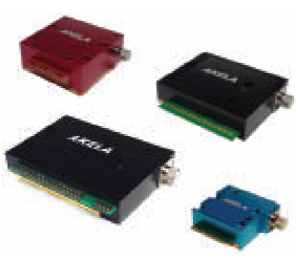

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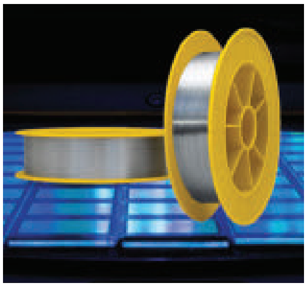

CeramOptecs' innovative UV-fibers offer exceptional solarization resistance in the 190–1200 nm range and support core diameters from 100 µm to 2100 µm — even in non-circular shapes. With low attenuation for blue high-power laser, strong resistance to harsh environments and reliable performance up to 400 °C, they serve critical photonics fields like spectroscopy, laser delivery, and semiconductor manufacturing.

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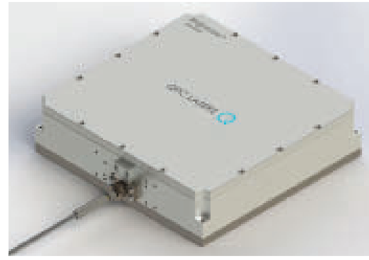
1726-nm Acne Therapy Lasers



QPC Lasers offers fiber-coupled, highly reliable laser OEM modules with optimal performance for acne treatment. Features include powers to 100 W, Brightlock® spectral locking ensuring narrow, stable output at the 1726 nm line, internal power and wavelength monitoring sensors, as well as visible pilot beams and protective blast shields.

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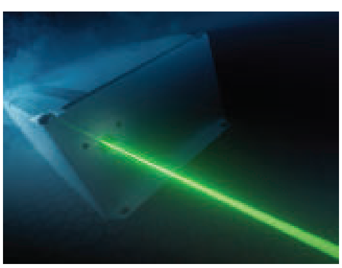

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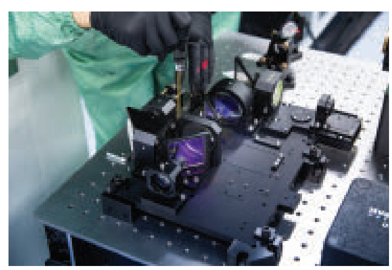

Hyperion's OCT lens assemblies are engineered for high-resolution, low-distortion imaging in optical coherence tomography systems. Featuring custom optical design, active alignment, and tight centration control, these assemblies deliver superior axial resolution. Ideal for biomedical imaging and diagnostics, they ensure precision and reliability in compact form factors.

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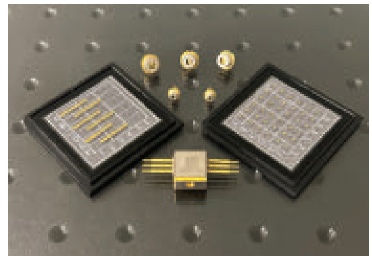

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Pacific Northwest, Rocky Mountains, CA, HI, MA, & NV
Robert L. Gordon
Senior Sales Manager
Voice: +1 413-499-0514, Ext. 207
Fax: +1 413-443-0472
robert.gordon@photonics.com

South Central U.S., Southeastern U.S., Midwest, CT, ME, NH, NJ, NY, PA, RI, & VT
Michael D. Wheeler
Senior Sales Manager
Voice: +1 413-499-0514, Ext. 204
Fax: +1 413-443-0472
michael.wheeler@photonics.com

Wyatt L. Young
Business Development Representative
Voice: +1 413-499-0514, Ext. 108
Fax: +1 413-443-0472
wyatt.young@photonics.com

Rebecca L. Pontier
Director of Sales Operations
Voice: +1 413-499-0514, Ext. 112
Fax: +1 413-443-0472
becky.pontier@photonics.com

Reprint Services
Voice: +1 413-499-0514
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Backlighting could prove extraterrestrial life

In 1938, Orson Welles, perhaps most famous for a sled named Rosebud, accidentally incited panic in radio listeners who tuned into his Halloween Eve retelling of H. G. Wells' 1898 novel *The War of the Worlds*. While the number of people who reportedly went into hysteria after hearing the infamous broadcast has been greatly exaggerated over the years, it is true that some believed Grovers Mill, N.J., was under attack by Martian invaders bent on Earth domination.

This will most likely never happen. Not because this American classic is a fictional account, but because it is exceedingly unlikely for intelligent life to have developed anywhere near our solar system, let alone twice in the same system at around the same time. But what about unintelligent life?

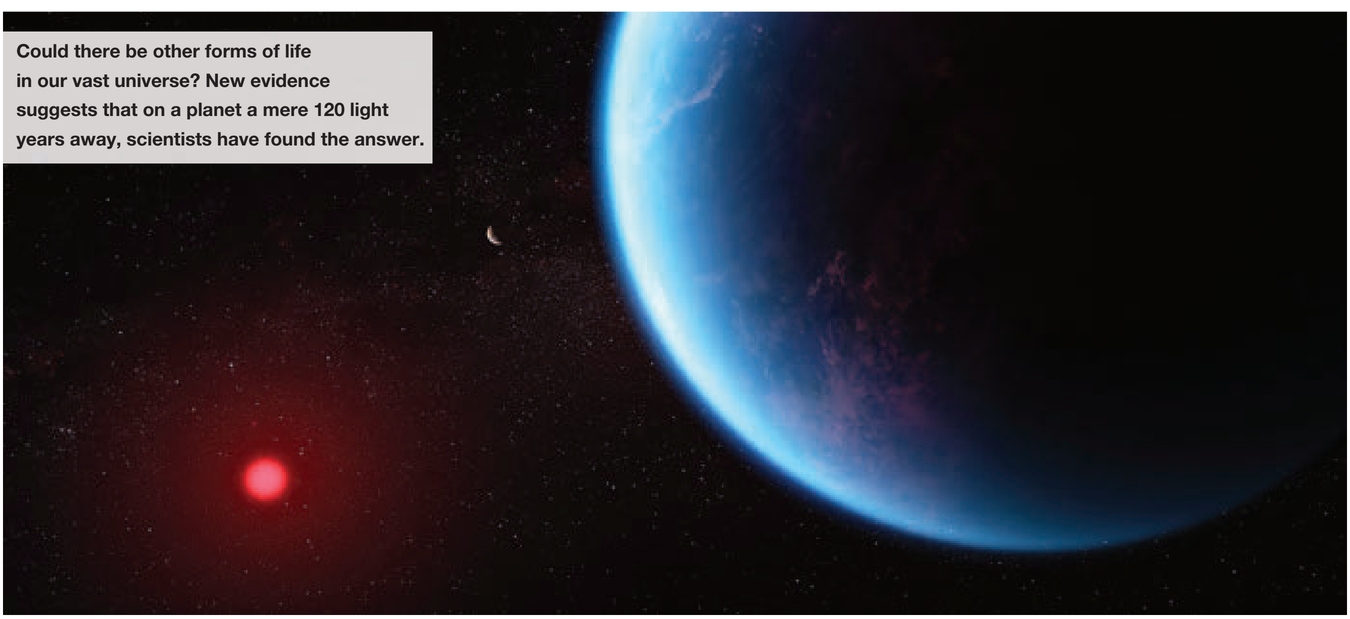
In a constellation far, far away, ~120 light years, in fact, researchers may have found evidence of plant life on planet K2-18b using NASA's James Webb Space Telescope. Not only is this exciting for obvious reasons, but it may also lend credence to an astronomical theory that researchers should search beyond Earth-like planets for signs of life.

Nestled in the Leo constellation, K2-18b is a sub-Neptune-size planet orbiting in the habitable zone of a cool dwarf star uninspiringly named K2-18. With a radius 2.6× the size of our very own big blue marble, K2-18b is theorized to be a Hycean world, which is typically characterized by having a large surface ocean covered by an atmosphere of mostly hydrogen. While this is not confirmed, the planet's Hycean makeup was positive in a spectra examination of its atmosphere, which showed an abundance of methane and carbon dioxide along with a lack of ammonia. But what researchers did not expect to find was a reading for dimethyl sulfide — a compound that, on Earth, is produced only by life.

The bulk of Earth's dimethyl sulfide is produced by phytoplankton in marine environments, which would make sense if K2-18b is indeed confirmed to be a Hycean world … because of, you know, all the water. Normally, it would be difficult to gather chemical data from distant atmospheres independently, due to their host star's higher brightness. To overcome this, researchers waited until K2-18b was fully eclipsed by its charge, allowing Webb's instruments to analyze the starlight that passed through K2-18b's atmosphere.

Though it worked the first time, more tests need to be run to ensure that the first readings weren't a fluke. Plans are in the works to capture future spectra using the spectrograph within the telescope's mid-infrared instrument. If this is successful, not only will extraterrestrial life be confirmed, but the search for habitable planets will widen to include sub-Neptune water worlds in addition to our more familiar rocky planets. This could also mean that a war of the worlds is more likely to be instigated by hyperintelligent phytoplankton than the more humanoid-looking creatures from Hollywood.

The research was published in *Astrophysical Journal Letters* (www.doi.org/10.3847/2041-8213/adc1c8).



Could there be other forms of life in our vast universe? New evidence suggests that on a planet a mere 120 light years away, scientists have found the answer.

Image courtesy of NASA, CSA, ESA, J. Olmsted (STScI).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