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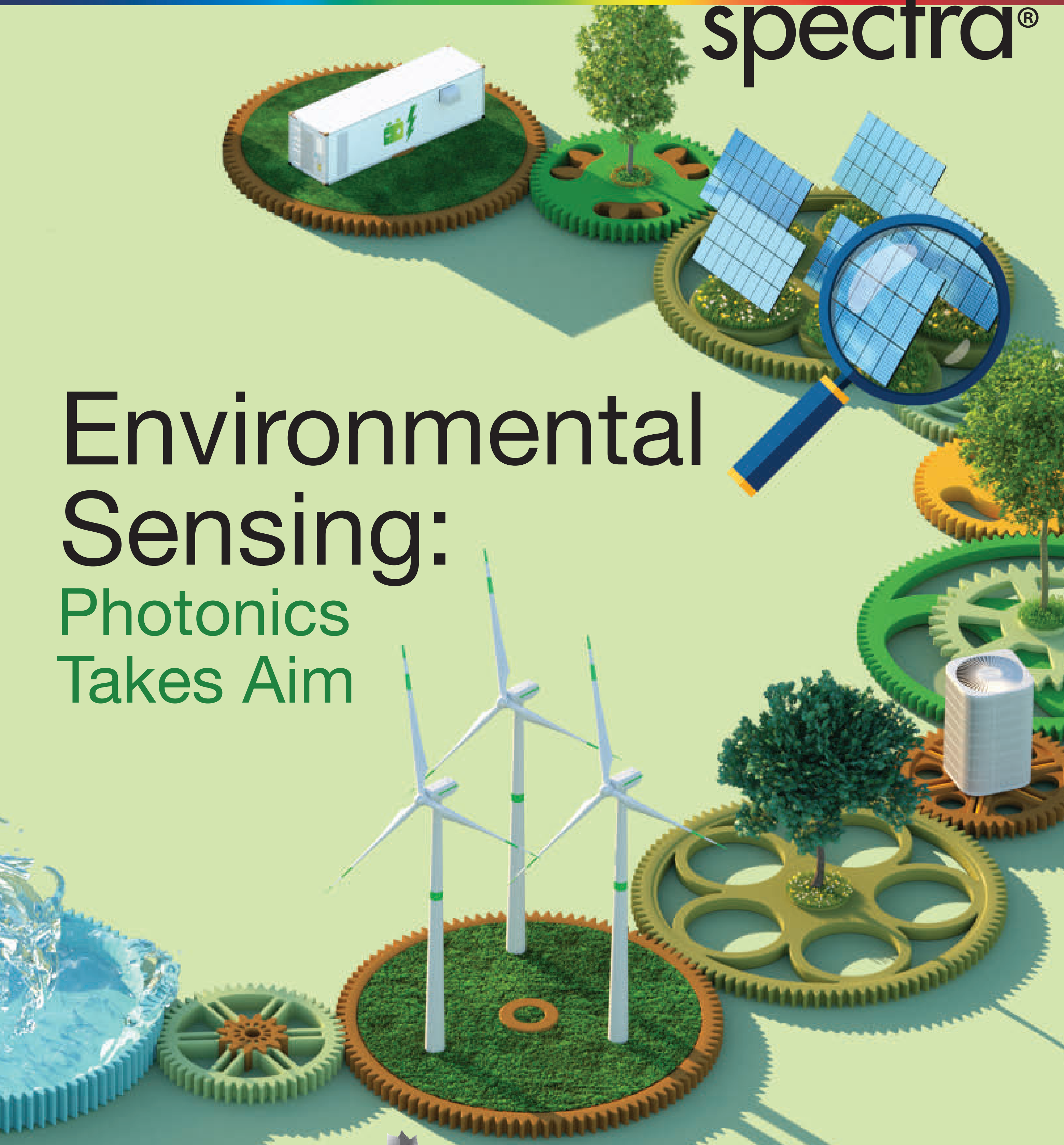

Environmental Sensing:

Photonics Takes Aim

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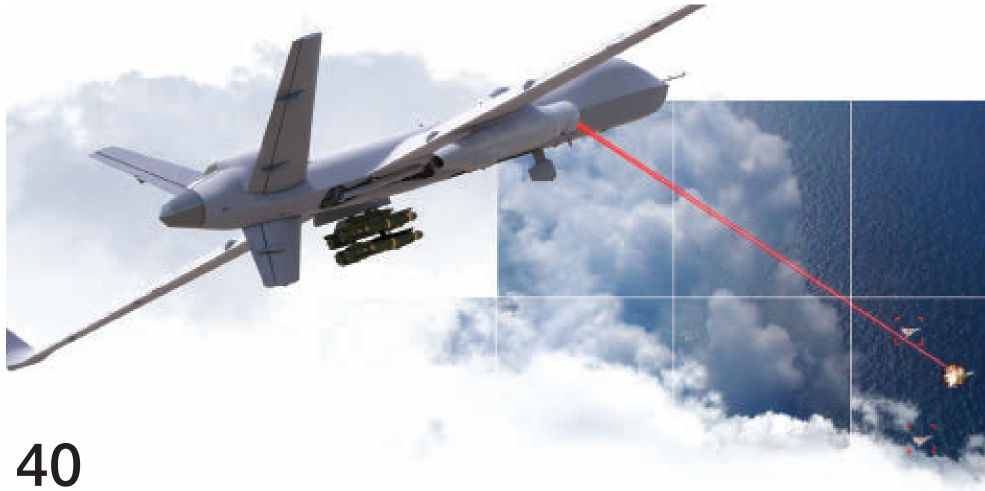

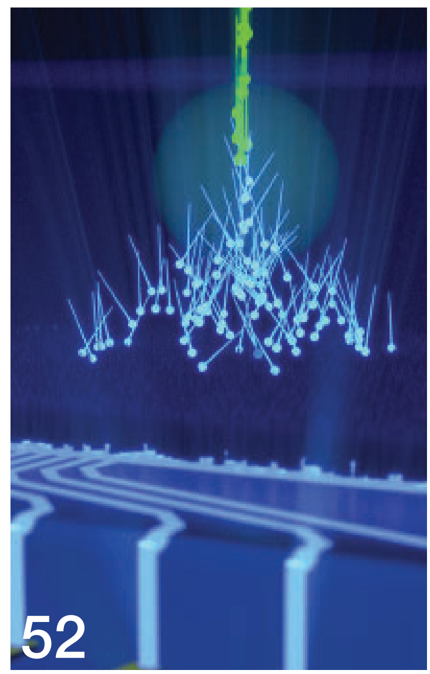

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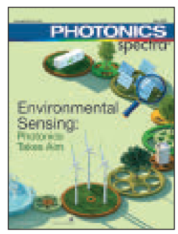
Departments

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

Gauging water quality, forecasting solar power, and monitoring emissions are core deployments of optical and photonic remote sensing technologies. A look at these applications reveals their importance to a sustainable future. Background image courtesy of iStock.com/Floriana and magnifying glass image courtesy of iStock.com/panimoni. Cover design by Senior Art Director Lisa N. Comstock.

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Editor's Note

The business of photonics: In, since, and beyond the pandemic

Five years since the World Health Organization declared it a global pandemic, COVID-19 remains a catalyst for targeted advancements in science and technology. The pandemic demonstrated that coronaviruses cast a wide net of opportunity for the scientific R&D community. In photonics, efforts to advance the understanding of coronaviruses diverge into many distinct areas of study. The development of systems to preempt and improve testing methods is one point of considerable progress, though many others exist.

This issue of *Photonics Spectra* is the 60th to be published since the World Health Organization's March 2020 declaration. A couple hours of digital backtracking revealed that, in some context, 53 of the previous 59 issues mentioned COVID-19.

This digital backtracking exercise served another purpose; perusing five years of magazines reinforced the notion that the last half-decade has seen more than a few developments in photonics' business sector. A few observations stand out.

First, at a time when investment and financial entities are forecasting a sharp rebound in merger and acquisition activity in 2025 and 2026, business combinations have hardly become streamlined — even if they have flatlined. The global regulatory environment deserves some attention here. Hamamatsu's acquisition of NKT Photonics, which the companies announced in June 2022, took nearly two years to close after facing scrutiny from the Danish Business Authority. MKS Instruments' purchase of Atotech took more than a year to wrap, with approval from China's State Administration for Market Regulation representing a hurdle.

Regulatory clearance isn't the only thing that can extend an acquisition. II-VI's purchase of Coherent spanned 18 months. The bidding war that characterizes this transaction ultimately involved four companies.

Another trend: productization in quantum. Commercial solutions including measurement systems, imagers, coolers, and quantum-grade materials are joining quantum cascade lasers and atomic clocks in the quantum marketplace. Importantly, these new-to-arrive products are diversified in their areas of intended application. Quantum cryptography, compute (both hardware and software), and sensing solutions are all moving toward the mainstream, perhaps signaling positive forthcoming developments for the applications that they support.

Finally, there is an uptick from within photonics' business sector to pioneer efforts targeting sustainability. This extends from the implementation of sustainable manufacturing practices to new applications and projects, including in photovoltaics, agriculture, and green energy.

This last theme serves as inspiration for this issue's cover story. Contributing editor Marie Freebody isolates optical remote sensing for environmental applications, offering a look at photonics' utility for emissions monitoring, water quality assessments, and solar forecasting. Read more on page 34.

While research and academia often take the lead on initiatives in these areas, it is the business sector that is driving much of the progress that Freebody spotlights.

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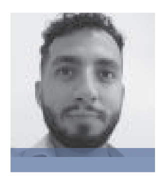

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Everything Old Is New Again: Photonics Is Repeating Semiconductor Manufacturing's Script

From silicon photonics' humble beginnings in data center interconnects, the field now encompasses chip-scale packaging standards, applications ranging from personal health to autonomous transport, novel computing paradigms, and connectivity that ranges from chiplet interconnects to planetary-scale connectivity. The problem confronting us now: Old methods of manufacturing must be supplanted with scalable, modern alternatives. This talk spotlights the commonality in the challenges presented by the diverse applications that the photonics industry is pursuing. Lessons can be borrowed from semiconductor manufacturing. When dovetailed with novel technologies that address stubborn pain points common to the manufacturing and testing of photonic devices of all sorts, the insights are enabling an industry that finds itself on the launching pad without a flight plan. The talk closes with success stories from the emerging ecosystem and a look at the hopeful future we can now anticipate and work toward, together.
To view, visit **www.photonics.com/w1185**.

From Photonic Interposers to Embedded Optical Interconnects: Solving the PIC Packaging Bottleneck

This discussion showcases innovative strategies to enhance the scalability and cost-effectiveness of photonic chip packaging. Two key approaches are highlighted: the co-packaging of electrical and photonic integrated circuits (PICs) on a shared interposer substrate using advanced optical coupling techniques, such as evanescent surface coupling. Additionally, the concept of the waveguide-embedded system is introduced. This technology integrates optical waveguides directly into printed circuit boards, providing a high-performance, fiberless alternative to traditional co-packaged optics for AI and high-performance computing data centers. By eliminating the need for fiber optic cables within servers, the waveguide-embedded system delivers higher density and bandwidth, reduced loss and crosstalk, improved thermal management, and easier maintenance and repair.
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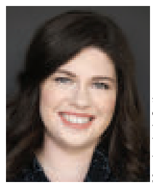
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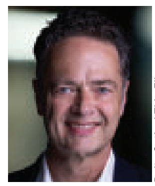
Delta Optical Thin Film
Oliver Pust.

The editors of *Photonics Spectra* and *BioPhotonics* magazines invite you to the Microscopy Summit, a webinar series showcasing the latest advancements in wavefront engineering, neuroimaging, and ultrasensitive detection. Premiering on May 14, this marks Photonics Media's first virtual summit focused on evolving trends in life sciences and biomedical research.

Join industry experts from APE, Bruker Nano, Meadowlark Optics, Delta Optical Thin Film, Evident Scientific, and HÜBNER Photonics for an in-depth exploration of microscopy's role in research and medical applications. Sessions will cover detection methods pushing the limits of sensitivity, insights into neural dynamics, and advanced imaging techniques affecting scientific discovery.

Registration is free and sessions will be available on demand after the premiere. Attendees can interact directly with presenters through a live chat — an opportunity to ask questions, share experiences, and contribute to the photonics community.

Website

To learn more about the program and to register, visit **www.photonics.com/MS2025**.

Multispectral SRS Imaging and Ultrasensitive Detection with a Novel Picosecond Light Source
Ingo Rimke, APE

Imaging the Dynamics of the Nervous System
Kevin Mann, Bruker Nano

Spatial Light Modulators in Microscopy: The Possibilities of Programmable Wavefronts
Janelle Shane, Meadowlark Optics

Fluorescence Microscopy Reimagined: The Power of LEDs and Multi-Bandpass Filters
Oliver Pust, Delta Optical Thin Film

Upcoming Summits

Laser Optics — *June 11*

Optical Design — *August 13*

Micromachining — *September 17*

Quantum — *November 19*

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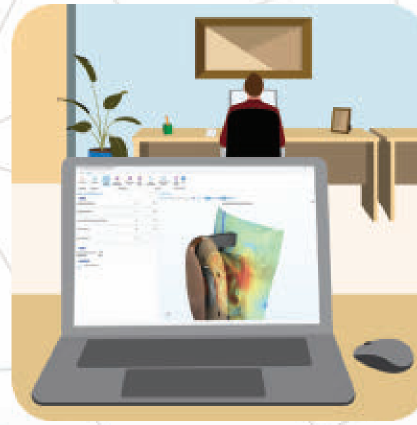
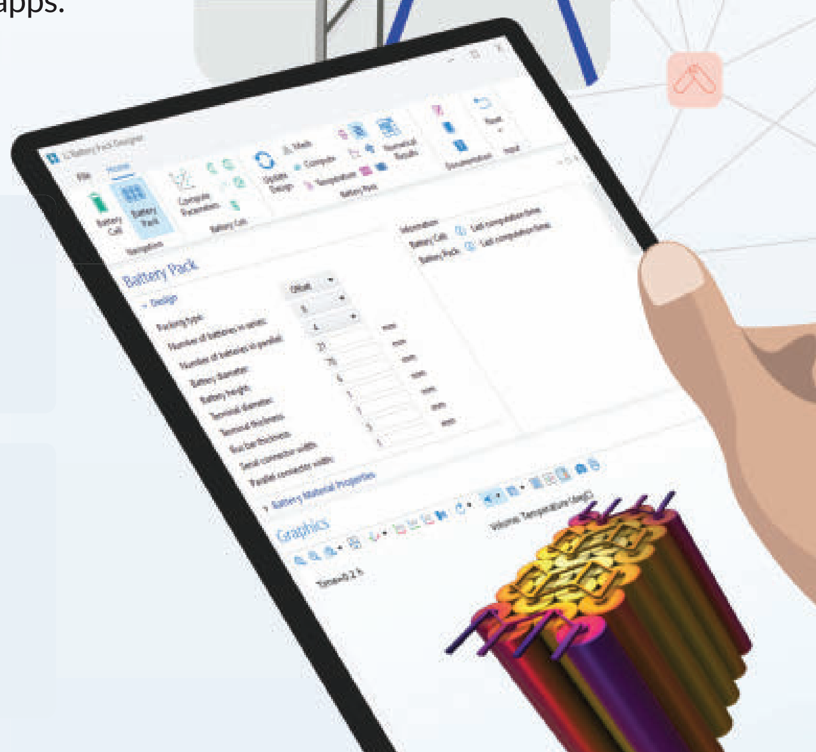




Battery Pack
Graphics

Relativity Networks raises $4.6M for next-generation optical fiber tech

Relativity Networks, a provider of next-generation fiber optic technology, raised $4.6 million in pre-seed funding to address the growing demand for data centers and their power requirements. The company's technology aims to help the data industry meet energy challenges by expanding development beyond urban cores, into locations with more than abundant power, Relativity Networks said.

The company's hollow-core fiber technology allows data to move faster with lower latency than conventional fiber, thereby enabling data to travel 1.5× farther without influencing latency that can throw multilocation data operations and applications out of sync. Traditional fiber optic cables typically limit data centers to within 60 km of each other due to latency constraints, and Relativity Networks' technology extends this range to 90 km, the company said. This increased geographic flexibility aims to enable organizations to strategically position their data centers closer to existing and emerging power sources.

"Currently, new data centers can't be built fast enough to satisfy the rapidly expanding AI-driven economy and the lack of available power is an existential threat to fueling that growth," said Jason Eichenholz, Relativity Networks' founder and CEO.

"By moving data faster with lower latency at nearly the speed of light, we are providing the industry new geographic optionality to address the energy-intensive data needs of today's AI-driven digital economy."


Relativity Networks

Jason Eichenholz, Relativity Networks' cofounder and CEO **(left)**, and Rodrigo Amezcua Correa, cofounder and CTO.

Eichenholz previously cofounded and took lidar company Luminar public. He holds more than 90 patents in optics- and photonics-enabled technologies and has led the R&D and commercialization of numerous products.

Relativity Networks, founded in 2023 following Eichenholz's time at Luminar, is commercializing patent-pending hollow-core fiber technology originally developed by cofounder and CTO Rodrigo Amezcua Correa at the University of Central Florida's College of Optics and Photonics (UCF CREOL). The company's pre-seed funding was raised by a group of private investors following an initial investment from Eichenholz. Relativity Networks has already secured multimillion dollar contracts and deployed its technology in several U.S. field installations, it said.

Thorlabs buys VCSEL developer, longtime partner Praevium Research

Thorlabs acquired longtime collaborator Praevium Research, a developer of high-speed tunable VCSELs. As a division of Thorlabs, Praevium will continue to operate out of its current location in California under the Praevium Research name. The company will also retain its current leadership with Christopher Burgner as its general manager and founder Vijay Jayaraman as a senior scientist, and continue to focus on the development of novel semiconductor lasers and detectors in partnership with the Thorlabs team in Jessup, Md.

Praevium Research has collaborated with Thorlabs since 2008, when it joined the Thorlabs Strategic Partner Program. During the past 17 years, the companies have partnered on the development and commercialization of several technologies, notably for optical coherence tomography applications. Praevium's core competencies are in the design and fabrication of semiconductor lasers, detectors, and photonic integrated circuits, and their application in medicine, spectroscopy, sensors, and communications.

The acquisition occurred two years after Thorlabs acquired Rochester, N.Y.-based JML Optical in January 2023.

$2.8B

— the expected value of the global terahertz technology market by 2032, according to Global Market Insights

NUBURU makes further changes to leadership

Industrial blue laser company NUBURU is working to execute its transformation plan as the company makes extensive changes to its board of directors. During the past year, the company has been in and out of compliance with the New York Stock Exchange. NUBURU regained compliance in January, following a pair of agreements with S.F.E. Equity Investments SARL and Liqueous LP.

The first agreement, with S.F.E., will fund the company's operations for 12 months in exchange for certain governance changes. These changes included the resignation of Ron Nicol, the appointment of Alessandro Zamboni as chairperson, and the reinstatement of Matteo Ricchebuono as a director.

The second agreement, with Liqueous LP, will provide NUBURU with three installments of $1 million and a payment of $500,000. The payments are conditioned upon NUBURU's continued performance under prior funding arrangements made with Liqueous, among other conditions.

Further changes to the company's board include the appointments of Dario Barisoni and Shawn Taylor as well as the resignations of Daniel Hirsch, Elizabeth Mora, and Brian Knaley. According to the company, the resignations are consistent with the company's transformation plan, and Knaley will continue to support the company as needed throughout the transition period.

Per 8-K filings announcing the deluge of board changes, Zamboni will lead the company in implementing its transformation plan, or in the event of its failure, until the sale, recapitalization, or dissolution of the company.

The transformation plan is expected to include the recapitalization of the company, the acquisition of new assets, the transfer and licensing back of certain current assets, and the expansion of the management with expertise relevant to NUBURU's expanded assets.

This month in history

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

1995

Researchers from Sandia National Laboratories in collaboration with AT&T Bell Laboratories demonstrated an extreme-ultraviolet advanced lithography tool that printed integrated circuit features of 0.1 μm. This represented a significant reduction in feature size compared to the integrated circuit feature limits of the time, which were ~0.5 μm.

2005

Scientists at Riken and at Osaka University demonstrated a laser-based nanofabrication technique that promised a hundredfold or more boost in productivity over general laser scanning systems.

2015

A team from the Fraunhofer Institute for Silicate Research developed a film based on piezoelectric printing pastes that rendered flexible polymer films sensitive to deformation. The film additionally registered changes in temperature — a quality that made it suitable for proximity detection.

2020

Physicists at Ludwig Maximilian University along with colleagues at Saarland University demonstrated the transport of an entangled state between an atom and a photon via an optical fiber over a distance of up to 20 km. The demonstration marked a record for distance traveled by an atom and a photonic channel in an entangled state.

German, Dutch collaborators detail quantum internet progress

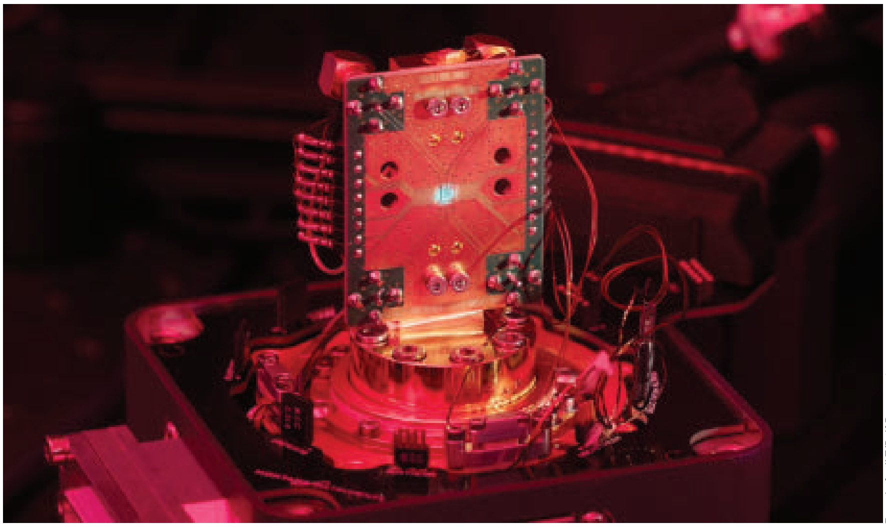
The German state of North Rhine-Westphalia is setting up what it is calling "the first node for the quantum internet of the future." The system was delivered by the Fraunhofer Institute for Laser Technology (Fraunhofer ILT) which co-developed it with the Netherlands Organisation for Applied Scientific Research (TNO).

The system will be tested and further developed, with the first regional connections expected to be made in Germany between Aachen, where it currently resides, and Jülich and Bonn.

The international team, led by QuTech in Delft, Netherlands, is developing metropolitan-scale quantum networks to provide access to quantum computers for users from industry and research, to connect quantum computer platforms, and to make entangled qubits usable for the secure encryption of sensitive data.

These networks have so far only been able to be implemented locally or regionally. Long-distance connections have proved to be elusive due to the lack of repeaters to amplify signals transmitted by individual photons without breaking quantum entanglement.

The research team led by QuTech and backed by TNO and the Technical University of Delft demonstrated the connection between two quantum computers in the Netherlands, between locations in Delft and The Hague, with 25 km of underground optical fiber, which reproducibly created quantum entanglement along the fiber.



Fraunhofer ILT/Ralf Baumgarten

The heart of the quantum internet node is a cultured diamond with specifically introduced nitrogen vacancy centers. It emits single photons that can carry and transport information about the state of the qubit.

Together, TNO and Fraunhofer ILT revised the design so that individual components are now easier to replace during testing. The Aachen-based institute also contributed various optical assemblies. After assembly and a test operation phase including its characterization at TNO, the node was delivered to Aachen in January.

"We envision that metropolitan scale quantum networks will enable very powerful, secure connections between quantum computers and between quantum sensors," said Bernd Jungbluth, who heads the Quantum Technologies strategic program at Fraunhofer ILT.

The team anticipates that the work will allow applications such as distributed quantum computing, which interconnects several computers to form a quantum system, to quickly scale their capacity and performance. Quantum networks are also important for secure remote access to quantum computers.

GlobalFoundries to create $700M packaging and photonics center

GlobalFoundries (GF) will create a center for advanced packaging and testing of U.S.-made essential chips within its New York manufacturing facility. Supported by investments from the State of New York and the U.S. Department of Commerce, the center aims to enable semiconductors to be securely manufactured, processed, packaged, and tested entirely onshore. The development will serve to further help GF meet the growing demand for silicon photonics and other essential chips for critical end markets including AI, automotive, aerospace, defense, and communications.

The facility is expected to offer advanced packaging, assembly, and testing for GF's differentiated silicon photonics platform. The center will also provide production capabilities for the advanced packaging, wafer-to-wafer bonding, assembly, and testing of 3D and heterogeneously integrated chips using 12LP+, 22FDX, and other platforms.

The site benefits from Trusted Foundry accreditation, which allows it to manufacture secure chips in partnership with the U.S. government. GF expects to provide full turnkey advanced packaging, bump, assembly, and testing for aerospace and defense customers.

GF's overall investment in the New York Advanced Packaging and Photonics Center is expected to be $575 million, with an additional $186 million investment in R&D over the next 10-plus years. New York State will provide up to $20 million in new support for the center, which is in addition to the previously announced $550 million in support for GF from the New York State Green CHIPS program. The U.S. Department of Commerce will provide up to $75 million in direct funding to support the center, supplementing the previously announced GF award under the CHIPS and Science Act.

iPronics raises $21M series A

iPronics

iPronics' Optical Networking Engine (ONE) is designed to enable artificial intelligence applications.

Photonic computing and programmable photonic integrated circuits company iPronics raised €20 million ($20.8 million) in a series A funding round. The funds will help accelerate the deployment of the company's Optical Networking Engine (ONE) in AI data centers, enabling fast, scalable, and high-bandwidth communication for energy-efficient AI.

iPronics' ONE technology offers an optically switched fabric for AI architectures, enabling at-will topology adaptation and extending programmability to physical layer connections. According to the company, it provides 1000× faster reconfiguration compared with other optic-based approaches, as well as lossless operation, lower cost-per-port, and higher reliability due to its solid-state chip design.

iPronics CEO Christian Dupont, appointed last year, said that the technology will allow larger graphics processing unit domains with fast optical interconnects, greater training compute capacity, and low latency interference.

iPronics, a 2019 spinout of Universitat Politècnica de València (UPV) reported advancements to its programmable photonic processors last year in partnership with UPV. In 2023, the company established a partnership with Vodafone and delivered its first shipments of its programmable photonic integrated microchips.

TRUMPF and SCHMID partner on high-speed chip production

TRUMPF and the SCHMID Group formalized a partnership targeting the development of an advanced packaging manufacturing process for next-generation microchips. The technique on which the partnership centers, the companies said, will enable manufacturers to increase the performance of high-end electronic components for smartphones, smart watches, and AI applications.

In advanced packaging, manufacturers combine individual chips on silicon components known as interposers. TRUMPF and SCHMID have developed a combined laser-etching process to allow these interposers to be made of glass.

Christian Weddeling, business development manager for TRUMPF, said that because the cost of glass used for advanced packaging in the semiconductor industry is significantly cheaper than silicon, the process will help enable manufacturers to reduce production costs and make devices more affordable for customers.

The two companies use a wet chemistry approach, which TRUMPF said shortens process times by a factor of 10. The extreme level of precision is necessitated by the thickness of the glass, which is between 100 µm and 1 mm thin. To create connections on the interposer, manufacturers must drill holes through the glass, creating so-called through-glass vias. Manufacturers often must create millions of holes in a panel to make the desired connections.

In the collaboration, however, an ultrashort-pulse laser from TRUMPF selectively changes the structure of the glass, which is then treated with an etching solution. The desired holes are created at the specified locations and then filled with copper to form the conductor tracks.

The method is additionally expected to have near-term applications for the production of chips for consumer electronics such as smartphones, TRUMPF said.

13.9%

— the predicted compound annual growth rate of the global passive optical network market by 2030, according to Grand View Research

Briefs

Edmund Optics acquired **son-x**, a developer of an ultrasonic-assisted diamond turning technology used for ultraprecise optics manufacturing. The Fraunhofer spinout company produces metallic mirrors used in the semiconductor, satellite, and defense sectors, and produces infrared optics. According to son-x, quantities range from one-off production for prototypes to series production of several thousand mirrors per year. Integrating son-x's expertise and resources, Edmund said, will enable it to produce highly complex multi-axis machined surfaces (up to five-axis) ranging in size from 1 mm to 1 m. The financial terms of the acquisition were not disclosed.

Dutch photonic chip foundry **New Origin** began construction on a facility to produce high-quality silicon nitride photonic chips. The company plans to produce its first photonic chips by the end of 2026.

Omnitron Sensors, a developer of microelectromechanical systems (MEMS)-based sensor technologies, secured more than $13 million in series A funding. The investment will help the company to expand its engineering and operations teams and accelerate the mass production of the company's first product, a MEMS step-scanning mirror for multiple markets. According to Omnitron, its technology enables optical cross-connects in AI data centers, optical subsystems in long-range lidar for autonomous navigation, see-through displays in extended reality headsets and eyewear, and precision laser spectrometry for methane gas detection.

The U.S. Department of Commerce will provide up to $105 million in proposed direct funding to **Analog Devices Inc.**; up to $79 million in proposed direct funding to **Coherent**; up to $10.3 million in proposed direct funding to **Intelligent Epitaxy Technology Inc.**; and up to $52.1 million in proposed direct funding to **Sumika Semiconductor Materials Texas Inc.** The planned awards stem from four nonbinding preliminary memoranda of terms under the CHIPS and Science Act.

Semiconductor technology company **VueReal** secured $40.5 million in series C funding to scale production capabilities and expand its global ecosystem to support the integration of micro-LEDs into commercial production. VueReal's MicroSolid Printing technology targets the efficient transfer of LEDs from wafer to backplane for the production of micro-LED displays and other micro semiconductor devices.

International trade body for optics-based anti-counterfeiting technologies **International Hologram Manufacturers Association** (**IHMA**) rebranded as the **International Optical Technologies Association** (**IOTA**). The organization said that the rebrand is in line with its belief that recent advancements in optical technologies have exceeded the importance holography once held in the anti-counterfeiting industry. IOTA membership will allow developers and suppliers of security features based on technologies that include holography, microlens arrays, micro-mirrors, plasmonics, nano-gratings, color change, caustics, polarization, photonic crystals, special print-generated effects, or a combination of these.

The **Dutch Research Council** and the **PhotonDelta Foundation** opened the "Photonic Technologies" call for applications. The initiative, supported by €7 million ($7.3 million) in funding from PhotonDelta, aims to deliver photonic materials, chips, devices, and systems that are not yet strongly represented in PhotonDelta's existing funded projects.

Focuslight Technologies renamed its **Focuslight Singapore** subsidiary to **Heptagon Photonics**. The move aims to strengthen branding alignment. Focuslight Singapore, established following last year's acquisition of optical component assets from ams OSRAM AG, oversees operations in Southeast Asia as part of Focuslight global operations system. It specializes in high-volume manufacturing and rapid production cycles.

Black Semiconductor, a developer of graphene-based chip technology, has moved its headquarters to Aachen, Germany, where it plans to develop a graphene photonic pilot line. Black's FabONE facility has up to 15,000 sq m for cleanroom and

ONCHIPS consortium to develop germanium-silicon quantum chip

The European Commission invested €3 million ($3.1 million) to develop a quantum chip that combines electronics and light using germanium-silicon (GeSi) technology. The goal of the project is to make quantum computers faster, more efficient, and scalable, allowing them to tackle challenges including drug discovery, cybersecurity, and artificial intelligence.

Supported by the Quantum Flagship, the ONCHIPS consortium unites leading institutions from across Europe to drive technological independence and quantum innovation.

Just as the first computers of the 1950s were impractical and unsuitable for widespread adoption due to their enormous size and limited processing power, today's quantum computers have their own challenges. "One major issue of scalability is that qubits are often limited in their ability to interact with one another," said project coordinator Floris Zwanenburg, a professor at the University of Twente's MESA+ Institute for Nanotechnology. "As the number of qubits increases, effective communication between them becomes more complex."

GeSi, a material that can efficiently emit light, presents a viable solution to overcome these obstacles.

"We are combining spin qubits for computation and photonics for communication on a GeSi platform that is compatible with traditional CMOS manufacturing, which could be a total game changer for scaling quantum computers," Zwanenburg said.

"By combining spin qubits (electrons) with photonic communication (light), the chip bridges the gap between processing quantum information and transmitting it over long distances. This will significantly help us solve a major bottleneck in quantum scalability."

GeSi has been used and studied as a material system in applications such as transistors in semiconductor physics. Scientists have worked with cubic GeSi for years and even built qubits using it. But the hexagonal light-emitting version of the material had never found its way into a quantum computer.

"In this 'hexagonal phase,' this special structure makes the material better at giving off light. The atomic structure means it is suitable for quantum applications and photonics, where controlling light is crucial for communication, computation, and storage," Zwanenburg said.

The team is using a monolithic integration approach to building their quantum chips. This cuts the size and complexity of the system and makes it easier to scale up, Zwanenburg said.

Set to conclude in 2026, ONCHIPS brings together European organizations and the company Single Quantum BV.

infrastructure construction, and Black is expected to begin pilot production in 2027, with volume production expected to kick off in 2029.

RhyGaze, a biotechnology company spun out of the Institute of Molecular and Clinical Ophthalmology Basel, secured $86 million in series A funding. The funding will enable further development of RhyGaze's gene therapy for optogenetic vision restoration in diseases causing blindness.

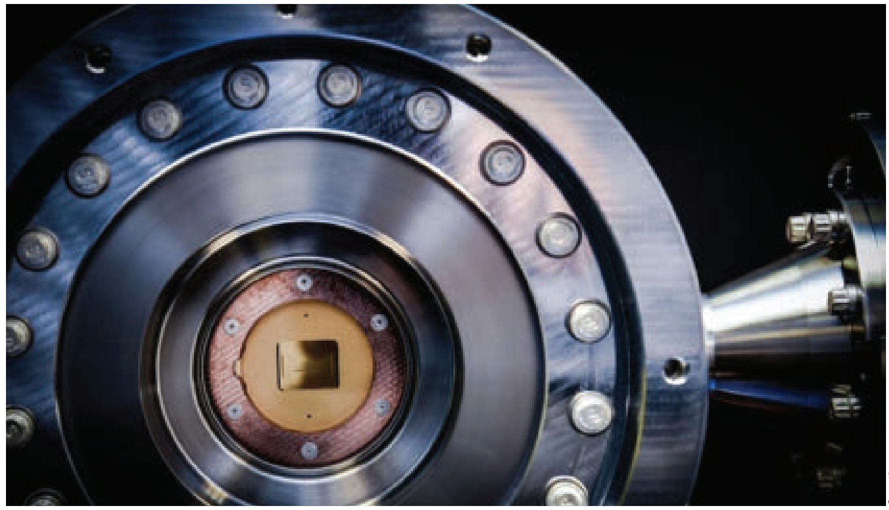
NLM Photonics, a developer of organic electro-optic modulation technology, received an investment from Emerald Technology Ventures and Oregon Venture Fund. The company plans to use the funding to deliver energy-efficient, high-performance electro-optic modulation technology to AI, data centers, and quantum computing, among other applications. According to NLM, the investment is part of its next phase of development to scale and commercialize its technology.

Fiber Optics Group acquired **IDIL Fibres Optiques**, a company specializing in optical fiber systems and optoelectronic subsystems. IDIL Founder and CEO Patrice Le Boudec will serve as IDIL's general manager and a member of the Fiber Optics Group's Strategic Committee. IDIL develops and manufactures four main product lines: fiber assemblies and components, optoelectronic systems and lasers, spectroscopy, and photonics engineering and services.

Quantinuum to build R&D center in New Mexico

Integrated quantum computing company Quantinuum plans to open a location in New Mexico to support collaborative research efforts that advance the photonics technologies underpinning the company's product development.

The facility is expected to open this year. Quantinuum's choice of location, it said, benefits from proximity to longstanding partners Sandia National Laboratories, Los Alamos National Laboratory, and the University of New Mexico. These partnerships, Quantinuum said, have aided the company in exploring innovative applications and use cases, and they support workforce development, education, and other efforts within the region.



Quantinuum

Quantinuum's trapped ion quantum computer.

Quantinuum, founded in 2021 through the merger of Cambridge Quantum Computing and Honeywell's quantum solutions division, posted multiple milestones last year, including a $300 million investment round from Honeywell, quantum computing advancements with partner Microsoft, and the development of a 56-qubit quantum computer. The company is a participant in the AIM Photonics-led QUPICS project and has established a partnership with Infineon Technologies targeting AI and other fields.

Lumentum makes CEO change

Lumentum Holdings named Michael Hurlston president, CEO, and a director of the company. Hurlston succeeds Alan Lowe, who served as the company's president and CEO since 2015. Lowe will continue to serve as a member of Lumentum's board of directors and as an advisor to the company.

Hurlston joins Lumentum from Synaptics, where he served as president and CEO and as a member of the board of directors since joining the company in 2019. Prior to Synaptics, Hurlston served as CEO and a member of the board of Finisar Corporation, which was acquired by Coherent (previously II-VI) in 2019. He also served in a variety of management roles at Broadcom and its predecessor corporation.

Lowe previously served as president of the former JDSU Communications and Commercial Optical Products business segment, which became Lumentum. He led Lumentum through a bidding war (involving II-VI as well as MKS) as Lumentum attempted to acquire Coherent in 2021.

Sensing and inspection specialist EVK joins Headwall Group

Hyperspectral imaging leader Headwall Group acquired EVK DI Kerschhaggl (EVK), an Austria-based technology company specialized in industrial sensor-based sorting and inspection systems. The acquisition supports Headwall's diversification of its product offerings and bolsters its presence in the industrial machine vision market. The financial terms of the deal were not disclosed.

According to Headwall, the acquisition is expected to broaden its market reach and provide growth opportunities in applications including food processing, plastics recycling, and materials sorting.

Headwall acquired fellow hyperspectral imaging company inno-spec GmbH last year and acquired diffraction gratings producer Holographix and spectral analysis software developer perClass BV in 2022.

Headwall Group

Mark Willingham, CEO of Headwall **(left)**, and Matjaz Novak, CEO of EVK.

Quantum Brilliance raises $20M

Quantum Brilliance, a developer of room temperature diamond quantum technology, raised $20 million that the company said will enable it to create a diamond foundry and co-develop quantum sensing prototypes. At the same time, the company said, it will use the series A funding to continue to advance its technology in collaboration with semiconductor partners.

Quantum diamonds have a wide range of potential uses across quantum computing, sensing, and networking. Their compact size, light weight, room temperature functionality, and suitability for mass deployment give quantum diamonds distinct advantages compared with other quantum technologies in certain use cases. Quantum diamonds are well suited for large-scale deployment, reliable performance in everyday environments and/or harsh conditions, and seamless integration into existing infrastructure.

Quantum Brilliance established a partnership with Oak Ridge National Laboratory (ORNL) in September 2024, under which Quantum Brilliance's room temperature diamond accelerators will be installed alongside ORNL's high-performance computing systems. The company also received a contract in the same month from Germany's Agentur für Innovation in der Cybersicherheit GmbH to build a mobile quantum computer by 2027. For this undertaking, Quantum Brilliance will work with quantum architecture company ParityQC.

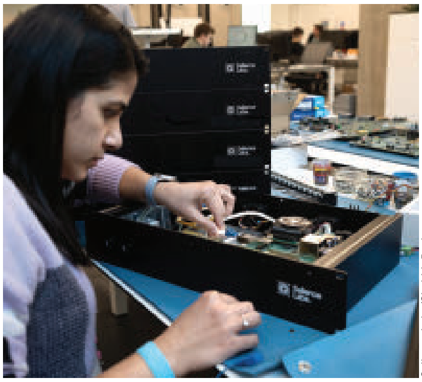
$10.9B

— the estimated value of the global laser diode market by 2027, according to MarketsandMarkets

Salience Labs closes $30M funding round

Salience Labs, a developer of photonic solutions targeting connectivity for AI data center infrastructure, closed a $30 million series A funding round. The capital will help the company to further develop its optical switches for large-scale AI connectivity.

"What our customers want is a photonic switch to connect their AI clusters that is compatible with existing infrastructure while delivering high bandwidth, low latency, and significant power savings," said Vaysh Kewada, cofounder and CEO of Salience Labs.



Salience Labs/Shabbir Bashar

Salience Labs is developing photonic switch chips composed of an optical circuit switch and a low-loss optical fabric supported by electronic control and software for fast switch configuration, temperature and power monitoring, and conventional software interfaces.

"The completion of this round will further our development and help us bring our product to customers to enable not just the savings, but large cluster connectivity."

In conjunction with the round's closing, the company appointed William Jeffrey to its board of directors. Jeffrey is chairman of the technical advisory committee on the ICM HPQC Fund, which co-led the funding round. The company also appointed Bonnie Tomei CFO.

Salience Labs is developing photonic switching technology to enable high-speed, ultralow latency networking fabrics that remove infrastructure bottlenecks for AI workloads by allowing all-optical networking between compute nodes. According to the company, its photonic switch chips

People in the News

Luxinar

Stefan Hackl.

Laser manufacturer Luxinar named **Stefan Hackl** managing director. In this role, Hackl leads the company's workforce at the Hull, England, manufacturing site and headquarters as well as the employees at Luxinar's sales and service offices in China, Germany, Italy, Korea, and the U.S. Hackl has leadership experience in the automotive industry and previously served as plant manager at SAS Interior Modules.

GlobalFoundries' board of directors appointed **Thomas Caulfield** executive chairman, **Tim Breen** CEO, and **Niels Anderskouv** COO. The appointments were made after GlobalFoundries board member **Ahmed Yahia** stepped down from his position. Caulfield served as president and CEO of GlobalFoundries since 2018. Breen has held the position of COO at the company since 2023, with previous experience as a senior member of the executive team at Mubadala Investment Company. Anderskouv brings 25 years of experience to his role and currently serves as chief business officer of GlobalFoundries.

VueReal

Robert Selley.

Micro-LED and sensing company VueReal appointed **Robert Selley** CCO. In the newly created role, he will oversee all global sales and business development activities and help drive the company's expansion across industry sectors including lighting, consumer electronics, automotive, AR/VR, and health. Selley has held executive leadership positions at global semiconductor companies throughout his career, including at Nova Semiconductor, FormFactor, Cascade Microtech, and MKS.

Meopta SRO appointed **Jan Vymazal** CEO, **Rudolf Kodytek** CCO, **Dusan Sevc** CFO, and **Kevin Liddane** senior director. Vymazal previously held leadership roles at companies including Edwards, the GGE Group, and Milacron. Kodytek led sales and marketing for major companies including Johnson & Johnson's Bonotrans Group and Cordis. Sevc was partner and private equity leader for Deloitte. Liddane most recently served in sales and business development roles at Berliner Glas Group and SwissOptic AG.

Exail

Bruno Desruelle.

Exail named **Bruno Desruelle** CEO of its photonics business line. Desruelle previously served as vice president of Exail's photonics line and also as managing director of its quantum sensors division. He is the founder and former CEO of Muquans, which was acquired by Exail in 2021.

Quintessent Inc., a developer of heterogeneous silicon photonics and quantum dot laser technology, named **Bob Nunn** COO. Nunn most recently served as CEO of Everactive, a startup company building battery-less Internet of Things solutions, and previously as managing director at Intel Capital.

IPG Photonics promoted **Mary Buttarazzi** to the positions of vice president, corporate controller, and chief accounting officer. Buttarazzi has more than 25 years of finance and accounting leadership with extensive management experience. Prior to joining IPG as vice president of finance in January, she served as the chief accounting officer and corporate controller of Orbia Advance Corporation.

The board of biotechnology company Lumencor promoted **Claudia Jaffe** to president and CEO. Jaffe, previously CCO of the company, founded Lumencor with Steven Jaffe. Steven Jaffe, who preceded Claudia as president and CEO, now serves as COO, maintaining his focus on engineering and operations.

Soitec, a designer and producer of semiconductor materials, named **Ruth Hernandez** chief sales eliminate the need for transceivers, thereby reducing costs.

Founded by Kewada, CTO Johannes Feldmann, and Wolfram Pernice, a professor at Heidelberg University and winner of the 2024 Gottfried Wilhelm Leibniz Prize of the German Research Foundation, Salience Labs is a spinout of the University of Oxford and the University of Münster. Applied Ventures LLC, the venture capital arm of Applied Materials Inc., co-led the funding round.

Partners integrate cytometers with robotics capabilities

Medical technology company Becton, Dickinson and Company (BD) and laboratory automation solutions developer Biosero established a collaboration agreement to facilitate robotic integration with BD flow cytometry instruments. The collaboration, the companies said, aims to accelerate drug discovery and development.

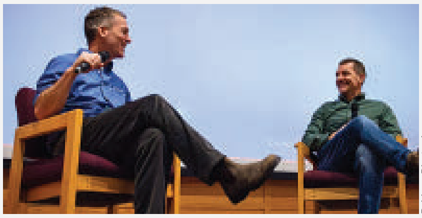
The first systems are expected to be available for research use later this year, according to the collaborators.

The companies intend to develop capabilities within BD's flow cytometer instrument software to be compatible with Biosero's Green Button Go software, which will jointly support biopharmaceutical and contract research organizations with their custom research needs and enable easy integration with

officer. Hernandez has more than 25 years of experience working with major semiconductor companies, including Texas Instruments, Maxim Integrated, and GlobalFoundries.

Bowman Consulting Group Ltd., an engineering services firm, named **Andy Dearing** executive vice president, overseeing all aerial imaging operations nationally. In this role, he will direct all high-altitude aerial orthoimagery, digital mapping, and lidar operations acquired in connection with the company's April 2024 purchase of Surdex. He will also manage the integration of the company's drone-based imaging and scanning services with Surdex's capabilities. Prior to joining Bowman, Dearing worked at GeoFutures and served as CEO of Boundless Spatial.

Nokia appointed **Justin Hotard** president and CEO. He will take over for current president and CEO **Pekka Lundmark**. Hotard joins Nokia with more than 25 years of experience with global technology companies, currently leading the Data Center & AI Group at Intel.



Bridger Photonics

Pete Roos **(left)** and Ben Little.

Bridger Photonics appointed **Ben Little** CEO, replacing company founder **Pete Roos**, who assumed the role of chief innovation officer. Little has previous leadership experience in data, software, and platform development. Little previously served as CEO of Bloomfire.

Blackbird Robotics

Rüdiger Brockmann **(left)** and Karl Christian Messer.

Blackbird Robotics appointed **Rüdiger Brockmann** CEO, taking over for Karl Christian Messer who held the position since 2017. Brockmann has more than 30 years of experience in the industry and laser sector, having held various top management positions in large groups as well as mid-size companies.

robotic arms. Traditionally, several steps in a lab's flow cytometry workflow for drug discovery and development require manual processes. With robotic integration, these steps can become automated. For example, samples are typically loaded and analyzed on a flow cytometer one multiwell plate at a time, requiring a time-consuming manual step each time the multiwell plate is changed. With robotic arm integration, tens or potentially hundreds of multiwell plates can be automatically changed without human intervention, the companies said.

Quintessent, IQE commit to AI optical interconnects supply chain

Quintessent Inc. and IQE PLC partnered to establish a large-scale quantum dot laser and semiconductor optical amplifier epitaxial wafer supply chain. The collaboration brings together the developer of quantum dot laser technology and heterogeneous silicon photonics, and the global supplier of epitaxial wafer products and services.

Through the agreement, supported by purchase order commitments from Quintessent, IQE will deliver production quantities of epitaxial wafers to Quintessent throughout 2025.

Quintessent and IQE have targeted improvements to the supply of high-quality, high-volume quantum dot epitaxial wafers for laser sources and semiconductor optical amplifiers via efforts throughout the past decade. Milestone advancements in this area include those stemming from research previously spun out of John Bower's laboratory at the University of California, Santa Barbara. Transitioning the gallium arsenide-based quantum dot research to high-volume production has resulted in highly optimized and high-performing gain material on 6-in. diameter epitaxial wafers that can produce several hundreds of millions of edge-emitting lasers and semiconductor optical amplifiers per year.

Quintessent closed an $11.5 million seed round last year. The company formalized a partnership with Tower Semiconductor in 2021, and in 2023, the partners claimed the first heterogeneous integration of gallium arsenide quantum dot lasers and a foundry silicon photonics platform.

PHOTON IP raises $4.9M seed round

PHOTON IP, a manufacturer of advanced low-power optical chips, raised €4.75 million ($4.9 million) in seed funding to accelerate the industrialization and commercialization of its technology. PHOTON IP's chip technology combines silicon photonics with active III-V materials and aims to address the limitations that existing schemes for photonic integration face in their inability to deliver necessary levels of performance and energy efficiency in a small footprint.

The company is specifically targeting manufacturing process simplifications stemming from improving the way that silicon and different III-V materials are integrated onto a single photonic chip. PHOTON IP's breakthrough, it said, clears a path toward mass deployment for advanced low-power optical engines for a wide range of applications.

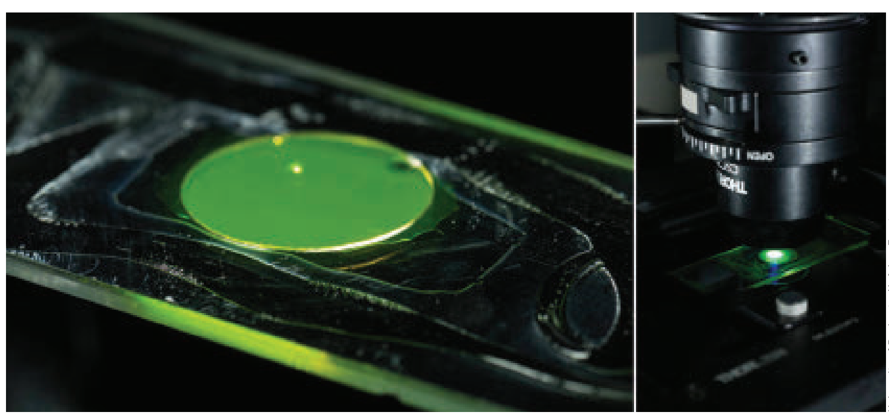
Innovation Industries, Faber, Brabantse Ontwikkelings Maatschappij, and PhotonDelta are among those that participated in the seed funding round. The current round follows an initial investment by VIGO Ventures in 2021 and PHOTON IP's first contracts secured with global customers, for which initial products are currently being co-developed and tested.

Glass-coated bacteria form live microlenses for advanced imaging

University of Rochester/J. Adam Fenster

Graduate student Lynn Sidor prepares bacterial cells that will self-assemble their own glass coating by using enzymes from sea sponges **(above)**. Sidor is working with biologist Anne Meyer and colleagues in optics and physics to create tiny, bacteria-based microlenses for advanced imaging.

Researchers designed and built a specialized microscope that illuminates samples from a wide range of angles **(below)**. They also developed an innovative microscopy technique to measure the optical properties of the glass-coated bacterial cells, allowing them to visualize how the bacteria focus light.



University of Rochester/J. Adam Fenster

ROCHESTER, N.Y. — Microlenses typically require complex, expensive machinery and extreme temperatures or pressures to produce them. A bio-inspired approach to making microlenses, based on the enzymes secreted by sea sponges, could offer a way to create inexpensive, durable, advanced microlenses for use in medicine, biology, and materials science.

Sea sponges grow glass skeletons made of silica, also called bioglass. This silica skeleton is both lightweight and resilient, allowing the sea sponge to withstand harsh marine environments.

Using the principles of synthetic biology, an international research team replicated the material that comprises the natural bioglass shell of the sea sponge to create a living optical lens. The University of Rochester-led team included researchers from the University of Colorado Boulder (CU Boulder), Delft University of Technology, and Leiden University.

The researchers fused the bioglass-creating enzyme produced by sea sponges to the surface of bacterial cells. The modified cells self-assembled a layer of bioglass at their surface. The bioglass shell transformed the bacterial cells into engineered optical devices that could scatter high-intensity, focused light.

"By engineering microbes to display these same enzymes, our collaborators were able to form glass on the cell surface, which turned the cells into living microlenses," CU Boulder professor Wil Srubar said. "This is a terrific example of how learning and applying nature's design principles can enable the production of advanced materials."

In addition to engineering the bacterial cells to express the silicatein enzyme made by sea sponges, the University of Rochester team, led by professor Anne Meyer, developed a microscopy technique to measure the optical properties of the cells. Working with materials scientists at CU Boulder, the researchers examined the bacteria's chemical properties to ensure that silica was present on the engineered cells.

The CU Boulder researchers analyzed the silica displayed by the bacteria and quantified the amount surrounding different bacterial strains by using imaging and x-ray techniques. They demonstrated that bacteria engineered to form bioglass spheres contained significantly higher silica levels than nonengineered strains.

In collaboration with the University of Rochester's Institute of Optics, the researchers created mathematical models that predicted the optical properties of the glass-coated bacterial cells. The combined results of the research teams confirmed that bacteria could be bioengineered to create bioglass microlenses with excellent light-focusing properties.

The silica-encapsulated bacteria focused light into intense nanojets that were nearly an order of magnitude brighter than unmodified bacteria. The researchers observed that silica-encapsulated bacteria are metabolically active for up to four months — long enough to allow the bacteria to sense and respond to stimuli over time.

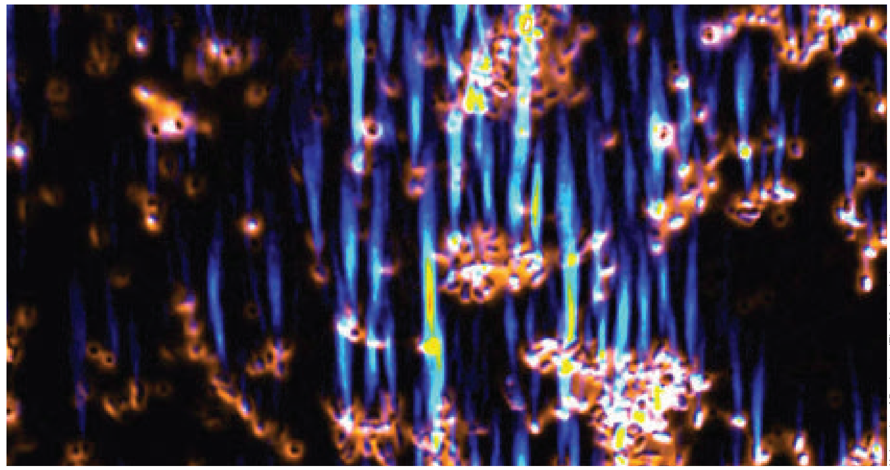
Because the microlenses are created by bacterial cell "factories," they are inexpensive and easy to grow. The bacteria can self-assemble the glass coating at standard temperatures and pressures. "These properties make them well suited for a unique range of applications," Meyer said.

"The ease of producing these microlenses could make them a good way to fabricate optics in locations with less access to nanofabrication tools, including outer space."

The bacterial microlenses are smaller than conventionally produced microlenses. Their small size could make them useful for creating high-resolution image sensors for biomedical imaging, allowing sharper visualization of subcellular features such as protein complexes. And in materials science, the microlenses could be used to capture detailed images of nanoscale materials and structures. They could also be used in clinical diagnostics to enhance the imaging of microscopic pathogens, enabling more accurate identification and analysis.

Because the glass-coated bacteria focus light into bright beams, they have the potential to image objects that are currently too small to be visualized. "This research is the first to engineer light-focusing properties into bacterial cells, and I am excited to explore the different possibilities that our work has opened up," Meyer said. Meyer and her colleagues recently received a grant from the U.S. Air Force Office of Scientific Research to study the biosynthesized microlenses in low-gravity environments.

The research was published in the *Proceedings of the National Academy of Sciences* (www.doi.org/10.1073/pnas.2409335121).



University of Rochester/The Meyer Lab

Glass-coated bacterial cells focus light into bright beams, paving the way for advanced imaging technologies. The developed microlenses could enable higher-resolution image sensors and enhance conventional microscopy.

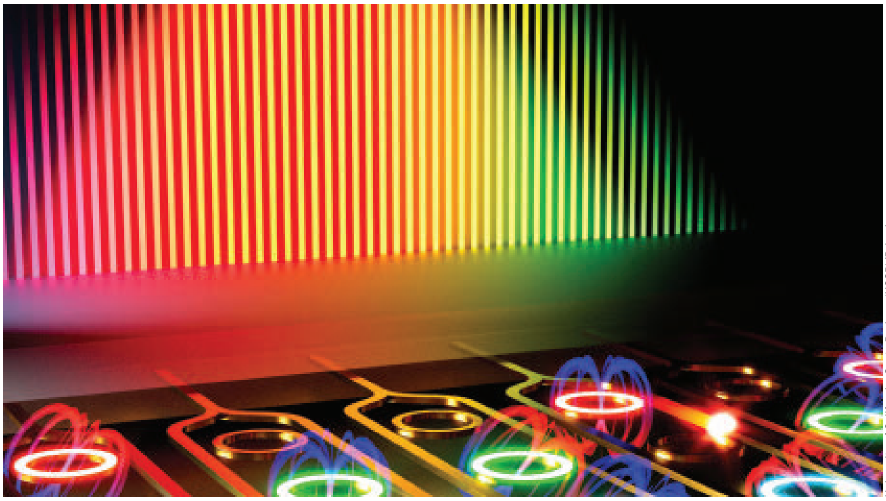
Magneto-optic material bolsters data processing efficiency

GOLETA, Calif. — A platform for in-memory photonic computing using magneto-optic material has the potential to offer efficient, nonvolatile data processing with unlimited read/write capabilities and sub-nanosecond programming speeds. The magneto-optic memory platform developed by researchers from the University of California, Santa Barbara (UCSB) and its partners addresses multiple limitations of existing photonic processing techniques.

Data-intensive applications, such as AI, require ever greater computational power at a time at which the computing capacity of digital hardware has started to plateau. Optical solutions use less energy and process data faster than traditional, electronic-based processing techniques.

In-memory computing, using photonic memories, allows data processing operations to be performed almost instantaneously. But current techniques for creating photonic memories have yet to achieve nonvolatility, multibit storage, high switching speed, low switching energy, and high endurance in a single platform.

The researchers developed a resonance-based photonic architecture that uses the nonreciprocal phase shift in magneto-optic material. They used cerium-substituted yttrium iron garnet (Ce:YIG). The optical properties of this magneto-optic material change in response to external magnetic fields, on silicon microresonators. These properties allowed the researchers to use magnets to store data and control the propagation of light within the material.



A conceptual illustration of a photonic memory array.

"These unique magneto-optical materials make it possible to use an external magnetic field to control the propagation of light through them," said researcher Paolo Pintus, an assistant professor at the University of Cagliari. Fundamentally, the project uses an electrical current to program micromagnets and store data, he said.

The researchers excited the clockwise and counterclockwise modes of the micro-ring resonator with a magneto-optic cladding layer of Ce:YIG. The interaction between the optical mode and the Ce:YIG material induced a nonreciprocal phase shift for the two counter-propagating modes, which appeared as a split resonance shift with opposite signs, dependent on the direction and strength of an applied magnetic field.

This approach to photonic in-memory computing enabled programming speeds of ~1 GHz as well as multilevel encoding. The magneto-optic memory cells can be reprogrammed multiple times to perform different tasks.

The magneto-optic memory platform demonstrated switching speeds that are 100× faster than the switching speeds of integrated photonic technology, the researchers said. At the same time, it consumed about one-tenth the power of traditional photonic processing techniques.

The researchers demonstrated that magneto-optic memories could be rewritten more than 2.3 billion times, which indicates a potentially unlimited lifespan. Existing optical memories, with their limited lifespans, can be rewritten up to 1000 times. Further, by controlling the propagation of light within the Ce:YIG material, Pintus said that the researchers could perform complex operations, such as matrix-vector multiplication. These operations, he said, are at the core of any neural network.

The timing of the work is also important. In the field of deep learning, the computation required to train deep neural networks grew by >300,000× between 2015 and 2020, while the efficiency of graphics processing units grew by only 300-fold. And although several photonic architectures have been proposed to address this bottleneck, the typical approach — to multiply a rapidly changing optical input vector with a matrix of fixed optical weights — is limited by material- and device-level issues.

The UCSB approach to encoding optical weights for in-memory photonic computing, using magneto-optic memory cells, offers several key advantages compared with existing architectures. By leveraging the nonreciprocal phase shift in magneto-optic materials, the researchers achieved a platform for on-chip optical processing that is fast (1 ns), efficient (143 fJ/bit), and robust (2.4 billion programming cycles).

The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-024-01549-1).

Chiral film generation charts a course for photonic device control

ITHACA, N.Y. — A scalable method to introduce chirality into the band structure of semiconductors could advance photonic technologies, including displays, sensors, and optical communications, that harness control over the polarization of light. The method succeeds in enabling simultaneous control over light, spin, and charge.

Chiral materials are often created through exciton-coupling, a process in which light excites nanomaterials to form excitons that interact and share energy with each other. Traditionally, exciton-coupled chiral materials have been made from organic molecules. Creating chiral materials from inorganic semiconductors has proved to be challenging due to the precise control needed over nanomaterial interactions.

Researchers from Cornell University, the Rochester Institute of Technology (RIT), and several European institutions collaborated on a method to form chiral films out of three different inorganic semiconductor nanoclusters through an evaporative deposition process. The resulting films all showed circular dichroism, which is a strong indicator of chirality.

"Circular dichroism means the material absorbs left-handed and right-handed circularly polarized light differently, like how screw threads dictate which way something twists," Cornell professor Richard Robinson said.

The researchers directed highly concentrated solutions of asymmetric, semiconductor "magic-size" nanoclusters of three achiral cadmium-based compounds through a controlled drying meniscus front. Magic-size nanoclusters are atomically and electronically identical, enabling greater wave function overlap and coupling between neighboring nanoclusters. The bandgap, composition, and size of semiconducting magic-size clusters can also be synthesized to tailor the chiroptic responses over many wavelengths.

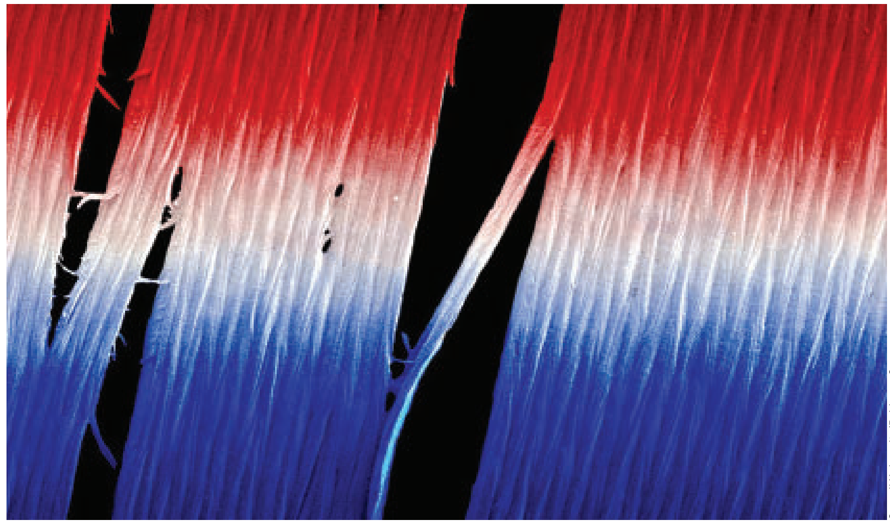
Using meniscus-guided evaporation, the researchers twisted the linear nanocluster assemblies into helical chains, forming homochiral domains several square millimeters in size. By controlling the evaporation geometry, the researchers achieved various domain shapes and sizes that could move smoothly between left- and right-handed chirality. “We saw this as an opportunity to bring a property usually found in organic materials into the inorganic world,” Robinson said.

The chiroptic films achieved via meniscus-guided deposition demonstrated an exceptionally large light-matter response, surpassing previously reported record values for inorganic semiconductor materials by nearly two orders of magnitude. G-factors (the anisotropy factors that measure the degree of chirality in a system) reached magnitudes as high as 1.3 for drop-cast films and 1.06 for patterned films, approaching theoretical limits.

RIT professor Steve Weinstein developed a theoretical framework to interpret the nanocluster fiber deposition patterns observed by the team. This framework helped the team recognize important mechanisms for achieving chiroptic films, including the fluid flows responsible for twisting the fibers.

“Our investigation examines the large-area films that are formed and the mechanisms behind them,” Weinstein said. “The result is the highest chiral signal reported for inorganic materials to date. This evaporation-driven technique not only induces nanometer-scale fiber twists but also allows us to tune their chiroptical properties by controlling the flow parameters.”

The use of three different semiconducting nanocluster systems highlights the scope of the method, indicating that it could apply to other nanocluster species or colloidal nanoplatelets.



Cornell University/Robinson Group

A scanning electron micrograph of a chiral ‘magic-size’ cluster film with micrometer-scale bands being broken into their nanometer-scale filament units. A false color indicates right-handed **(red)**, achiral **(white)**, and left-handed **(blue)** domains.

“I’m excited about the versatility of the method, which works with different nanocluster compositions, allowing us to tailor the films to interact with light from the ultraviolet to the infrared,” researcher Thomas Ugras said. “The assembly technique imbues not only chirality but also linear alignment onto nanocluster fibers as they deposit, making the films sensitive to both circularly and linearly polarized light, enhancing their functionality as metamaterial-like optical sensors.”

The technique for forming chiral films from achiral, solution-processable semiconductors could be used to design and fabricate complex chiroptical materials in ways that are both scalable and versatile. These materials could be used for holographic displays, quantum computing, ultralow-power devices, and medical diagnostics. For example, chiral nanomaterials could be integrated into wearable sensors to detect the way glucose rotates polarized light, enabling highly sensitive glucose monitoring through the skin. This technology would eliminate the need for painful finger pricks, paving the way for continuous, more comfortable glucose tracking.

Future work by the team will focus on extending the technique to other materials, such as nanoplatelets and quantum dots. The researchers said that they will also refine the technique for industrial-scale manufacturing processes that coat devices with semiconductor thin films.

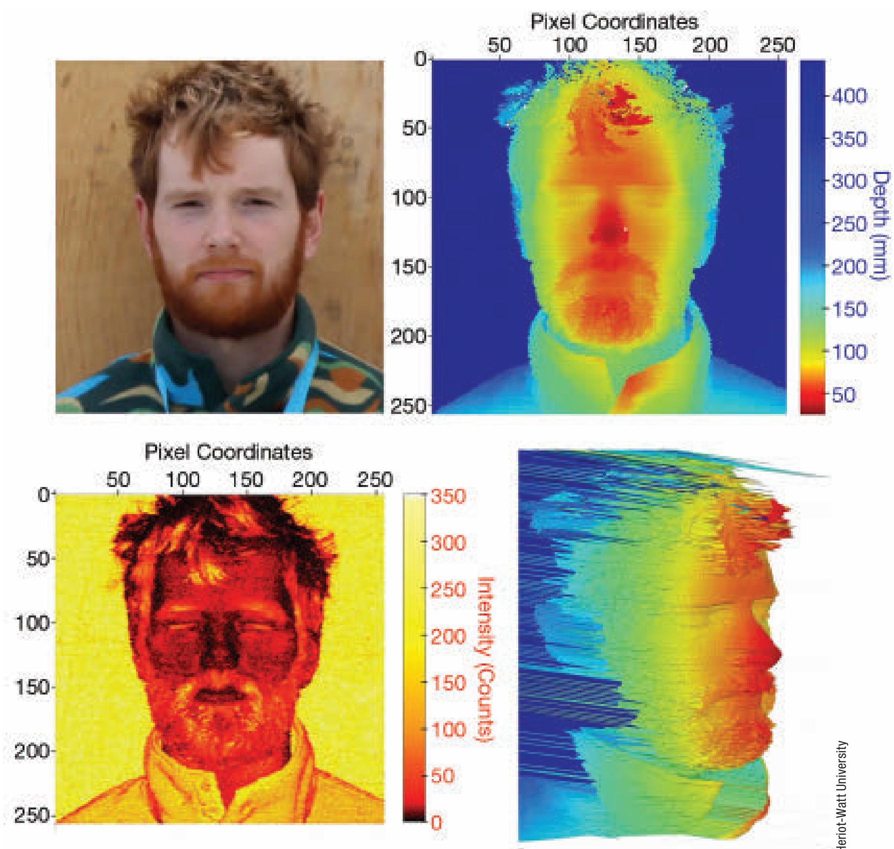
The research was published in *Science* (www.doi.org/10.1126/science.ado7201).

Single-photon lidar delivers detail-rich imagery from a distance

EDINBURGH, Scotland — Scientists developed a sensitive detection system that could vastly improve the accuracy of human facial and activity recognition at long distances and through obstructions such as fog, smoke, and camouflage. The researchers’ single-photon lidar system generated high-resolution 3D images with double the efficiency of similar lidar systems that are under development by other research groups, and at least 10× better image resolution, according to the developers.

The researchers built the system using a superconducting nanowire single-photon detector cooled via a cryocooler fridge designed and developed by the Quantum Sensors group of Robert Hadfield, professor of photonics at University of Glasgow’s James Watt School of Engineering. The work is a collaboration between the Single-Photon Group at Heriot-Watt University, using equipment developed by NASA’s Jet Propulsion Laboratory at Caltech, MIT, and the James Watt School of Engineering.

At a distance of 325 m, researchers 3D-imaged the face of one of their study co-authors in millimeter-scale detail. The same system could be used to accurately



A depth scan of research co-author Gregor Taylor taken 45 m away, using the single-photon lidar system.

detect faces and human activity at distances of up to a kilometer, the researchers said.

"The results of our research show the enormous potential of such a system to construct detailed high-resolution 3D images of scenes from long distances in daylight or darkness conditions," said lead author Aongus McCarthy, a research fellow at Heriot-Watt's Institute of Photonics and Quantum Sciences. "For example, if someone is standing behind camouflage netting, this system has the potential to determine whether they are on their mobile phone, holding something, or just standing there idle. So there are a number of potential applications from a security and defense perspective."

The researchers' breakthrough enabled them to measure the time it took for a laser pulse to travel from the system to the object and back with an accuracy of ~13 ps. This timing is ~10× better than the researchers had been able to do previously.

The system could lead to "step change improvements" in applications such as facial and human activity recognition, and the imaging of scenes through clutter and atmospheric obscurants, the researchers said.

A key advantage of the system is that it accurately measures distances in broad daylight, when scattered light from the sun typically has a negative effect on the measurement process. By using a laser wavelength that is greater than that which can be seen by the naked eye — at 1550 nm — the daylight background is significantly reduced. This wavelength is also ideal for high transmission in the atmosphere and in optical fibers.

Another advantage is that the laser output of the system is low-power and eye-safe.

The researchers tested their system at three distances visible from their rooftop laboratory: a neighboring rooftop 45 m away, a location on the ground 325 m away, and a distant radio mast exactly 1 km away. It was at the 45-m and 325-m locations that research co-author Gregor Taylor posed while his colleagues scanned his head.

The researchers are interested in testing the system over much longer distances.

"Could we recognize a vehicle type at 10 km, whether it's a car or a van or a tank?" McCarthy asked. The system could also be used to monitor the movement of buildings or rock faces to assess subsidence or other potential hazards, McCarthy said.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.544877).

Nano-ridge design approach yields a CMOS-integrated light source

LEUVEN, Belgium — Researchers at imec demonstrated the monolithic fabrication of electrically driven gallium arsenide (GaAs)-based multi-quantum-well nano-ridge laser diodes on 300-mm silicon wafers. The team made the demonstration in imec's CMOS pilot prototyping line and achieved room-temperature continuous-wave lasing with threshold currents as low as 5 mA and output powers >1 mW.

The work demonstrates the potential of direct epitaxial growth of high-quality III-V materials on silicon. It also charts a path to the development of cost-effective, high-performance optical devices for data communications, machine learning, and AI applications, the researchers said.

The lack of highly scalable, native CMOS-integrated light sources has been a major roadblock for the widespread adoption of silicon photonics, the researchers said. Hybrid or heterogeneous integration solutions such as flip-chip micro-transfer printing, or die-to-wafer bonding, involve complex bonding processes or the need for expensive III-V substrates that are often discarded after processing. This not only increases costs but also raises concerns about sustainability and resource efficiency.

For this reason, the direct epitaxial growth of high-quality III-V optical gain materials selectively on large-size silicon photonics wafers remains a highly sought-after objective.

The large mismatch in crystal lattice parameters and thermal expansion coefficients between III-V and silicon materials inevitably initiates the formation of crystal misfit defects. These defects are known to deteriorate laser performance and reliability. As a solution, selective-area growth (SAG) combined with aspect-ratio trapping (ART) significantly reduces defects in III-V materials integrated on silicon by confining misfit dislocations within narrow trenches etched in a dielectric mask.

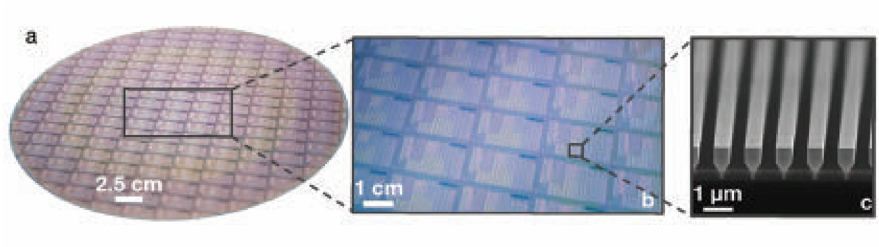
“Over the past years, imec has pioneered nano-ridge engineering, a technique that builds on SAG and ART to grow low-defectivity III-V nano-ridges outside the trenches,” said Bernardette Kunert, scientific director at imec.

This approach, she said, further reduces defects and allows for precise control over material dimensions and composition. The optimized nano-ridge structures typically feature threading dislocation densities well below 105 cm^{-2}.

Exploiting the III-V nano-ridge engineering concept has enabled imec to demonstrate the first full wafer-scale fabrication of electrically pumped GaAs-based lasers on standard 300-mm silicon wafers, entirely within a CMOS pilot line, according to Kunert.

Leveraging the low-defectivity GaAs nano-ridge structures in the demonstration, the lasers integrate indium gallium arsenide multiple quantum wells as the optical gain region, embedded in an in situ-doped PIN diode and passivated with an indium gallium phosphide capping layer. Achieving room-temperature, continuous-wave operation with electrical injection is itself a major advancement, overcoming challenges in current delivery and interface engineering.

The devices showed lasing at ~1020-nm slope efficiencies up to 0.5 W/A, and optical powers reaching 1.75 mW — showcasing a scalable pathway for high-performance silicon-integrated light sources.



A 300-mm silicon wafer containing thousands of gallium arsenide (GaAs) devices **(a)** with a closeup of multiple dies **(b)** as well as a scanning electron micrograph of a GaAs nano-ridge array after epitaxy **(c)**.

“The cost-effective integration of high-quality III-V gain materials on large-diameter silicon wafers is a key enabler for next-generation silicon photonics applications,” said Joris Van Campenhout, fellow silicon photonics and director of the industry-affiliation R&D program on optical input/output at imec.

“These exciting nano-ridge laser results represent a significant milestone in using direct epitaxial growth for monolithic III-V integration.”

The project under which the imec team is working is part of a larger pathfinding mission at imec that aims to push III-V integration processes toward higher levels of technological readiness, from flip-chip and transfer-printing hybrid techniques in the near term, over heterogeneous wafer- and die-bonding technologies and eventually direct epitaxial growth in the longer term, Campenhout said.

The research was published in *Nature* (www.doi.org/10.1038/s41586-024-08364-2).

Ultralight metal foams enable world's brightest x-ray source

LIVERMORE, Calif. — By combining the National Ignition Facility (NIF)'s x-ray laser and ultralight metal foams, researchers at Lawrence Livermore National Laboratory (LLNL) produced the brightest x-ray source to date — about twice as bright as previous solid metal versions, according to the scientists.

These ultrabright, high-energy x-rays can be used to image and study extremely dense matter, such as the plasmas created during inertial confinement fusion.

LLNL scientist Jeff Colvin compared the source to the machine used to find cavities by a dentist. "Your dentist's machine creates an electron beam that is crashed into a heavy metal plate. The electrons in the beam interact with the electrons bound to the metal atoms to create x-rays," he said.

"At NIF, we use the high-power laser beam instead of an electron beam to make the x-rays by 'crashing' the beam into silver atoms and creating a plasma."

The choice of silver is important, because the higher the atomic number of the metal atom, the higher the energy of the x-rays that it produces. The team used silver because it wanted to make x-rays with energy >20,000 eV.

The foam structure of the metal was also critical to achieving this goal. The team manufactured 4-mm-wide cylindrical targets using a mold and silver nanowires.

"We froze the nanowires suspended in solution in the mold, then applied a supercritical drying process to remove the solution, leaving the low-density porous metal foam," said LLNL researcher Tyler Fears.

"We made silver foam with a density about 1/1000 of solid density, which is not much higher than the density of air," Colvin said.

In such a foam, the NIF laser heats up a larger volume of the material and the heat propagates much faster than in a solid. The whole cylinder of foam heats up in ~1.5 billionths of a second.

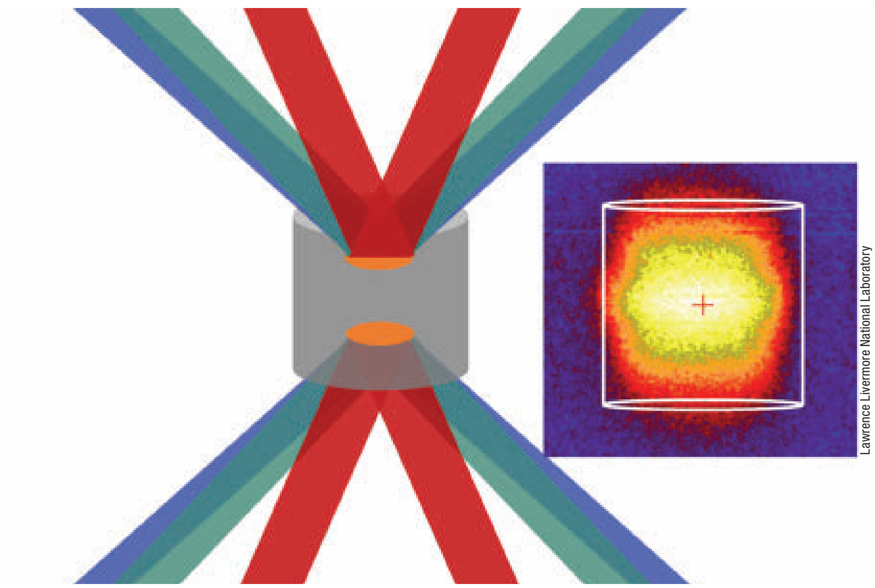
In addition to creating the x-ray source, the researchers explored differing foam densities to determine which provided the maximum energy output. They also applied a new data analysis technique to attempt to understand the physics of the generated plasma.

Using this data, they found that these bright, hot metal plasmas are far from thermal equilibrium. Models, such as those used to examine inertial confinement fusion at NIF, typically assume plasmas are close to equilibrium, with electrons, ions, and photons all having around the same temperature.

"Going forward, this means we need to rethink our assumptions about heat transport and how we calculate it in these particular metal plasmas," Colvin said.

The research was published in *Physical Review E* (www.doi.org/10.1103/PhysRevE.111.015201).

The National Ignition Facility (NIF) lasers overlap onto the millimeter-scale cylindrical silver foam target. The resultant heating creates x-rays, which are then imaged **(right)**.



Lawrence Livermore National Laboratory

Conical polymer fibers reduce inflammation risk for optogenetics

KONGENS LYNGBY, Denmark — To deliver light to the brain safely and efficiently, researchers at the Technical University of Denmark designed tapered optical fibers made with soft, biocompatible polymer. The tapered fibers are optimized for light-based neural stimulation techniques, such as optogenetics. They could be used in studies to develop treatments and interventions for a range of neurological conditions.

The tapered fibers feature a conical shape that allows light to leak from the sides of the fiber along the length of the tapered tip. The conical design increases the volume that can be illuminated, enabling homogeneous light delivery to a large volume as well as spatially resolved illumination, while being minimally invasive.

Until now, tapers for light-based neural applications have been used only with optical fibers made with silica. The stiffness of the silica material can cause damage to tissue when the fiber is used for prolonged periods of time. "Making the fibers from soft, flexible polymers rather than stiff, sometimes brittle glass can reduce tissue inflammation over long periods of implantation," said professor Marcello Meneghetti.

"Long-term inflammation and implant breakage are persistent challenges in silica- or silicon-based neurophotonics," he said. "The mechanical mismatch between implants and brain tissue triggers inflammation, and the brittleness of these materials leads to fractures at submillimeter scales."

After observing the growing use of glass fiber tapers for efficient modulation and recording of neuronal activity, the researchers decided to adapt the technology to optical fibers made with polymer to mitigate the possibility of breakage and inflammation. According to Meneghetti, polymer-based fibers are >10× less stiff than glass-based fibers.

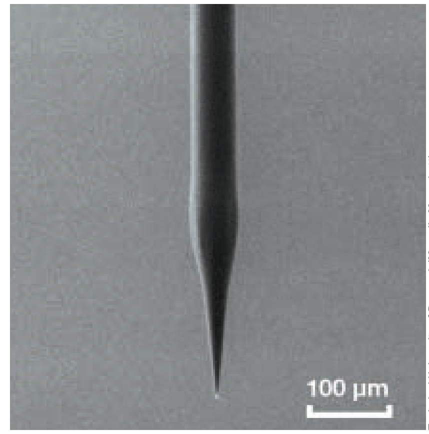
The researchers developed a reliable, reproducible way to fabricate tapered polymer optical fibers for sending light to the brain. They used numerical models to determine the optimal materials and best taper geometry. They developed a chemical etching process to fabricate the fibers and fabricated two types of polymer optical fibers using thermal fiber drawing. They made the tapers with fibers that were 50 μm in diameter.

To achieve the shape intended for the fiber tips, the researchers tested various solvents and protocols. They verified the accuracy of the taper geometry and the surface integrity and investigated the effects of different parameters on the etching process and on the quality of the tapers that were produced. Finally, they tested the polymer fibers by using them to illuminate slices of agarose gel, which is known to have optical properties similar to brain tissue. The tapered optical fibers were found to more than double the lateral spread of light, compared with standard optical fibers with the same diameter and constituent material.

The researchers optimized the tapered fibers to produce a large illumination volume for neuroscience research techniques, such as optogenetic experiments and fiber photometry, that rely on the interaction between genetically modified neurons and visible light delivered to and/or collected from the brain.

"Our polymer tapers make it possible to modulate the behavior of and record activity from more neurons, thus allowing the study of larger brain circuits," Meneghetti said. "This could produce deeper insights into how complex brain circuits function, how behaviors are controlled, and how brain diseases or disorders might disrupt these circuits."

Next, the researchers plan to demonstrate the tapered fibers in an animal model to evaluate the functionality of the fibers and the ability of polymer-based



Technical University of Denmark/Marcello Meneghetti

Researchers developed tapered polymer optical fibers that are optimized for delivering light to the brain. A scanning electron microscopy image of one of the tapers is shown here.

optical fibers to reduce the chance of inflammation. In the future, the fabrication process could be combined with post-processing techniques, such as nanofabrication, which could lead to fully integrated devices that not only deliver and collect light, but also detect electrical signals and sense temperature or chemical changes in the brain. Such a device could provide a more comprehensive understanding of brain activity in both healthy and diseased states.

The research was published in *Optics Letters* (www.doi.org/10.1364/OL.546470).

Frequency comb design broadens bandwidth and uses less power

LAUSANNE, Switzerland — Traditionally, building compact and efficient electro-optic (EO) frequency combs has been a challenge: Although they were introduced in 1993, their development has been hampered by their need for large amounts of power and their bandwidth restrictions. Femtosecond lasers and Kerr soliton microcombs have also been used to measure light.

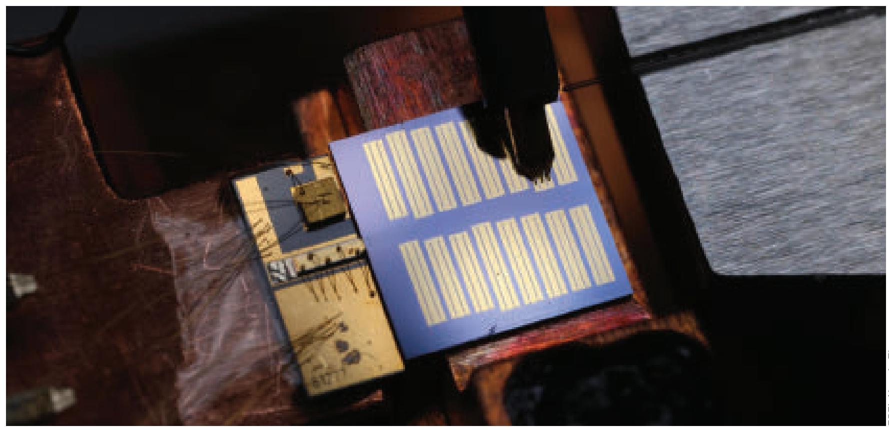
Though these technologies are effective, they require complex tuning and high amounts of power, limiting their field-ready use.

An integrated design for EO frequency combs expands the bandwidth of the comb and significantly reduces its microwave power requirements, compared with previous designs. An international team comprising researchers from École Polytechnique Fédérale de Lausanne (EPFL), the Colorado School of Mines, and the Chinese Academy of Sciences, led by professor Tobias Kippenberg at EPFL, created the EO comb generator using an integrated triply resonant architecture. This architecture features three interacting fields — two optical and one microwave — that resonate in harmony.

The integrated EO frequency comb could benefit robotics, environmental sensing, spectroscopy, astronomy, and other fields that require the precise, efficient measurement of light.

The researchers combined monolithic microwave integrated circuits with photonic integrated circuits (PICs) on a platform of thin-film lithium tantalate ($LiTaO_3$), a low-birefringence material. By embedding a distributed, coplanar waveguide resonator on $LiTaO_3$-based PICs, the team significantly improved microwave confinement and energy efficiency, reducing its microwave power requirements almost 20-fold.

Traditionally, lithium niobate ($LiNbO_3$) is used to enable EO frequency combs. This material can be used to make combs



EPFL/Junyin Zhang

The hybrid-integrated, electro-optic (EO) frequency comb generator. More than 2000 comb lines covering a 450-nm spectrum can be generated within a footprint of <1 sq cm.

that are precise and simple to operate, though combs made with $LiNbO_3$ offer limited spectral coverage. This is due to the large amount of microwave power required to drive the nonresonant capacitive electrodes and the strong intrinsic birefringence of $LiNbO_3$.

The birefringence of $LiNbO_3$ places an upper limit on the comb's achievable bandwidth. $LiTaO_3$ has 17× lower intrinsic birefringence than $LiNbO_3$.

The team designed a compact EO comb with broad bandwidth and low power requirements. With resonantly enhanced EO interaction and the reduced birefringence in $LiTaO_3$, the developed comb design demonstrated a fourfold comb span extension and a 16-fold power reduction compared with the conventional, nonresonant microwave design.

Driven by a hybrid integrated laser diode, the spectral coverage of the comb design spans >450 nm (>60 THz), with more than 2000 comb lines, exceeding the limits of current EO frequency comb technologies. The comb achieves stable operation across 90% of the free spectral range, eliminating the need for complex tuning mechanisms. The stability and simplicity of the comb design could advance the use of EO combs for field-deployable applications.

The comb fits within a 1- × 1-sq-cm footprint. Its compact size is enabled by leveraging the low birefringence properties of $LiTaO_3$, which minimize interference between light waves, enabling smooth, consistent frequency comb generation. The device is operated using a simple, free-running distributed feedback laser diode, making it much easier to use than Kerr soliton combs.

Additionally, the researchers found that strong EO coupling led to an increased comb existence range, approaching the full free spectral range of an optical microresonator.

The methodology used by the team to codesign microwave technology and photonics could be extended to a range of integrated EO applications. Broadly, the use of this methodology to create EO combs highlights the potential to integrate microwave and photonic engineering for next-generation devices.

The research was published in *Nature* (www.doi.org/10.1038/s41586-024-08354-4).

Graphene laser lift-off is used for wearables manufacturing

SEOUL, South Korea — In a step forward for stretchable, wearable technologies, researchers demonstrated a graphene-enabled laser lift-off (GLLO) technique that ensures smooth separation of thin-film flexible displays during the manufacturing process. The technique could accelerate the development of ultrathin, high-performance devices that fit comfortably against human skin.

GLLO, which was developed at Seoul National University of Science and Technology (SeoulTech), uses the optical, thermal, adhesive, and geometrical properties of graphene to prevent damage to ultrathin displays. A graphene layer improves UV light absorption, distributes heat evenly, and reduces adhesion in the thin film. These factors serve to reduce plastic deformation in the film during the ablation process.

Polyimide films are widely used to make thin-film flexible displays, because they offer thermal stability and mechanical flexibility. These films are used for technologies such as rollable displays, wearable sensors, and implantable photonic devices. But successful separation of an ultrathin polyimide film using traditional laser lift-off (LLO) techniques remains a challenge. When the thickness of the film is reduced to <5 μm, it becomes delicate and prone to mechanical deformation during the LLO process. The deformation causes wrinkling and rupturing in the film that can occur during the malfunction of photonic devices.

Reducing the thickness of the polyimide films used in flexible displays enhances the stretchability and mechanical reliability of the device. Next-generation applications, such as implantable and wearable photonic health care devices, will therefore require ultrathin-film displays to allow conformal contact with soft and curvilinear surfaces.

GLLO integrates a layer of chemical vapor deposition (CVD)-grown graphene at the interface between the film and the transparent glass carrier. This improves processability and lift-off quality. In addition, GLLO mitigates plastic deformation of the film and minimizes the carbon residue on the carrier.

Also, CVD-grown graphene enables the LLO performance to be programmed by controlling the number of integrated layers.

"Graphene's unique properties, such as its ability to absorb UV light and distribute heat laterally, enable us to lift off thin substrates cleanly, without leaving wrinkles or residues," said professor Sumin Kang, who led the research.

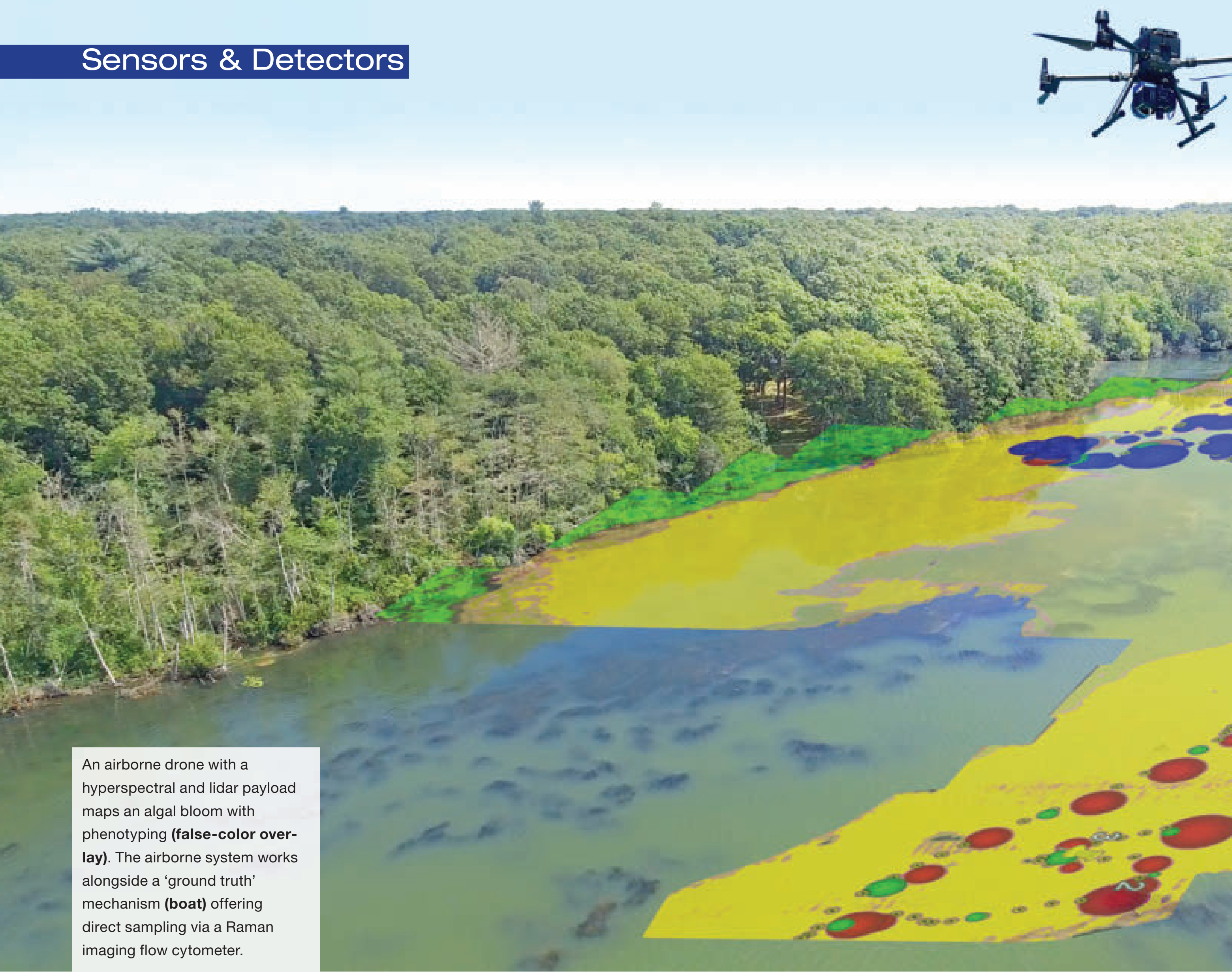
To demonstrate the effectiveness of the integrated graphene, the researchers compared the process window and lift-off quality of the polyimide film using conventional LLO and GLLO. They demonstrated the role of graphene layers during the ablation process through experiments and numerical simulations. Using the GLLO method, the researchers separated 2.9-μm-thick polyimide film substrates without any mechanical damage or carbon residue. In contrast, traditional methods left the substrates wrinkled and the glass carriers unusable due to the residue.

The researchers created OLED devices on ultrathin polyimide film substrates and processed the OLEDs using GLLO. The OLEDs retained their electrical and mechanical performance, showing consistent current-density-voltage-luminance properties before and after lift-off. They also withstood extreme deformations, such as folding and twisting, without functional degradation. Additionally, the use of GLLO reduced carbon residue on the glass carrier by 92.8%, enabling the carrier to be reused.

"Our method brings us closer to a future where electronic devices are not just flexible, but seamlessly integrated into our clothing and even our skin, enhancing both comfort and functionality," Kang said. In addition to enabling ultrathin, flexible, high-performance devices for daily use, GLLO could open possibilities for the use of CVD-grown graphene in laser-based manufacturing applications, such as emerging displays, wafer-level packaging, and energy-harvesting devices.

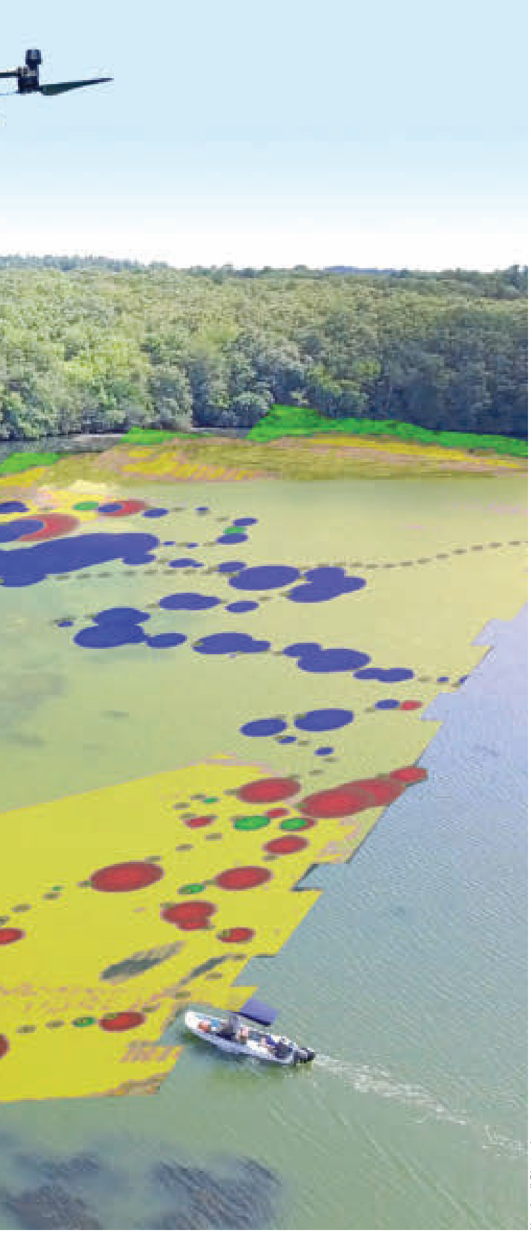
The research team plans for further enhancements to the GLLO technique, with a focus on complete residue elimination and enhanced scalability.

The research was published in *Nature Communications* (www.doi.org/10.1038/s41467-024-52661-3).



An airborne drone with a hyperspectral and lidar payload maps an algal bloom with phenotyping **(false-color overlay)**. The airborne system works alongside a 'ground truth' mechanism **(boat)** offering direct sampling via a Raman imaging flow cytometer.

Component and System-Level Breakthroughs Extend Environmental Remote Sensing from Detection to Prevention



Headwall Photonics

Innovation in photodiode sensitivity underpinned by AI integration, device miniaturization, and energy-efficient designs delivers sharper forecasts and a more sustainable future.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

As the world grapples with escalating environmental challenges, demand has never been greater for durable and high-performance monitoring technologies. As a result of the number of different environmental applications that require advanced detection, as well as the volume of necessary deployments for these solutions, opportunities are surging for systems that offer improved levels of precision and adaptability.

Photonics innovations are already essential to many remote sensing applications. Optical sensing technology thrives in environments that are remote, hazardous, and extreme, enabling improved outcomes in emergency situations and challenging settings. Modalities ranging from lidar to opto- and photoacoustic sensing to thermal imaging are among the many techniques that are well established in the realm of optical remote sensing.

The sophistication of today's solutions begins at the component level and extends to full systems. Photodiodes enable precise and rapid data collection across diverse scales, from the microscopic to expansive terrains. Sensing incoming light from UV-IR LEDs or lasers, commercial photodiodes support the lidars and spectrometers that play a critical role in many advanced detecting, monitoring, and forecasting systems. AI integration into these systems is anticipated, as are continued improvements in sensitivity and spectral range as well as device miniaturization.

At the same time, the technology gains that are central to today's ever-improving solutions are only part of a broader trend, insofar as it relates to current needs in environmental sensing and detection. "As recognition that industrial and civic activities are the causes of environmental problems becomes established, the purpose of sensing may shift from understanding environmental issues to preventing the occurrence of environmental problems, evaluating pollution improvement (purification), and quantifying the environmental contributions of businesses," said Jake Li, marketing research manager at Hamamatsu.

"Additionally, the increase in the production of biofuels and the manufacturing of new industrial products, such as bioplastics, may create new sensing needs."

From assessing flood damage and monitoring air quality, to forecasting solar energy and optimizing agricultural conservation practices, optical remote sensing is revolutionizing environmental management. As the sensing and monitoring technologies that enable these and many other applications continue to improve, the distinct advantages that they deliver are finding utility across existing and new-to-emerge sectors. Notable advantages include noncontact and nondestructive measurement as well as the capability to collect vast data sets in real time.

The result is faster, better-informed decision-making in both situation assessment and prevention.

Urban pollution monitoring

Especially in large metropolitan areas, motor vehicles remain a significant contributor to urban ozone and particulate pollution. This problem persists despite the introduction of periodic emissions inspection programs and tightening air quality standards aimed at protecting human health and the environment. In the U.S., the Federal Highway Administration (FHWA) Spring 2024 long-term forecasts of national vehicle miles traveled (VMT) show total VMT increasing (at an average annual rate of 0.5%) between 2019 and 2050.

Vehicle inspection and emissions testing firm Opus Inspection Inc. has developed technology that aims to help with ensuring that standards are not circumvented on emission tests. The company's remote sensing solution uses fast-response photodiode arrays to measure vehicle emissions from the roadside as motorists drive by. The device provides real-time roadside inspection


Opus Inspection

Opus Inspection Inc.'s remote sensing systems enable roadside emissions inspection in real time using fast-response photodiode arrays to measure vehicle emissions.

that can be used to monitor full motor vehicle fleets.

"In Denver, remote sensing devices are used to complement the local periodic inspection programs by screening the cleanest emitters for exemption from the program," said Niranjan Vescio, director of remote sensing at Opus Inspection. "In other programs, they identify the highest emitters for urgent reinspection and repair."

Portable spectroscopy systems are commonly used to identify concentrations of so-called criteria pollutants — such as ozone, nitrogen dioxide, and particulate matter, all of which are notorious for their adverse health effects and damage to crops and ecosystems. These systems operate efficiently without requiring physical sampling, which makes them ideal for dynamic, real-time monitoring.

Many such systems are equipped with photodiodes. Developments in manufacturing processes and, further upstream, materials science, have enabled photodiodes to withstand extreme temperatures, high radiation levels, and mechanical stress. The resulting components capture subtle changes in light intensity and wavelengths that are vital for detecting trace pollutants and capturing minute changes in the environment.

Particulate matter is a common thread between general emissions monitoring and other environmental applications, such as assessing water quality. Particulate monitoring typically involves the use of light-scattering methods: Light from a source (a laser or LED emitter) is scattered and then measured using a photodiode array, typically silicon. The demand for more efficient, accurate, and reliable gas monitors has increased the demand for deep-UVC LEDs and silicon carbide (SiC) detectors for UV gas sensors as well as MIR and SWIR LEDs and indium gallium arsenide (InGaAs) or lead selenide (PbSe) photodiodes for IR gas monitors.

LED and detector manufacturers, including Marktech Optoelectronics, are pioneering active emitter-detector technologies that integrate multiple-wavelength LEDs and photodiodes into a single compact package. These multi-chip devices enable water quality instruments to simultaneously detect various analytes in water samples and several gases in continuous emission monitors. By streamlining functionality, innovations such as these enhance detection capabilities and significantly reduce the complexity and cost of environmental monitoring.

"SWIR and MIR LEDs coupled with compound semiconductor detectors such as InGaAs and PbSe photodiodes are newer optical sensing technologies used to monitor carbon dioxide and methane releases and levels in the atmosphere," said Mark Campito, CEO of Marktech. "These newer solid-state or semiconductor-based optical detectors and LED emitters are replacing older thermal emitters and pyroelectric infrared detectors."

Methane, a major air pollutant and greenhouse gas, is often released due to equipment malfunctions in industrial facilities, or pipeline leaks. In 2022, more than 1000 methane leaks were identified worldwide. According to Li, gas detection through optical absorption by IR or UV light is 3× more sensitive than traditional technologies for the detection of methane and also enables leaks to be pinpointed more quickly and easily. This means that maintenance can be conducted swiftly upon the detection of a leak.

Emissions monitoring at every scale

Though the emission of an array of greenhouse gases can be assessed locally at chemical plants, assessing overall levels in the atmosphere requires global monitoring, which can be achieved using

Comparison of Photodiode Materials: Silicon and Indium Gallium Arsenide

Parameter	905 nm	1550 nm
Cost	Low (cheap lasers and detectors)	High (expensive InGaAs components)
Eye Safety	Limited (low power)	High (absorbed by cornea)
Range	Medium	High
Weather Resistance	Medium	Best (less absorption in fog)
System Size	Compact	Larger
Power Consumption	Low	Higher
Detectors	Silicon (cheap, common)	InGaAs (expensive, sensitive)

Inertial Labs

satellite-based optical sensor systems. Real-time lidar systems are integrated with global navigation satellite systems and an inertial navigation system. Photodiodes play an essential role in these systems, too, converting reflected light signals into an electrical signal with high sensitivity and fast response speed.

Their function in such systems, however, overcomes a challenge that stems from the fact that lidar systems operate under background noise created by sunlight (and other light sources). Even though light filters largely compensate for these factors, a low dark current level and high selectivity are essential for the photodiode to reduce the effect of noise.

For example, measuring air quality in a parking lot with two different lidar systems produces different point clouds depending on atmospheric conditions. In rain, snow, fog, or in a dusty parking lot, a system operating at 905 nm may provide a completely different picture than that of a system operating at 1550 nm. On the other hand, the same 1550-nm lidar survey carried out at an altitude of 120 m in the remaining areas results in a slightly better picture than that of a 905-nm system used at an altitude of 50 m.

"Modern lidars often work with several laser pulses simultaneously, which requires detecting multiple signals with high accuracy. Photodiodes with a matrix structure of photodiode arrays can simultaneously analyze many signals," said Anton Barabashov, vice president of business development at Inertial Labs, a designer, integrator, and manufacturer of inertial measurement units and other sensing systems.

"Thanks to this, we can scan large areas, and the detail of objects increases."

Soil and Earth monitoring

Soil emits significant levels of greenhouse gases including carbon dioxide, nitrous oxide, and methane — each of which contributes to climate change. Optical sensing technologies such as NIR spectroscopy and back-thinned CCD (BT-CCD) image sensors track these emissions and support precision agriculture by improving crop health and soil condition assessments. Additionally, satellite-based sensors and lidar are used to detect pollutants, mining tailings, and plastics on land and in oceans. InGaAs photodiodes have enhanced SWIR imaging for these applications, enabling the identification of hazardous mining by-products as well as potential resources within old tailings, such as lithium or other valuable elements.

"Carbon emissions from the soil in farming primarily occur when soil organic matter decomposes due to microbial activity," Li said. According to Li, several technologies have been developed to help reduce these emissions. This has allowed farmers to gain additional revenue through selling carbon credits, he said.

Hyperspectral technologies are bridging the critical gap between satellite-based observations and local sampling in Earth monitoring. Advanced visible-NIR and SWIR imaging systems deliver high-resolution, actionable data by capturing detailed spectral signatures at spatial resolutions far greater than satellites can achieve. This makes them indispensable for analyzing soil health as well as applications such as detecting algal blooms and monitoring methane emissions. Operating from aerial or ground-based platforms, these systems provide precise environmental insights at scales and resolutions unattainable by satellites or traditional sampling alone.

"With hyperspectral imaging, we are not just observing the environment — we are uncovering the detailed chemistry that drives it," said David Blair, remote sensing general manager at Headwall Photonics.

"This level of insight is critical for tackling today's environmental challenges with smarter, more sustainable solutions."

Shining a light on water safety

Water contamination from industrial and agricultural runoff is a pressing concern; pollutants such as nitrites and nitrates affect lakes, oceans, and drinking water.

For companies including Silanna and Marktech Optoelectronics, developers of rugged IR and/or deep-UVC LEDs for spectrometry systems, considerations regarding device portability and real-time results are paramount. Today's water quality sensors and emission monitors use mercury vapor lamps, which have limitations. They require warm-up periods, cannot be pulsed, and produce high heat, leading to sensor lens fouling. They also emit a broader spectrum of light, including higher UV wavelengths that may cause damage to human end users. In contrast, newer 235- and 255-nm deep-UVC LEDs exhibit lower heat output and eliminate lens fouling.

"They do not contain toxic compounds, can be instantly turned on and off, and their pulsing capability further extends their long lifespan," Campito said. "These advantages make deep-UVC LEDs and detectors a safe, efficient, and compact solution."

Other optical approaches use colorimetry, fluorescence, scattering, and/or spectroscopic methodology to analyze the chemical components and particulates in water samples. For example, a value of the turbidity (the amount of suspended particulate matter in a water sample) can be obtained by measuring the amount of scattering from an IR LED — typically 860-nm LEDs — combined with a silicon photodiode array. IR light minimizes color interference or absorption due to particles with different colors. In fluorescence water quality monitoring, meanwhile, fluorometers with an LED at a peak wavelength that is close to the excitation wavelength of the fluorophore is used. The photodiode detects the emission wavelength from the fluorophore. Optical filters can then be used on the LED and photodiodes so that only the fluorescence light emission is detected.

Ensuring seamless energy generation

Solar energy is one of the fastest-growing sources of renewable energy, owing to its cost-effectiveness and abundance. But it is inherently unpredictable due to fluctuations caused by weather conditions, time of day, and seasonal changes.

With the percentage of grid power from solar power plants increasing, and due to these variables, accurate solar forecasting is the subject of increased focus. Accurate forecasting enables grid operators to take necessary steps to balance supply and demand as well as take measures to mitigate energy instability, outages, and overloads.

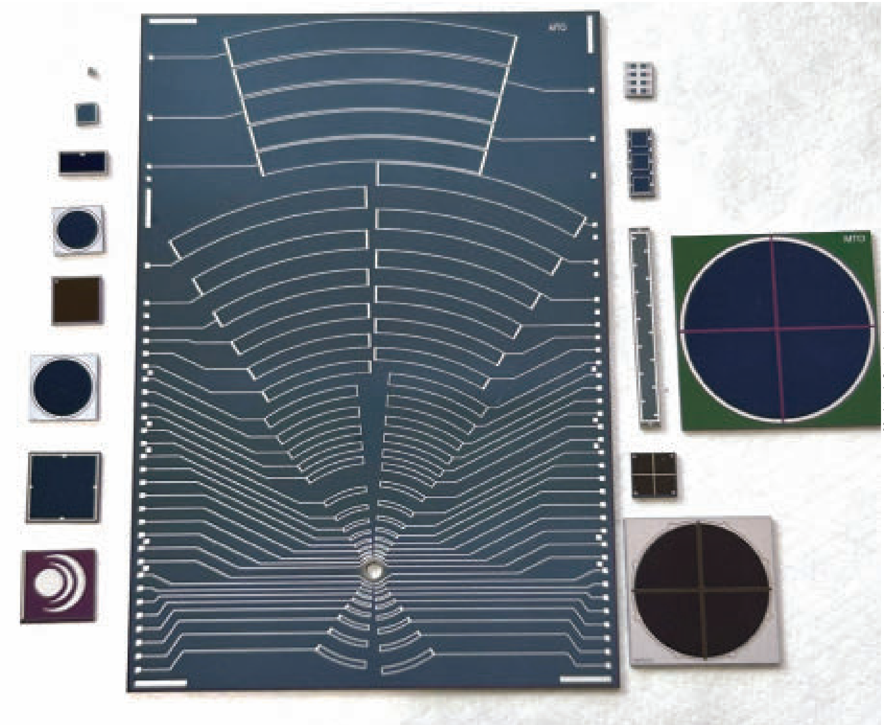
Recent advancements in fine sun sensors involve using quadrant photodiodes to precisely track the sun's position. These sensors analyze sunlight intensity across four quadrants to determine the sun's angle and enable solar panels to be optimally aligned. Fine sun sensors are adaptable both for terrestrial- and space-based systems, Campito said. Typically, silicon quadrant photodiodes are used for their sensitivity in the visible and NIR, while lithium-drifted silicon detectors and InGaAs photodiodes are preferred in high-precision or specialized applications such as aerospace or IR tracking. In the coming years, experts anticipate advancements in predictive technologies combined with AI analysis.

Optical sensing ubiquity

Photodiodes have steadily improved in size, speed, and sensitivity, driving advancements across environmental applications. Miniaturized photodiodes now power portable devices such as handheld air quality monitors, while materials such as SiC and InGaAs enhance responsivity for detecting faint signals in UV radiation monitoring. Faster response times enable real-time data processing,

Photodiode Metrics: Performance and Characteristics

1. **The size of the photodiode's photosensitive area**: A larger active area captures more photons, which improves sensitivity, especially in low-light conditions.
2. **Speed (response time/bandwidth)** determines how quickly the photodiode can respond to changes in light intensity, usually measured in bandwidth or rise time.
3. **Overall dimensions of the photodiode package**: Small dimensions simplify integration into dense electronic systems or optoelectronic chips.
4. **Sensitivity**: The ratio of electrical output (current or voltage) to incident light power is usually measured in amperes per watt. High sensitivity enables the detection of even weak light flux, which is vital for lidar scanning.
5. **Noise characteristics**: Intrinsic electronic noise, which limits the ability of the photodiode to detect weak signals, is measured as the noise equivalent power or signal-to-noise ratio.
6. **Wavelength range (spectral sensitivity)** is usually determined by the material from which the photodiode is made.
   - **Silicon photodiodes** for the visible and NIR range (250 to 1100 nm).
   - **Indium gallium arsenide (InGaAs) photodiodes** for the NIR and SWIR (650 to 2600 nm).
   - **Indium arsenide antimonide**, **lead selenide (PbSe)**, **and mercury cadmium telluride photodiodes** for 2500-µm and longer wavelengths.



Marktech Optoelectronics

Single **(left)** and multiple-element silicon photodiodes, plus assorted linear arrays and quadrant photodiodes **(right)**. The complex 65-element silicon photodiode **(center)** can be mounted on an aircraft wingtip to detect laser pulses bounced off ice particles to monitor particle size distribution.

vital for dynamic scenarios such as tracking pollutant plumes.

There seems to be an ever-growing expectation that sensing solutions will continue to get better, faster, and cheaper. And so expectations keep rising.

For Saul Nuccitelli, director of the Texas Water Development Board's Flood Science and Community Assistance Division, there is an increased expectation that lidar can better penetrate vegetation and other obstructions to provide a clearer picture of true bare-earth conditions. Today, SWIR LEDs coupled with InGaAs photodiode-based cameras image through clouds, smoke, dust, and certain plastics. "In flood damage assessment, optical sensing technologies have transformed how elevation data is collected," Nuccitelli said.

Flood damage varies significantly with water depth. For instance, 6 in. of flooding may only require floor and drywall repairs. But 18 in. can damage electrical systems, drastically increasing cost. Traditional methods rely on estimating elevation based on building polygons or corner averages, which often lack precision.

Now, ground vehicles equipped with advanced optical sensors and AI capture images of individual homes, focusing on the bottom of front doors as a reliable marker for first-floor elevation. This innovative approach offers more precise data at a fraction of previous costs.

"As the cost to obtain this information drops and quality increases, this technology can be a game changer for developing more accurate flood damage estimates at a large scale," Nuccitelli said.

To meet growing demand, integration with AI is set to further boost data interpretation, as seen already in automated weather predictions. Even as this ascending technology blossoms, and as environmental challenges continue, LEDs and photodiodes will retain a growing role of their own in optical sensing for energy and climate solutions with energy-efficient designs aligning with ecological goals.

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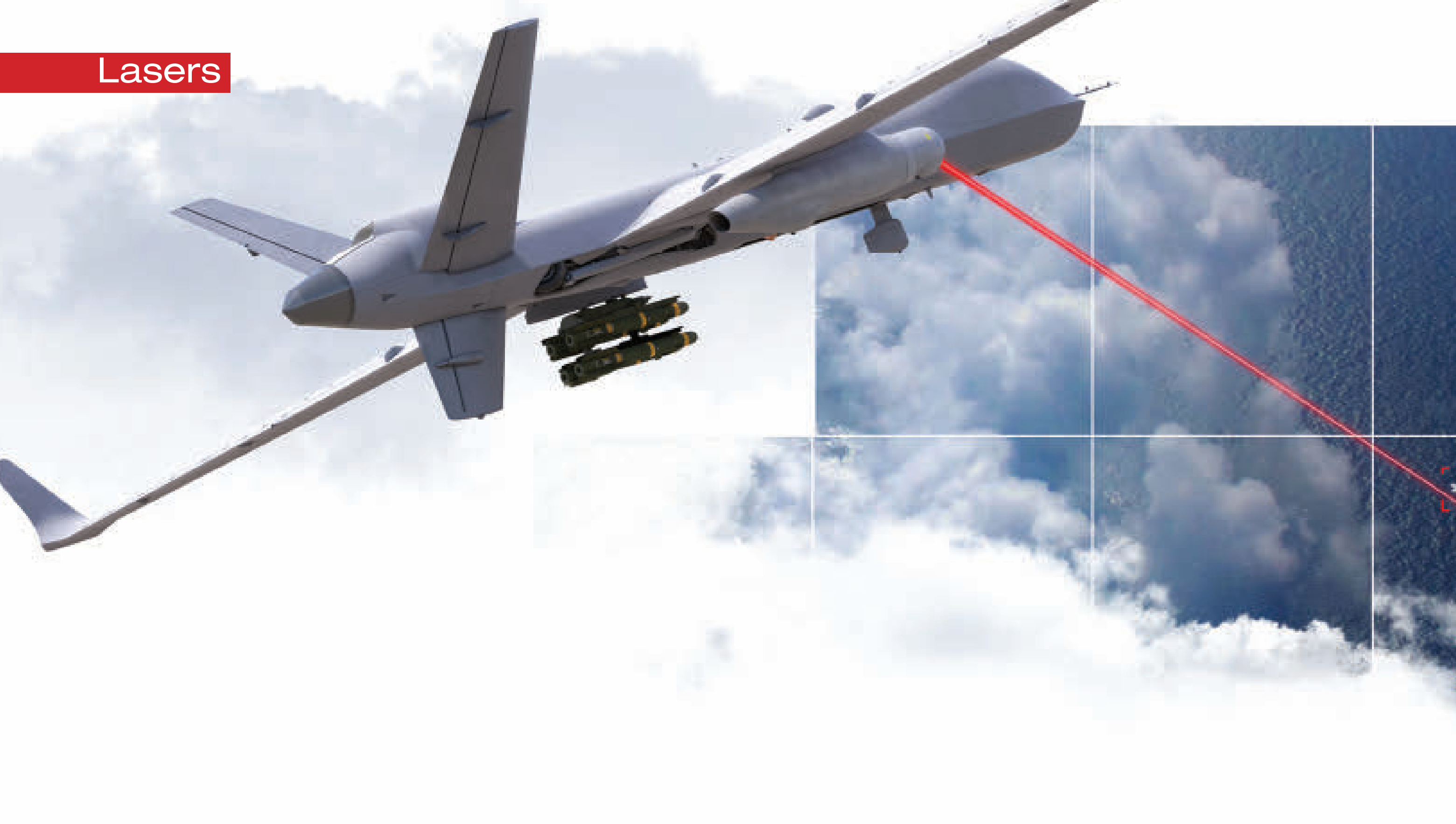
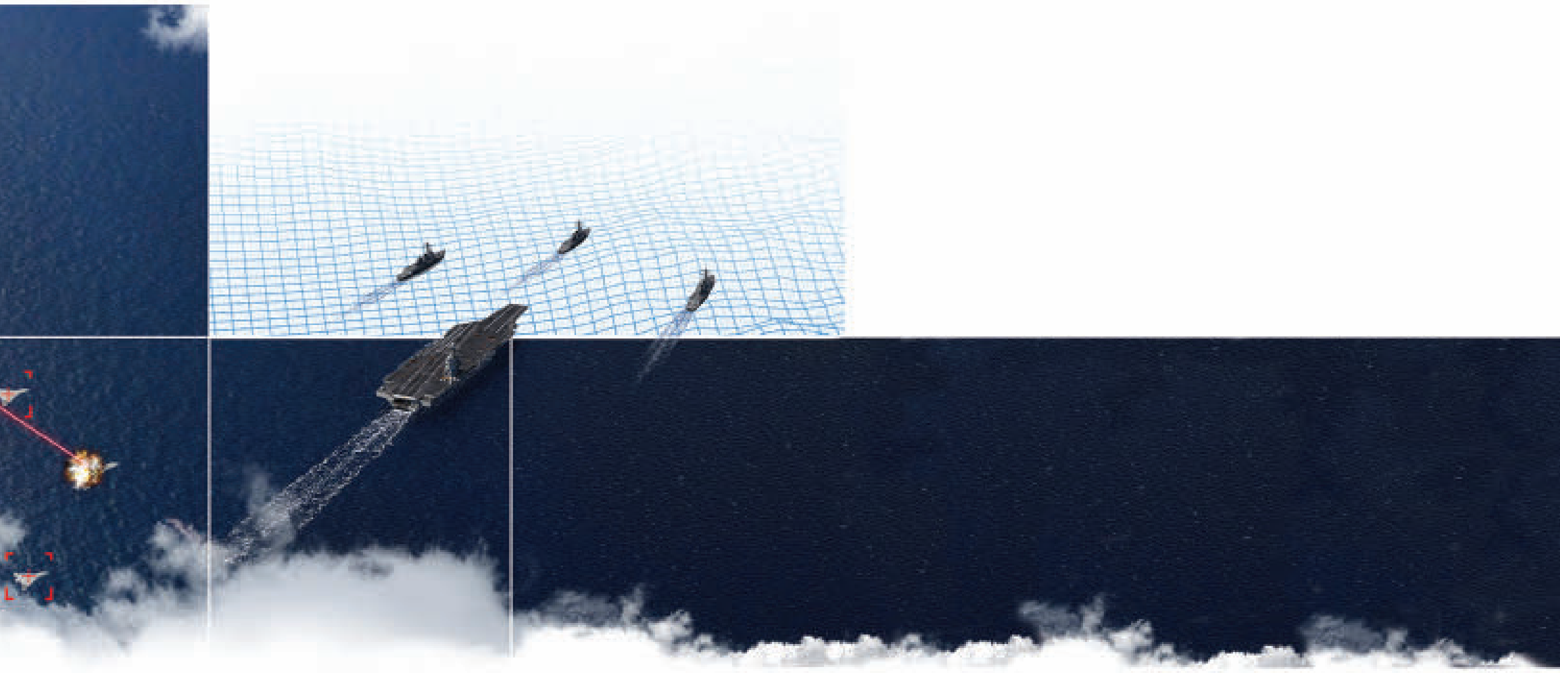


Directed Energy Technologies

Mount an Energetic Response to the Drone Threat

Amid abundant opportunity for directed energy systems, the viability of the technology's deployment hinges on sustained investment.

Opening image courtesy of General Atomics.
All other images courtesy of OFS.



BY MICHAEL EISENSTEIN
CONTRIBUTING EDITOR

"Keep your eye on the sky" is a critical rule in modern warfare, due to the rapid proliferation of low-cost, speedy uncrewed aerial vehicles (UAVs). These aircraft can be fitted with surveillance equipment for tracking the enemy or loaded with weapons or explosives to take out targets. Today, drones are a mainstay in modern conflicts, including the Israel-Gaza and Russia-Ukraine wars.

"It's almost like it's back to World War I with trench warfare, because you're being hunted by a drone every single time you turn around in any of these battle spaces," said Gregory Quarles, CEO Emeritus at Applied Energetics. Eliminating UAVs with conventional weaponry can be challenging and costly, particularly when they travel in swarms. Quarles' company is among those developing directed energy weapons as an alternative.

The term directed energy encompasses a range of different technologies, but much of the current effort in this space is focused on the development of high-energy laser (HEL) weapons that deliver dozens or hundreds of kilowatts of focused energy to blind, disable, or destroy hostile targets.

Though expensive to construct, these systems offer a cost-effective defense solution. "Once you buy the system, you're talking about the cost of a pot of coffee to shoot down a UAV," said Scott Forney, president of General Atomics Electromagnetic Systems (GA-EMS). Future directed energy systems could potentially achieve sufficient power and range to disable even more serious threats, such as hypersonic missiles.

Field tests, including several conducted in the last five years, have demonstrated the feasibility of HEL-based directed energy weapons. However, it remains costly and technically challenging to design and assemble a system that can consistently deliver a high-quality beam while also managing issues such as heat production, precision aiming, and maintaining stable performance on a chaotic battlefield. Solutions are emerging for these problems, but consistent government investment will be needed to produce a practical tool suitable for broad deployment. "To really make this a viable technology, we need to have sustained volume so that we can dedicate the necessary resources to it," says Derek Angel, aerospace and defense market manager at optical fiber manufacturer OFS.

The best and brightest

The notion of using lasers as anti-missile defense stretches back several decades, though Quarles said that the field really picked up momentum in 2000 with the U.S.' development of the High Energy Laser Joint Technology Office within the Department of Defense. This office worked with the military to support the development of a solid-state HEL that could deliver upward of 100 kW of energy. In 2009, Northrop Grumman reported its demonstration of the first such system.

Since then, anti-missile solid-state lasers operating in the range of hundreds of kilowatts have remained a focus of the defense sector. As of mid-2024, the Department of Defense had established a road map to support the development of a 500-kW beam by the end of fiscal year 2025.

Sources such as these, operational in the range of hundreds of kilowatts, offer

Raman fiber laser modules are optimized for high brightness fiber laser pumping, including for directed energy and aerospace and defense applications.

necessary capabilities. "When you see people working in the hundreds of kilowatts, they're usually talking about things like counter-cruise missiles … targets moving much faster that you need to engage [with] at much longer distances," said Andrew Stentz, vice president of emerging products and technology, aerospace and defense at Coherent. During the past four years, companies including Lockheed Martin, nLight, and GA-EMS have demonstrated 300-kW HEL systems that could eventually be deployed for such purposes.

But these are still prototypes, and their real-world practicality remains an open question; some in the military have expressed skepticism about the defensive capabilities of current-generation HEL systems. And in recent years, defense contractors have shifted toward lower-energy systems operating in the 10- to 50-kW regime, which is well suited for debilitating or destroying UAVs within the kilometer range. Last October, for example, Leonardo DRS and BlueHalo demonstrated successful destruction of multiple drones with their vehicle-mounted 26-kW LOCUST HEL system.

Source material

Most HEL directed energy systems are based on fiber lasers, which are compact and highly energy-efficient compared with other solid-state laser formats. The lasers use hair-thin strands of transparent gain material, such as silica glass, doped with a rare-earth element, such as ytterbium, which, according to Angel, offers a certain advantage in an aerospace and defense context. "[The] wavelengths that ytterbium emits happen to be absorbed quite well by things that are flying and involved in weapons systems," he said.

Today's fiber lasers generally deliver output power in the range of 3 kW. To achieve HEL capabilities, multiple fibers such as these must be coupled to a beam-combining module that integrates the beams to produce higher-kilowatt-range energies. Some modules use coherent beam combining, in which an array of parallel beamlets is precisely matched in terms of wavelength, polarization, and phase. Alternatively, in spectral beam-combining modules, a diffraction grating is used to combine multiple beams with distinct wavelengths into a single overlapping beam.

But fiber lasers are not the only game in town. GA-EMS, for example, is developing systems based on distributed-gain lasers, in which light from emitter diodes passes through a series of thin "slices" of crystal gain material, with a refractive index-matched liquid coolant in between each segment. This design eliminates the need for a beam-combining component while also mitigating the heat that can undermine the performance of other nonfiber solid-state laser designs. "We have had no problem cooling the crystal, because we have plenty of safety margin in our design," Forney said.

Beating the heat

Energy efficiency and thermal management are two of the greatest challenges in developing HEL weapons. At the time when Northrop Grumman was developing its first HEL directed energy system, according to Quarles, the inefficiency of existing laser materials and architectures was so high that up to 1500 kW of input energy might be required to achieve an output of 100 kW.

This situation has improved with contemporary laser sources — but not dramatically. “On a good day, those systems are 30% efficient, so you’re throwing away 70% of the power from them,” said John Ballato, a materials scientist at Clemson University, who specializes in fiber laser technology. “The diodes, the pumps — they generate a staggering amount of heat,” Ballato said. This requires robust, reliable cooling solutions that enable the laser to withstand repeated firing over a relatively short period of time, including heat sinks and liquid coolants.

The optical fibers used in HEL systems are highly energy-efficient, with greater opportunities for heat dispersion than other solid-state laser formats. “They are hundreds of microns thick and meters long, so you can drive all the heat out in the transverse direction and that’s a huge advantage,” Stentz said.

But fiber lasers operating in the multikilowatt regime still generate enough heat to potentially undermine beam quality. According to Ballato, laser performance can be impeded by various nonlinear effects as the beam travels through the fiber, such as stimulated Brillouin scattering, wherein interactions between the light and the gain material result in power loss due to the conversion of laser light to other wavelengths. These effects are barely noticeable at low energies or in short fibers, but routinely manifest in HELs. “When you take the power that you generate divided by the cross-sectional area, you have energy densities that exceed the surface of the sun by many tens of thousands of times,” Ballato said. “With that type of power confined to that small of a diameter over 5, 10, 15 meters of length, even nominal ‘nothings’ become important ‘somethings.’”

Solutions to mitigate this effect, such as widening the fibers used in the system, create the potential for another problem: transverse mode instability (TMI). “As you get to bigger fibers, you have more ‘paths’ for the light to go down the fiber,” Ballato said. TMI is also exacerbated by thermal effects, and results in a less coherent beam.

Several companies, including OFS, have introduced fiber designs to precisely address these detrimental effects. “We developed chemistry and geometries that suppress TMI and stimulated Brillouin scattering, and which allow us to reach a narrow line with 3-kW output,” Angel said. Ballato’s group, meanwhile, is heavily focused on further improving materials to bring the magnitude of these effects as close to zero as possible. The group has previously developed silica-based fiber formulations that can potentially deliver stable output energies of up to 13 kW.

Rugged optical coatings are also essential for preserving laser performance at higher energies — and heat is not the only enemy present on a smoky, dusty battlefield. Any exposed surface is potentially susceptible to foreign-object damage in such an environment. "If debris falls onto the lens or the mirror and the laser is firing, it can become a point of damage, and the mirror can fail catastrophically — so catastrophically that you get a beam-size hole through the optic," said Mike Hyman, chief technology officer at Optimax. The company is prioritizing the use of foreign-object damage-resistant coatings in optical components intended for use in directed energy systems. Optimax has also developed a rigorous testing regimen that includes systematically dirtying those components to evaluate how well they retain performance and stability.

Ready for battle

System design and optimization aside, the challenge of packaging HELs into an effective and practical weapon is itself a major undertaking. SWAP—short for size, weight, and power—is a key metric in the directed energy community that determines the footprint of the laser system, and where it can be deployed as a result.

Among other things, SWAP is informed by the cooling requirements of the laser, and HEL systems operating at hundreds of kilowatts can occupy considerable space. For example, the 300-kW system, developed by GA-EMS for a demonstration in 2021, occupies a 21.5-ft-long cargo container. "That container includes the laser, the thermal management system, the beam director, and the control system," Forney said. "And we basically were attaching a diesel generator and a diesel tank."

A system of this size can readily be transported overland. But it also presents a potentially vulnerable target for adversaries, particularly if situated near the front as an early line of defense against aerial attack.

Lower-power directed energy weapons can be far more portable, enabling flexible deployment. This past summer, the Australian Department of Defense demonstrated a 36-kW anti-UAV directed energy system built by AIM Defence. The suitcase-size package weighs <100 lbs. Applied Energetics is developing pulsed-laser-based directed energy systems that can match or exceed the peak output power of conventional continuous-wave lasers while reducing many of the heat and inefficiency issues that plague such systems. And importantly, the technology under development all fits into a compact package. "Our system can potentially achieve a form factor of roughly 12 × 12 × 10 in., with a power draw of a kilowatt," Quarles said.

The field is also contending with challenges related to targeting. It might take

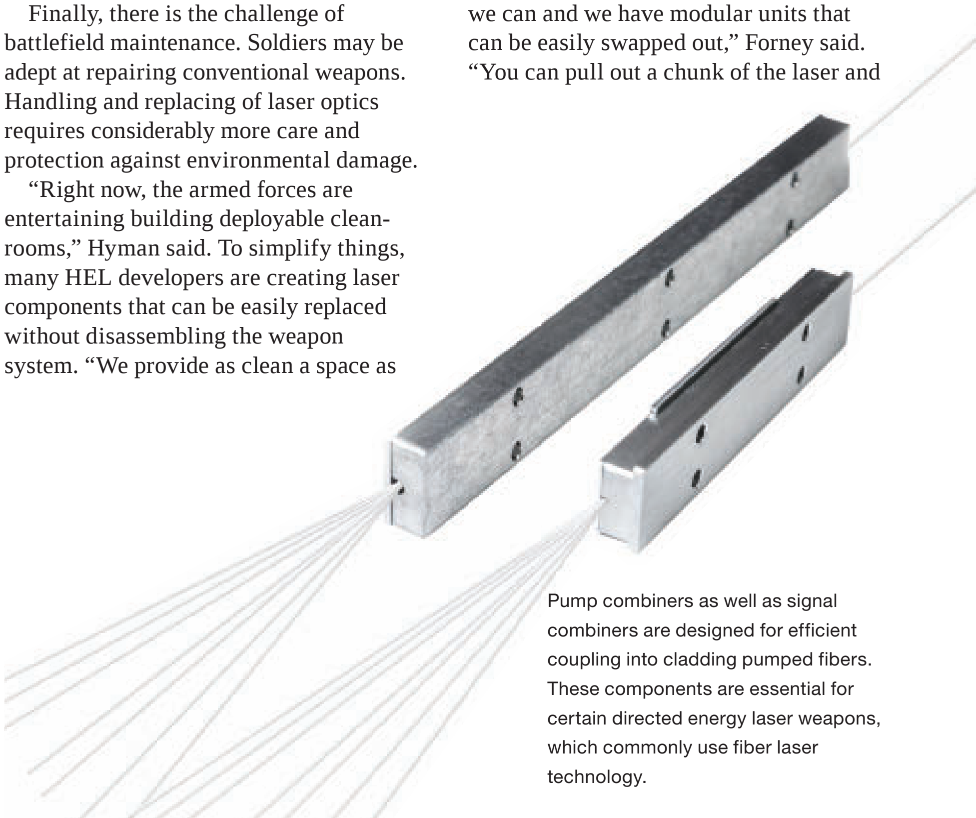
Soldiers may be adept at repairing conventional weapons. Handling and replacing laser optics requires more care and protection against environmental damage.

up to 10 s of continuous laser exposure to destroy a target, depending on the power of the beam, and even the simpler objective of disabling UAV electronics still requires seconds of precise, stable aim. Turbulence and other atmospheric irregularities can dramatically undermine this precision. “The hard part about getting lasers to operate at any range on the ocean or on the ground is that you really have a lot of dirty air to get through,” Forney said.

GA-EMS and other companies are working to overcome these effects by implementing strategies based on adaptive optics. These approaches measure distortions created by atmospheric effects and then precisely adjust the laser optics to compensate. Forney is also enthusiastic about airborne deployment of HELs. This could greatly simplify the aiming challenge by using uncrewed planes to position lasers above much of the smoke and turbulence that would confound ground-based armaments. At the same time, it would also bring these weapons much closer to their targets.

Finally, there is the challenge of battlefield maintenance. Soldiers may be adept at repairing conventional weapons. Handling and replacing of laser optics requires considerably more care and protection against environmental damage.

“Right now, the armed forces are entertaining building deployable cleanrooms,” Hyman said. To simplify things, many HEL developers are creating laser components that can be easily replaced without disassembling the weapon system. “We provide as clean a space as we can and we have modular units that can be easily swapped out,” Forney said. “You can pull out a chunk of the laser and



Pump combiners as well as signal combiners are designed for efficient coupling into cladding pumped fibers. These components are essential for certain directed energy laser weapons, which commonly use fiber laser technology.

reinstall one that's either refurbished or new for that application."

Energizing aerial defense

These and other innovations could potentially deliver combat-ready directed energy systems in the near future. Unfortunately, manufacturers have struggled to achieve the steady funding that is required to make this happen. "How do you afford the R&D expense and the continued research element of this if the volume's not there? There is no consistent program of record — there's a lot of starting and stopping," Angel said.

The high cost of directed energy weapons development remains a deterrent, even for the well-funded U.S. Department of Defense. In a talk from 2023, David Kiel, director of the Directed Energy Warfare Office at the Office of Naval Research, said that senior Navy officials have balked at the estimated $1 billion price tag for directed energy weapon development. There is interest from the Navy, Kiel said in the discussion, but the directed energy community and system developers will need to overcome doubts from those who believe that the weapons do not work. Until investment arrives, it will be challenging to develop systems that work as intended. "We have got to get past this prototyping phase, and closer to first production runs of systems to really understand how they can be utilized," Hyman said.

But an inflection point may be near. Daniel Creeden, general manager of advanced defense solutions at Coherent, believes recent demonstrations show that the current generation of counter-UAV HEL systems are almost ready for prime time. "They seem to be very, very effective," Creeden said. "It is not meant to be an end-all-be-all for everything, but it addresses a unique set of threats that's a real problem."

Quarles concurs, citing ongoing conflicts worldwide and escalating tensions in areas such as the Taiwan Strait and Korea, as well as abundant opportunities for domestic deployment of UAVs for nefarious purposes, including terrorism or espionage. "I really foresee that in the next 24 months, there will be much wider acceptance of the technology in the Department of Defense," Quarles said.

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A system of this size can readily be transported overland. But it also presents a potentially vulnerable target for adversaries, particularly if situated near the front as an early line of defense against aerial attack.

Silicone Surface Mount Optics Promise Performance Gains in Commercial Illumination

BY GREG SHARP, TIM SIGELKO,
AND SYDNEY KOCSIS, LUMENFLOW

Surface mount optics (SMOs) are the optical version of surface mount technology (SMT) components such as resistors and capacitors that are ubiquitous in electronics. Like their electronic counterparts, SMOs are delivered on a standard tape and reel, allowing users to align them onto printed circuit boards (PCBs) with speed and precision using pick-and-place equipment (Figure 1).

As is true of all industrial optics, application conditions and requirements determine the optimal optical material. Due to their high heat resistance, silicone SMOs withstand the solder reflow process without melting or deforming, and they seamlessly integrate with the PCB

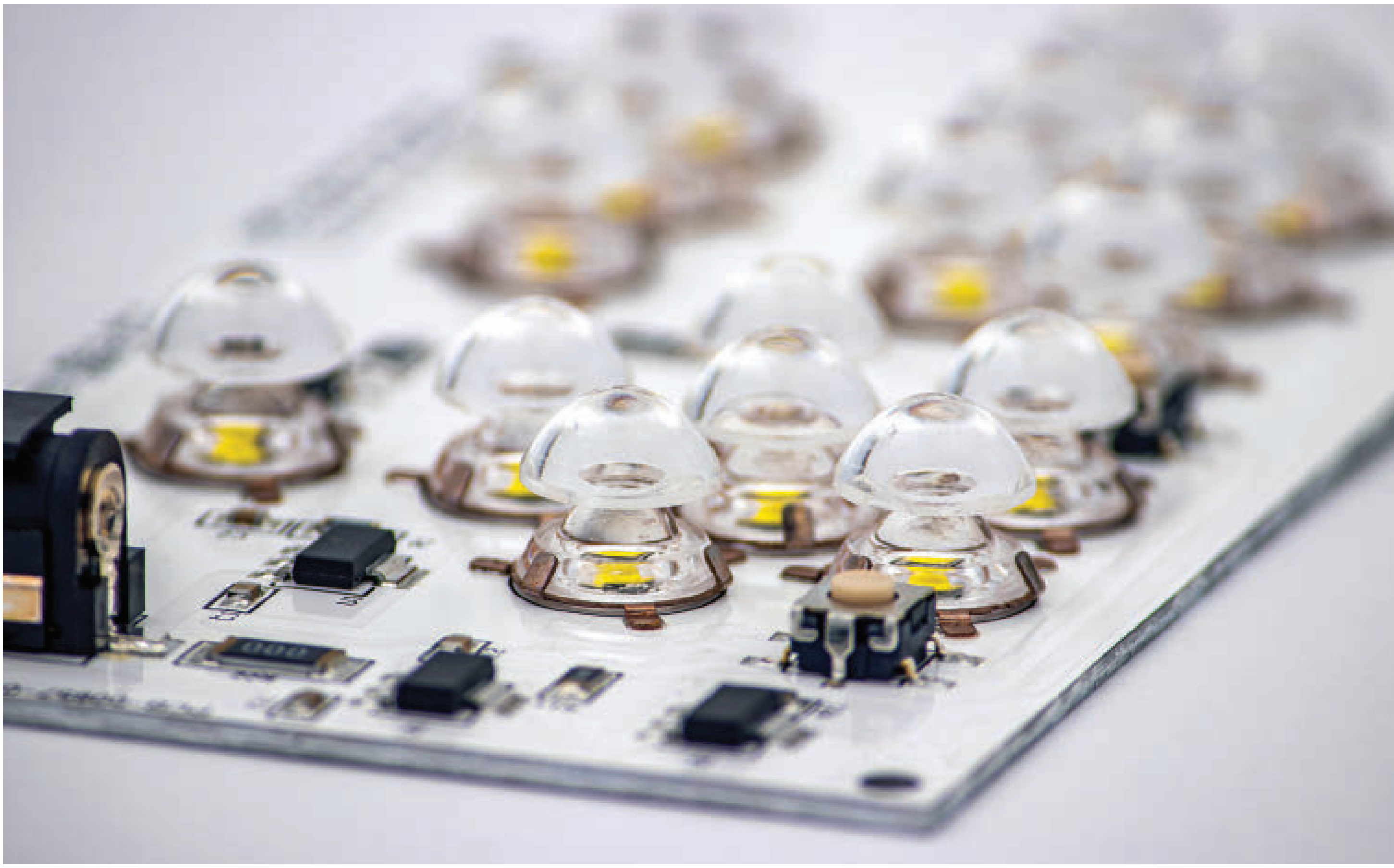


Figure 1. Surface mount optics (SMOs) are aligned onto printed circuit boards (PCBs) using pick-and-place equipment. This assembly step is one of many shared similarities that SMOs share with surface mount technology (SMT) components — their electronics counterparts.

All images and table courtesy of LumenFlow.

assembly process to reduce time and cost. Thermoplastic optics are also well known and widely used in industry, offering their own advantages including durability and electrical insulation.

However, distinct material differences expand the use potential of low-cost polymer optics to applications beyond those for which thermoplastics are viable. For example, the silicone polymer polydimethylsiloxane (PDMS) has higher energy in the siloxane bond than the carbon and oxygen bond of epoxies and common thermoplastics. This high-energy bond results in superior thermal endurance as well as UV stability — advantages that make optical silicone an optimal material in challenging environments.

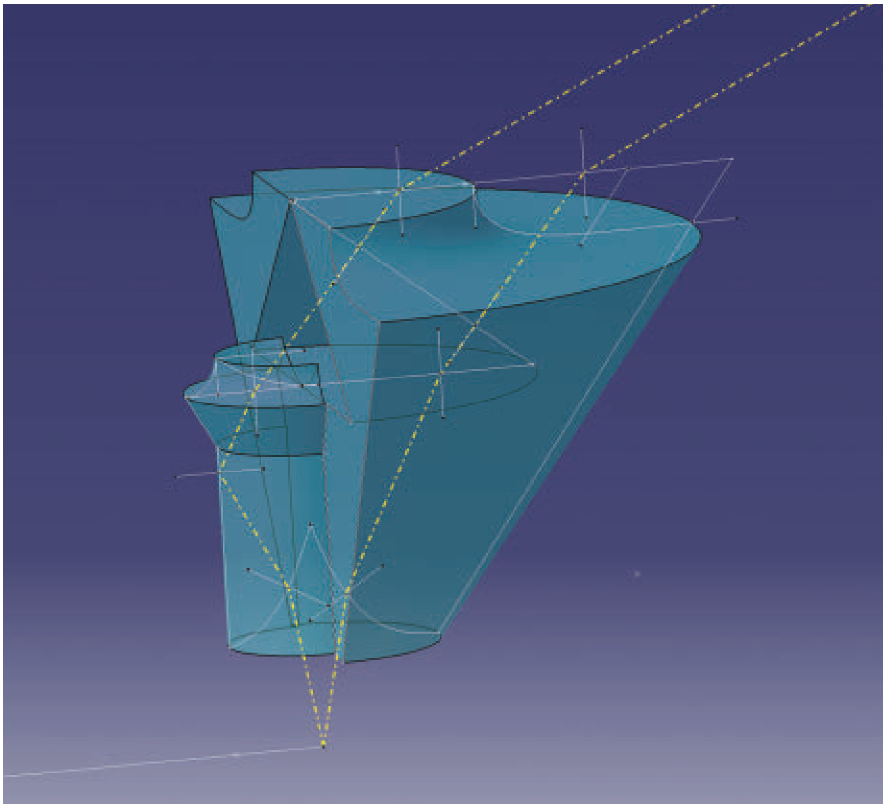


Figure 2. This full silicone lens features undercuts that are designed into the optic. A central undercut enables off-axis, uniform plane illumination using a light source. The addition of solder clips makes the optic a surface-mount solution.

Broadly speaking, though there is generally no need to switch to silicone in application environments that do not expose the restrictions of plastic optics, the design freedoms enabled by silicone open possibilities beyond many common design spaces.

Processing comparisons

Silicone and thermoplastics have different molding processes and require different processing skills, tooling, and equipment. Thermoplastics are melted pellets that are injected into a mold with high pressure and are cooled to cure. Silicone is a two-part liquid thermoset material injected at low pressure and flows into a mold as a low-viscosity liquid. Its low viscosity and high wettability allow it to flow into very small details during processing and make it an excellent candidate for replicating small features such as diffractive/holographic (nano)structures.

But this wettability creates certain processing challenges. For example, since silicone enters the mold as a liquid, the mold must be water-tight to prevent leaks that can produce excess flashing around the parting lines of the mold. Precision parting lines must therefore be implemented to prevent unnecessary rework of parts post-molding.

Silicone Material and Surface Mount Optics: Benefits and Advantages

Silicone

- High heat resistance: 200 °C operating temperature.
- UV stable: will not yellow.
- Waterproof: used for higher ingress protection rating.
- Vibration dampening: no buzz, squeak, or rattle.
- Greater transmission into the UV: 50% transmission at 265 nm.
- Mechanical features include undercuts, voids, and negative draft angles.

Surface mount optics

- Labor savings: Optics can be secured in place through the same solder reflow process as other surface mount technology (SMT) components, and these optics do not require secondary processing to secure to a printed circuit board (PCB), whereas traditional optics require an operator to glue and/or clip an optic in place after PCB assembly.
- Surface mount optics (SMOs) are placed by automated assembly equipment providing better alignment of the LED and the optic, resulting in better optical efficiency.
- Manual optical mounting may require a dispensed liquid that could interfere with other components, resulting in rework or scrap of materials. SMOs eliminate manual processes and offer improved precision to reduce the scrap costs.
- Easily switch from one optical design to another by swapping reels on pick-and-place equipment.

Injection molding thermoplastics creates molded-in stress due to the high pressures required to fill the part. This pressure may influence the shrink rates during cooling, causing parts to sink and/or warp. The injection speeds used with thermoplastics are also much faster than silicone, affecting molecular chains. The materials' molecular orientation may further contribute to deferential shrinkage and consequent warpage. Further, the stresses may create birefringence in thermoplastics. The slow fill speeds and pressures that silicone requires means that molded-in stress is not a by-product of injection molding, and parts shrink uniformly as they cool.

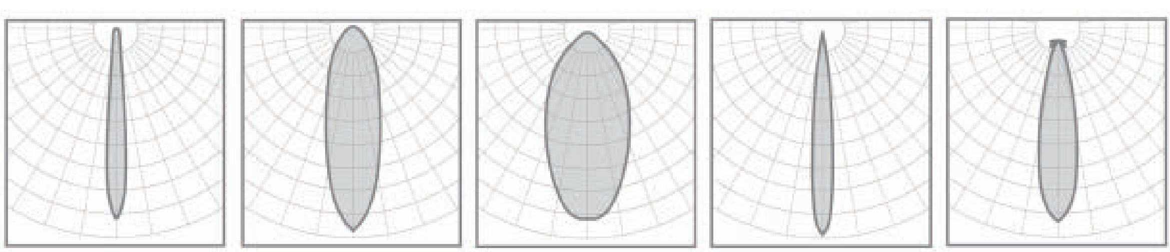
These thermal and molding properties, compared with optical thermoplastics, make silicone the ideal material for molding flatter, wider parts. Large, thick cross-sectional parts can be molded in a single shot, which eliminates the need for multilayer or multi-shot plastic injection molding (which may be used for automotive headlamps).

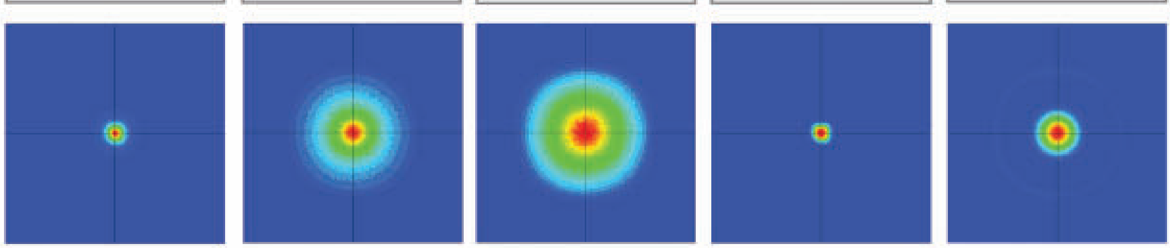
Thermal considerations

Thermal management in optical systems is a growing concern on multiple fronts, as packages become smaller and LEDs become brighter, and hotter as a result. Silicone presents higher thresholds for softening and deforming in hot environments than thermoplastics. For applications in which the photon density is high,

Standardized Surface Mount Optics for Initial Evaluation

Product	SMO DFL10d	SMO DFL30d	SMO DFL50d	SMO 10° Compound	SMO 30° Compound
Part Number	5034001	5034002	5034003	5034301	5034304
Material	SILASTIC MS-1002 moldable silicone	SILASTIC MS-1002 moldable silicone	SILASTIC MS-1002 moldable silicone	SILASTIC MS-1002 moldable silicone	SILASTIC MS-1002 moldable silicone
Diameter	10.5-mm OD	10.5-mm OD	10.5-mm OD	10.5-mm OD	10.5-mm OD
Height	8.74 mm	6.42 mm	5.89 mm	10.6 mm	8.6 mm
Attachment	Clamp-ring soldered	Clamp-ring soldered	Clamp-ring soldered	Clamp-ring soldered	Clamp-ring soldered
FWHM	11°	30°	54°	12°	24°
FWTM	24°	93°	105°	19°	41°
Efficiency	84%	89%	90%	86%	85%





FWHM: full width at half maximum; FWTM: full width at tenth maximum; OD: outer diameter.

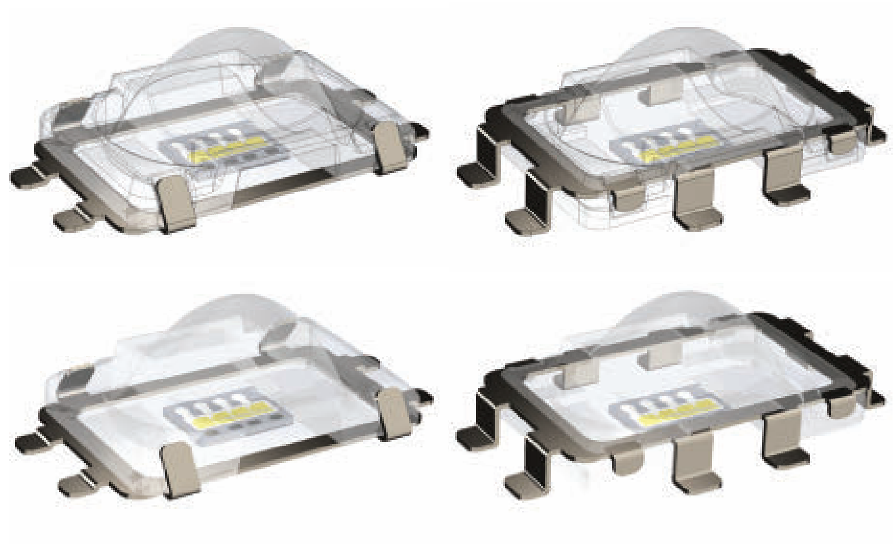


Figure 3. Alternate solder clip configurations for surface mount optics (SMOs) packaging.

such as automotive headlamps, stadium lighting, and street lighting, silicone's high operating temperature of up to 200 °C offers a necessary benefit. Silicone will retain its shape and avoid any loss to its optical properties. And short exposures to higher temperatures, for example, in solder reflow ovens, yields no loss to mechanical or optical properties of the part.

It should be noted that designers who are experienced with thermoplastics no longer need to increase the size of systems to physically isolate their optics from the heat sources. They can also create exotic shapes that are impossible to mold in rigid materials to condense the size of the optical system. The full silicone optic in Figure 2, for example, uses multiple aspherical optical surfaces and a central undercut to achieve off-axis, uniform plane illumination using a VCSEL with two off-axis peaks.

Here, plastic optics require separate parts to achieve comparable performance to silicone, with its high flexibility and elongation to twist and stretch out of a mold. Thermoplastics are more rigid, and complex geometry, including undercuts, can crack or break upon removal from the mold.

Commercial implications

Combining the material properties of silicone with enhanced design freedoms and a metal solder clip, SMOs have been developed to further reduce assembly costs. Today, a variety of silicone SMOs are commercially available for proof-of-concept testing (see the table on page 49). These offerings target general applications. The current designs are singlet lenses and doublet compound lenses. Singlet lenses create more tightly collimated beams with varying spots. Compound lenses will spread and collimate the light for uniform area illumination and a relatively sharp edge roll-off.

Tests to evaluate the performance of the developed optics were performed using commercially available white LEDs. The results indicated that the developed optics may be paired with any LED of a similar footprint and yield similar results. Additionally, the optics can be redesigned to better suit a particular LED model and/or reach desired performance targets as determined by the target application. Beyond optical design, to control the surface profile, various materials can be mixed with the silicone to produce different optical effects, such as scattering centers, coloring agents, phosphors, and reflective and absorptive materials.

One of the most evident benefits of using SMOs is in assembly, eliminating secondary processes and saving time and labor costs. Unlocking this advantage relies on an attachment method featuring a six-tab clip, stamped from tin-plated metal, which is crimped to the optic. Three of the tabs cradle the side walls of the surface-mount optic, and the other three remain flat for soldering. Alternative solder clip designs are being developed for different applications as shown in Figure 3. Typically, optics are manually glued or clipped in place after the PCB has been fully assembled. Silicone SMOs withstand reflow conditions, meaning they can be bonded to the PCB through a single pass in the reflow oven in the same way as a standard SMT component.

Reflow studies showed that both the LED and the optic can be placed at the same time, removing the need for a second pass through the SMT process. Post-soldering placement accuracy of SMOs is on the order of 0.25 mm. The benefits in assembly using silicone SMOs eliminate secondary processes, saving manufacturers time and reducing labor costs.

Outlook

Several applications are starting to ramp up volume production, though most potential SMO products are still in the early stages of design, productization, and exploration with commercial companies. As product sizes shrink and optics sit closer to the light sources, designers need more heat-tolerant materials. If the system can be designed with larger distances from the source and the optics, there may not be an overt need to convert to silicone.

However, a path for attachment — and costs of attachment — can drive the design to an SMO style of optic.

In this context, SMOs represent a continuing component innovation offering competitive efficiency. Enabling automation and seamlessly integrating with existing PCB processes, SMOs deliver a fast and precise solution for optical alignment and assembly. And in this context, silicone optics provide superior heat resistance, weatherproofing, vibration dampening, greater transmission, and design freedom. These material advantages should be leveraged to face challenging thermals, complex geometries, and/or assembly costs.

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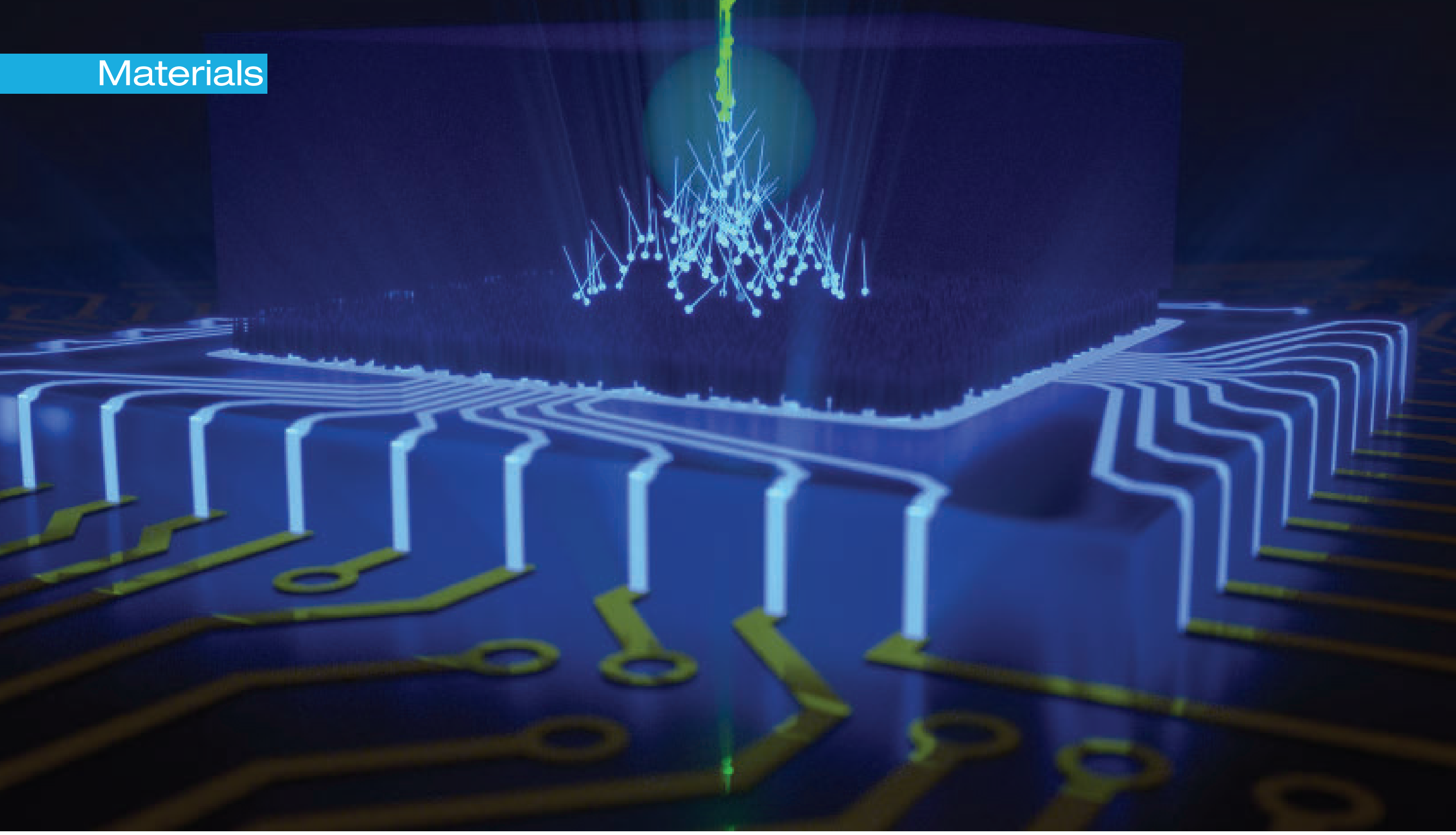
Thermal management in optical systems is a growing concern on multiple fronts, as packages become smaller and LEDs become brighter, and hotter as a result. Silicone presents higher thresholds for softening and deforming in hot environments than thermoplastics.



Black Silicon

Offers Enhanced Responsivity in Near-Infrared Photodetection

Nanostructured black silicon represents a straightforward approach to avoid bottlenecks in aerospace and defense sensing.

All images courtesy of ElFys.

BY TONI PASANEN
ELFYS INC.

Detecting and measuring near-infrared (NIR) radiation with high sensitivity is essential for many modern defense and security technologies. Applications deploying laser-guided systems, as well as range-finding and night-vision devices, require efficient photodetection to ensure precise operation under varying conditions. Another requirement for these applications is the high speed of photodetection. Speed is vital to enable instantaneous reaction to rapid changes in the light signal.

Achieving both high sensitivity and fast photodetection speed within the NIR band presents a significant technical challenge. At the component level, conventional photodiodes fabricated from silicon face several performance limitations for NIR applications. Given these drawbacks, opportunity exists for innovative alternative solutions to overcome these hurdles. The use of nanostructured black silicon for the photodiode is one such approach.

Responsivity versus speed

The critical performance metrics describing the sensitivity and speed of a photodetector are responsivity and rise time, respectively. Responsivity refers to a photodiode's conversion of incident light into an electrical signal. High responsivity is essential for detecting weak or distant light signals, which is important for applications such as laser guidance and surveillance.

Rise time describes the speed at which a photodetector responds to changes in light intensity. It is defined more precisely as the time it takes for the detector electrical signal to rise from 10% to 90% of its final value after the device is subjected to light.

In photodetection, silicon photodiodes are commonly used due to their compatibility with existing semiconductor fabrication processes, plus their wide availability and overall cost-effectiveness. Although silicon is an excellent material for visible light detection, the absorption

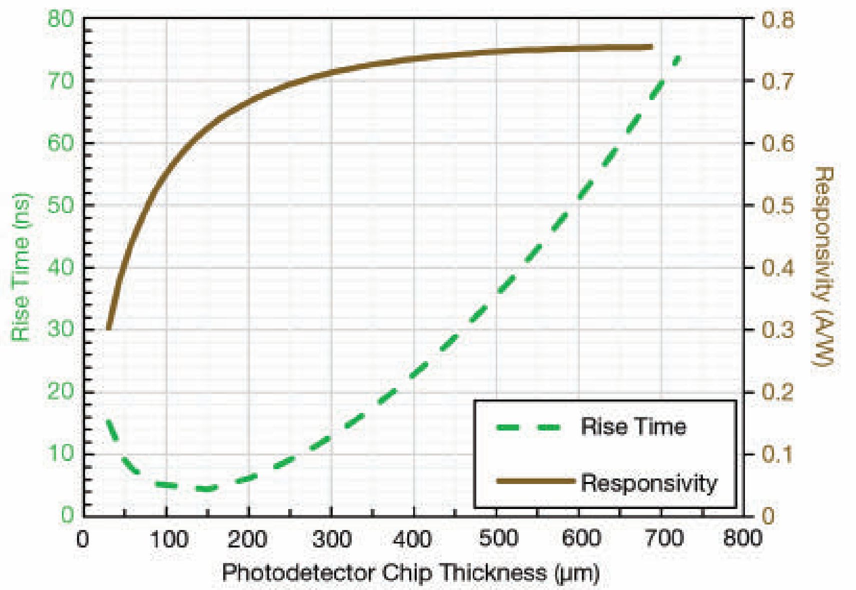


Figure 1. Simulated rise time and responsivity of a black silicon four-quadrant photodiode at 1064 nm as a function of chip thickness. The rise time calculation assumes a 40-sq-mm active area and full depletion at 150-V bias.

of NIR radiation in silicon is weak due to the decreasing absorption coefficient with increasing wavelength, which causes the photodetector response to drop. Silicon's limitations for the NIR wavelength range — which become especially apparent beyond 950 nm — pose a significant challenge to the defense and security industries, in which the 1064-nm wavelength is of considerable importance. Several applications in the field, such as missile target designation, laser warning systems, and laser rangefinders, commonly use the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser at this wavelength.

A straightforward way to improve the responsivity in the NIR region is to

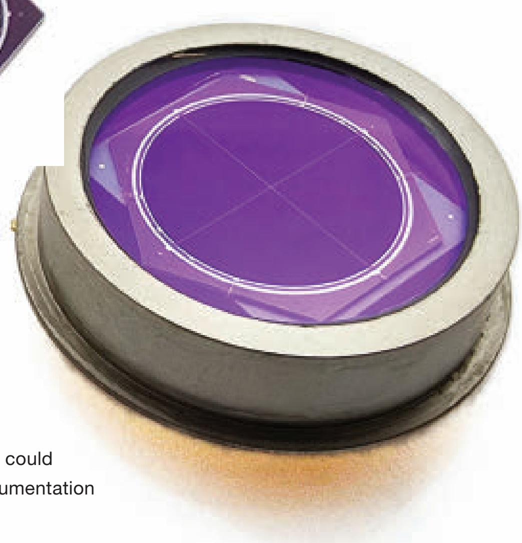


Figure 2. A black silicon four-quadrant detector chip **(above)** and a packaged component optimized for 1064 nm.
In addition to defense applications, black silicon-based four-quadrant detectors are beneficial for other applications for which precise laser beam tracking or alignment is needed. The technology holds promise for medical imaging technologies and industrial process control. Black silicon nanostructures could also enable new capabilities in scientific instrumentation and analytical devices operating in the NIR.

increase the effective optical path length that light travels in the silicon material; and an obvious way to achieve this is to increase the thickness of the photodetector. When light needs to pass through a thicker piece of material, it naturally has a higher likelihood of being absorbed.

However, increasing the detector chip thickness simultaneously increases the rise time and makes the device slower. The reason for this is that in addition to the resistor-capacitor (RC) time constant of the detector circuit, the rise time also depends on the time that it takes to collect the light-generated charge carriers within the silicon material to the electrodes. NIR radiation penetrates deep in silicon, far away from the charge carrier-collecting *p-n* junction, which is typically located at the front of the device. A thicker chip increases the distance that carriers must travel in the depletion region to reach the electrodes. Simply, the transit time becomes longer.

Moreover, increased thickness necessitates the use of higher bias voltages to avoid part of the absorption occurring outside the depletion region (where no electric field exists). Without sufficient bias, the extremely slow diffusion-type movement of the charge carriers completely dominates the rise time.

This points to the inherent trade-off that exists between the two fundamental

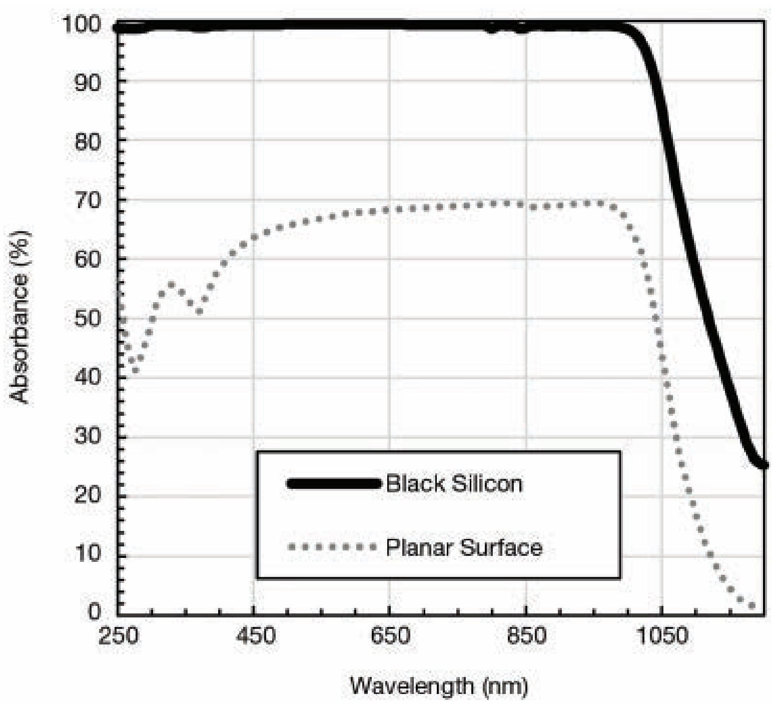


Figure 3. The spectral absorbance of silicon with a black silicon or planar uncoated surface **(above)**.

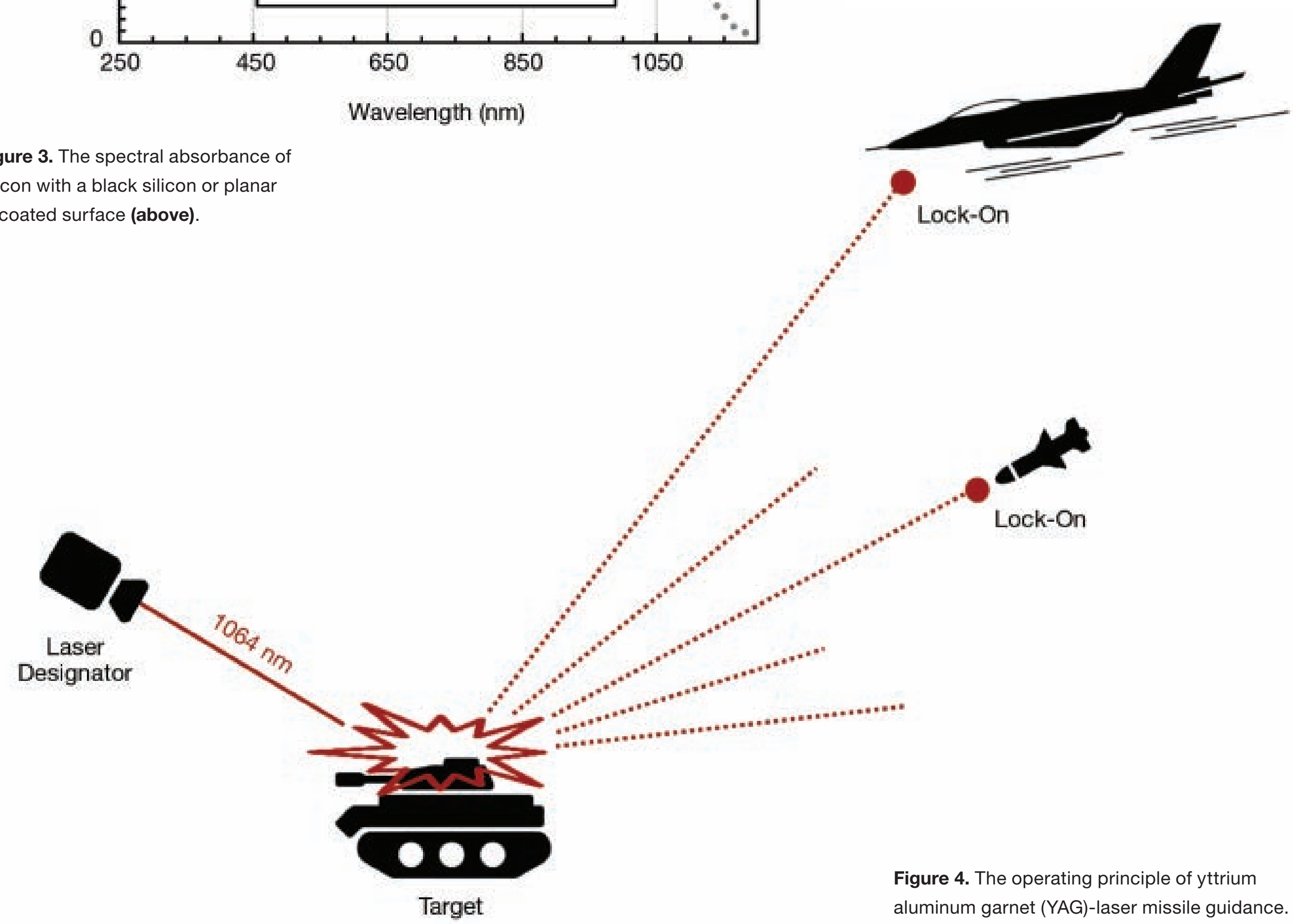


Figure 4. The operating principle of yttrium aluminum garnet (YAG)-laser missile guidance.

performance metrics of the photodetector. The chip thickness must be carefully optimized for the specific application to maximize the detector performance.

Figure 1 highlights this by showing a simulation on photodetector rise time and responsivity at the 1064-nm wavelength as a function of detector chip thickness. While a minimum rise time, indicating fastest operation, is achieved with a chip thickness of ~150 µm, the responsivity is heavily reduced due to weaker NIR absorption. In contrast, highest absorption and responsivity are obtained with a thick photodetector chip, though the device operates slowly. The optimal combination is somewhere between these two extremes and depends on the application.

Photodiodes based on III-V semiconductor compounds offer an alternative solution for NIR detection. These materials absorb NIR radiation efficiently even if the layer is very thin, and they provide for high operation speed. However, processing of the III-V materials is more expensive than with silicon due to the complexity of the epitaxial processes used to grow the thin films, the higher cost of the needed substrates, and the lower scalability of the manufacturing processes. The material quality with III-V semiconductors is also typically lower than in silicon, which limits the available photodiode size. III-V compounds are also not naturally compatible with silicon-based electronics. This makes integration with CMOS circuits more challenging.

Better antireflection for responsivity gains

When light hits the photodetector surface, a portion of it is reflected away due to the difference in the refractive index between air and the photodetector material. This reflection loss can significantly reduce the amount of light entering the device: For a bare silicon surface, reflectivity is typically as high as 30% for normal incidence at NIR. This means that 30% of the light is lost before it reaches the active region, resulting in an equally large drop in the responsivity.

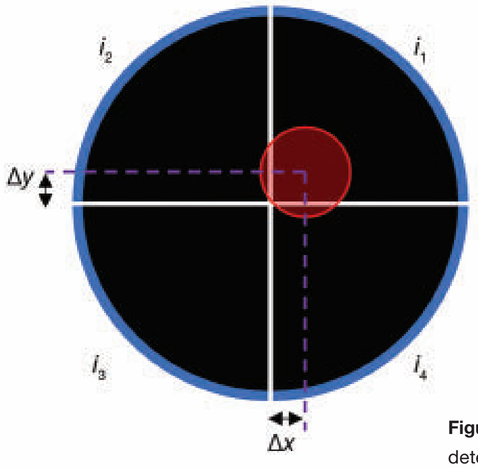
A commonly used technique to reduce the optical losses is to introduce an antireflection (AR) coating on the detector surface. AR coatings have an intermediate refractive index between air and the photodetector material, and use of this coating on the surface minimizes reflections by creating destructive interference for reflected light waves. More light is enabled to enter the silicon material, and more photons are absorbed as a result. The material and thickness of the AR coating are optimized so that the reflection minimum occurs at the wavelength range of interest.

As an alternative to the AR coating, the approach of texturizing the photodetector surface opens the possibility to leverage additional (and often very distinctive) optical properties. An advanced version of the technique of texturization of the photodetector surface uses nanostructured black silicon (Figure 2). Black silicon consists of nanostructures smaller than the wavelength of light and acts as an effective medium with a gradual refractive index transition from air to silicon. Since the nanostructures eliminate the optical interface between these two materials, they efficiently suppress reflections across a broad range of wavelengths and incident angles from the ultraviolet to the visible and extending to the NIR (Figure 3).

Black silicon has other interesting optical properties. Notably, the irregular surface of black silicon scatters incoming light, effectively increasing the optical path length within the photodetector material. This in turn increases the likelihood of photon absorption, particularly for longer wavelengths in the NIR region (Figure 3). Therefore, black silicon enables thinner photodetector chips to achieve the same (or better) light absorption compared with thicker counterparts. This relaxes the trade-off between the responsivity and speed of the detector and gives more freedom to optimize the performance of the device for a specific target application.

Black silicon four-quadrant detectors

Though not all precision munitions harness laser technology, laser-guided missiles represent one effective use of 1064-nm sources in defense and military applications. With laser-guided missiles, four-quadrant detectors are often used. These sensors divide the detection area into four equal segments. As a laser beam



$$x = \frac{(i_1 + i_4) - (i_2 + i_3)}{i_1 + i_2 + i_3 + i_4}$$

$$y = \frac{(i_1 + i_2) - (i_3 + i_4)}{i_1 + i_2 + i_3 + i_4}$$

Figure 5. A four-quadrant detector can determine the position of a laser beam on the detector surface by comparing the output currents between the quadrants.

shines onto the surface of the photodetector, the position of the beam on the surface determines the amount of light received by each of the four quadrants.

One of the main challenges facing conventional four-quadrant detectors is the limited responsivity that can be provided at 1064 nm while still maintaining fast speed of operation. Conventional silicon photodiodes even with an optimized AR coating typically exhibit responsivity of <0.5 A/W at this wavelength at room temperature.

By enhancing light absorption and minimizing losses due to reflection, black silicon photodiodes exhibit higher quantum efficiency, translating to improved responsivity. Indeed, black silicon four-quadrant detectors can achieve responsivities >0.6 A/W, representing an improvement of up to 30% compared with conventional technologies. Higher responsivity combined with low dark current offers the capability to lock on to the target at longer distances, improving hit accuracy and circular error probable in application. It also makes the system more robust against any disturbances in the air that weaken the signal, such as smoke or dust. Furthermore, as a more sensitive detector can detect weaker signals at greater distances, it allows an operator to designate targets from farther away. This increases the standoff distance, reducing the risk of the operator being within range of enemy fire or counterattacks.

In application: YAG-laser guidance

YAG-laser missile guidance refers to the use of a YAG laser to designate (and guide) missiles to their targets. This technology is widely used in precision, laser-guided munitions to strike targets with high accuracy.

In the YAG-laser guidance system, a laser designator is used to mark, or "paint" the target with a beam at 1064 nm (Figure 4). The operator uses the YAG laser designator to illuminate the target. The device can be operated manually by ground-based infantry or mounted, such as on an aircraft. The laser beam reflects off the target's surface, creating a "spot" onto which the missile can lock. The designator often operates in a coded pulse mode, sending a specific laser pulse sequence to ensure that the target is uniquely identifiable and avoid interference with the environment and other systems that may be present.

As the missile is launched, it enters its initial trajectory. The missile may use inertial navigation during the early phase of the flight, to travel toward the general area of the target. The missile is equipped with a laser seeker, which activates as the missile approaches the target area, and the seeker detects the reflected laser beam by a location-sensitive NIR photodetector and determines the location of the laser spot. Data from the laser seeker is translated into real-time adjustments to the missile's trajectory via the onboard guidance control system. This system adjusts the missile's guidance fins or thrust vectoring systems to keep the flight path aligned with the reflected laser signal and to maintain focus on the target.

Laser beam tracking systems that are used for this application rely on rapid and accurate photodetection to monitor the position of a laser beam. As a result, these systems commonly use four-quadrant photodetectors.

After the laser beam hits the surface of the photodetector, and the beam position determines the amount of light at each quadrant, each quadrant then generates a photocurrent proportional to the light intensity that it receives. A comparison of the differences in signals between the quadrants enables the system to calculate the beam's position relative to the center of the detector (Figure 5). This information is similarly forwarded to the control system, which facilitates any necessary adjustment to the position of the tracking mechanism and the trajectory of the missile to re-center the laser beam on the photodetector.

Such systems obviously set demanding requirements for photodetector performance. The speed of the missile demands that the photodetector respond promptly to changes in light intensity to avoid missing the target.

At the same time, the responsivity must be assured, because the light signal may often be weak due to the long distance to the target and disruptions in the environment, including smoke, rain, and/or fog.

Meet the author

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A butterfly is imaged under ultraviolet **(left)** and visible light. Ultraviolet imaging provides insights that enable the approach's use in a range of applications — from environmental to industrial.

Ultraviolet CMOS Technology Opens a Spectrum of Possibility

BY FRANÇOIS YAYA
OXFORD INSTRUMENTS — FIRST LIGHT IMAGING

All images courtesy of Oxford Instruments — First Light Imaging.

Supported by advancements in sensor components and materials, ultraviolet CMOS technology enables numerous applications — and streamlines others.

The ultraviolet (UV) range of the electromagnetic spectrum has historically been split into three bands. These three bands — UVA (315 to 400 nm); UVB (280 to 315 nm); and UVC (100 to 280 nm) — corresponded to barium-silex, barium-silex-Pyrex, and Pyrex filters. All three filter types are widely available.

As some of the shortest and most energetic wavelengths in the spectrum, UV light at any wavelength exhibits distinct characteristics, which are harnessed across various domains (Figure 1). For example, UVA is valuable for fluorescence imaging, and UVB light can be used for medical treatments, such as psoriasis therapies. The highly energetic UVC band is commonly used for sterilization.

Accordingly, UV-emitting sources are already used in a wide range of applications in both industry and R&D. Now, the prospect of using UV-sensitive sensors to record data over time and store the data for subsequent analysis is increasing in interest.

However, most CMOS sensors for visible light imaging are fabricated from silicon. This material exhibits low transmission efficiency in the UV range.

To optimize transmittance, all elements within the camera's optical path, including the microlenses integrated into the CMOS sensor and the protective window, must be meticulously engineered and treated for UV (Figure 2a,b). The shorter UV wavelengths, and significantly lower penetration depth compared with visible light, mean that photons are less prone to absorption by the photodiodes within the sensor. Also, the quantum efficiency is typically lower than for visible light.

Manufacturers have worked to overcome this constraint through the development of image sensors capable of accommodating UV cameras and UV imaging more broadly. In the early days of working to meet this challenge, CCD sensors became more sought after due to their higher sensitivity and reduced noise. CCD sensors transfer the generated charges from an array of photodiodes after photons hit pixels, leading to lower noise. However, CCD sensors come with limitations and known artifacts, such as blooming.

During the last few decades, CMOS technology has undergone significant improvements. Owing to advancements in lithography, these gains are most noticeable in the sensors' ability to handle noise. The resulting image quality has approached levels comparable to that which CCD sensors can deliver. In addition to image quality, CMOS sensors, now operating in or for the UV range, offer an effective alternative to their CCD counterparts. Among other benefits, they are cost-effective, consume ~100× less power than CCDs, and offer higher operational speeds[1].

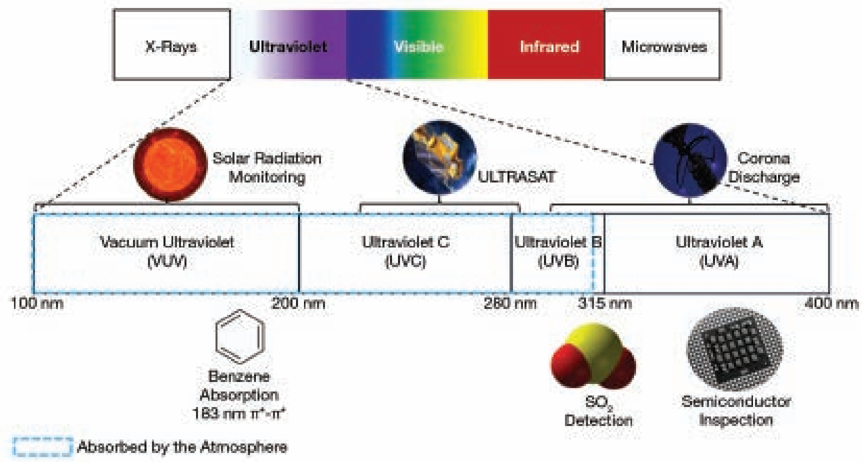

Figure 1. A graphical representation of UV CMOS applications by wavelength, with specific examples, as grouped by the distinct UV spectral bands.

Technical and material innovations

Adapting CMOS technology for the UV range requires developers to consider the high energy of UV photons and the corresponding effects of this characteristic on sensor design. With UV photons, penetration depth — or the distance at which light intensity decreases as it moves through the sensor — is low.

CMOS manufacturers have explored various approaches to address the low penetration depth. In 2011, Sony released its first back-side-illuminated CMOS sensor. Compared with the front-side-illuminated sensors, which represented the original approach to building sensors, the photosensitive matrix in the Sony design was positioned closer to the surface. This enabled better light collection, including for the shorter UV wavelengths (Figure 2a).

In a similar vein, fabricators have turned to thinning silicon substrates to enhance UV photon collection. Further, certain designs apply antireflective coating to maximize the transmission of photons; indeed, UV light interacts strongly with the sensors' surface, which makes

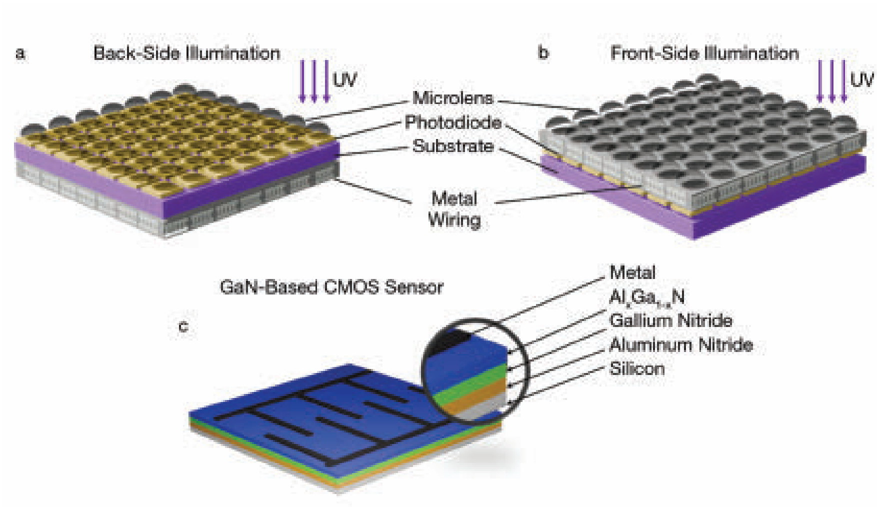

Figure 2. Design architectures of back-side- and front-side-illuminated UV CMOS image sensors **(a, b)**. A gallium nitride (GaN)-based CMOS image sensor, isolating material layers **(c)**.

it more prone to noise. Algorithms have been implemented in several recent cases to mitigate this. The effect of correlated double sampling, for example, reduces noise by subtracting the background noise on the pixel level. The latest iteration of CMOS sensors features an on-chip digital signal processing mechanism that reduces noise more rapidly, making these sensors ideal for fast imaging applications. UV-sensitive sensors are available on the market, and research is ongoing to improve their durability and quantum efficiency.

As these innovations have taken off, various materials have been under investigation. Materials that have a large bandgap due to the high energy of UV photons and effectively transmit UV light have gained preference for UV imaging and sensing.

Photodetectors made of various materials are currently under development as well, though progress must be made before multi-pixel and CMOS integration is achieved. Among the most popular of these options, nitride alloys — particularly of gallium, aluminum, and indium-aluminum — offer large bandgaps. At the same time, oxides, such as zinc and/or magnesium-zinc, also respond well to UV light, but in some applications, customers may need to select a specific range in the UV. For instance, ternary zinc germanium oxide responds well to UVC but not UVA or UVB.

For high-energy imaging applications (imaging alpha particles, neutrons, gamma rays, and more) diamond and silicon carbide (SiC)-based sensors are strong candidates due to their wide bandgap and resistance in harsh environments[2]. Operating in or under UV light is challenging due to its high energy, and UV CMOS sensors, which are usually under prolonged UV radiation, can undergo reduced performance over time, or experience irreversible damage, in the worst cases. Although the fabrication of multi-pixel sensors combining CMOS technology with large bandgap materials is still complex and costly, sensors based on SiC are emerging for such applications.

Applications: Industrial and R&D

UV CMOS technology currently enables applications that are firmly established — though, in many cases, still improving — as well as those in basic and applied research. Among the most notable applications, UV CMOS sensors help to inspect damaged high-tension electric cables by detecting corona discharges that ionize the air and emit UV photons. UV light also enables the discernment of different types of plastics. And most body fluids strongly absorb in the UV, making UV sensors a powerful resource in disciplines such as forensics.

As much as technological advancements have positioned UV CMOS to aid numerous imaging applications, recent improvements in manufacturing are likely to lead to many more advancements. There is an increasing demand in the industrial sector for automation systems to handle repetitive and tedious tasks for high-throughput productions. Human-based quality checks can be subjective, as well as time-intensive, whereas automated systems support unbiased, reliable, and contactless methods.

Under this umbrella of inspection tasks, nondestructive testing refers to techniques that check properties of a material without contact. This method is essential to industries such as automotive, aerospace, and electronics.

UV CMOS sensors are excellent candidates for nondestructive testing deployments due to their ease of integration, versatility, and facilitation of high-speed, high-resolution imaging. By combining rapid detection with machine vision algorithms, these systems enable efficient materials sorting, automatic inspection, process control, and countless other possibilities.

In the semiconductor industry, electronic components are miniaturized to unprecedented sizes. Identifying fine cracks, defects, and dust contamination on wafers is crucial, because these factors often determine whether a device will function as intended. UV CMOS technology excels in providing detailed and fast imaging, though UV CMOS technology cannot match the detail of electron-based microscopies, due to the diffraction limit of light's shorter wavelengths, which reveal minute details in the blink of an eye. But, electron-based microscopies can complement UV CMOS to provide deeper insights into specific wafer areas.

UV CMOS in the field

The application benefits of UV CMOS can apply to areas outside of industrial settings. In agriculture, UV CMOS sensors mounted on drones have the potential to identify fruit flowers for artificial pollination, which can provide a path to improved yields. In surveillance applications, cameras similar to the infrared imagers already in use could be used to detect hazardous or biological agents. And with the growing interest in artificial intelligence, large volumes of images generated by high-speed recording CMOS sensors can be used to train models that could ultimately be used to assist humans, resulting in rapid analysis and decision-making in real time.

In astrophysics, the potential of UV light has always garnered high interest. But this has remained underexplored, mainly for technological bottlenecks. It is also worth noting that absorption and diffusion of UV light by the ozone layer makes ground-based observations complex, and these necessitate the deployment of instruments in outer space. UV CMOS sensors, which are more cost-effective than CCD options, consume less power and can more effectively withstand harsh environments, such as UV radiations.

With recent advancements in UV CMOS technology, astrophysicists are aiming to uncover critical information about high-energy processes, such as stellar formation, hot sources, and interstellar media. This technology allows scientists to trace stellar nurseries and gain a better understanding of the early stages of star formation. Additionally, UV CMOS sensors can be mounted on a satellite and seize the atmosphere composition of exoplanets. Gases that have strong absorption in the UV spectrum, such as helium, hydrogen, and even ozone, can indicate whether life-forms are present.

For example, UV CMOS technology was integrated on a satellite called the Ultraviolet Transient Astronomy Satellite (ULTRASAT). This wide-field Schmidt telescope in orbit aims to deliver a comprehensive understanding of the high-energy transient universe. It refers to high-energy events that take place in a brief timescale in the cosmos. ULTRASAT excels in the near-ultraviolet range from 230 to 290 nm. Its observations are expected to contribute to multiple fields, including the study of supernovae and neutron stars, galaxies, and gravitational waves.

Scheduled for launch in 2027, ULTRASAT uses UV CMOS technology to

UV CMOS: Application in Action

In an application example, attempts were made to detect sulfur dioxide (SO_2) emission out of a refinery's chimney. A CB1 UV camera from Oxford Instruments — First Light Imaging, with an f/2.8 100-mm UV sensitive objective (CERCO) was used for the test. This objective is apochromatic and demonstrates excellent transmission between 240 and 900 nm. A UV (310-nm ± 5-nm) bandpass filter was used to select the wavelength where the absorption of UV by SO_2 is optimal.

It is well known that the processing of crude oil involves combustion, and the sulfur contained inside the oil is rejected by the chimney after oxidation as SO_2. While emission is not detected with visible light, results enabled the observation (black) of the presence of SO_2 (Figure 3). This was possible due to the 310-nm (± 5-nm) bandpass filter used in the test. This setup allows for imaging of emitted gases from a certain distance, ~10 s of m.

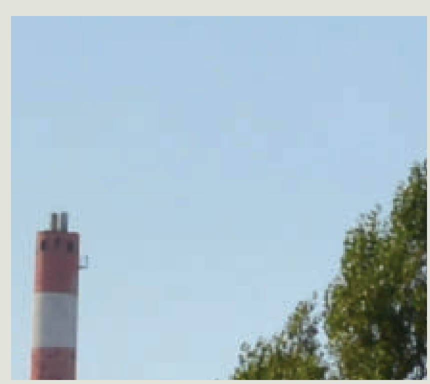

Figure 3. A refinery chimney emitting sulfur dioxide (SO_2) imaged in ultraviolet **(left)** and visible light **(right)**.

capture high-resolution images in real time. Deutsches Elektronen-Synchrotron (DESY) developed the camera, which features a focal plane array with four independent 45- × 45-sq-mm back-side-illuminated CMOS sensors and a pixel size of 9.5 × 9.5 µm. To address the low penetration depth of UV, DESY designed a sensor with a proper antireflective coating, called T2. This coating has a high quantum efficiency in the near-ultraviolet range for the target application.

Gas spectroscopy

On Earth, gas detection, particularly of noxious gases, is also a significant focus. Scientists in the last few decades have gained a heightened awareness regarding global warming, often highlighting ozone. This gas protects the planet from harmful radiation, and it exhibits a strong absorption in the deep-UV (<300 nm).

On a larger scale, numerous pernicious gases in ambient quantities pollute the atmosphere and have negative health effects when they enter the respiratory tract. Therefore, monitoring and quantifying these gases is crucial to minimizing risks. Nitrogen dioxide, i.e., from car exhaust, thermal power plants, and steel manufacturing; sulfur dioxide (SO_2), from fossil fuels; and benzene, from residential wood-heating, are gases that each absorb in UV and are therefore detected and quantified using UV CMOS sensors.

Looking ahead

Despite significant advancements in UV CMOS technology, certain challenges remain, limiting the full potential of these sensors for some applications. The main issue: UV CMOS is relatively low in terms of sensitivity and quantum efficiency compared with visible light sensors. Although thinner material layers enhance UV transmission, there is still room for improvement. Overcoming these obstacles and improving the sensor fabrication processes will expand the scope of UV CMOS sensors and enhance their overall efficiency, durability, and performance in harsh environments.

It is fortunate, in this sense, that CMOS technology has been around for decades and continues to benefit from a well-established road map, even if only for the visible and infrared ranges. UV CMOS opens its own spectrum of possibilities — but it does not exist in a vacuum. With continuous improvements, UV CMOS sensors are pushing limits and signaling a new era for the CMOS industry.

Meet the author

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References

1. M. Bigas et al. (2006). Review of CMOS image sensors. *Microelectronics J*, Vol. 37, No. 5, pp. 433-451.
2. N.G. Wright et al. (2008). Prospects for SiC electronics and sensors. *Mater Today*, Vol. 11, No. 1-2, pp. 16-21.

Confirming the Benefits: OCT Tracks Laser Penetration in Oscillation Welding

BY NATALIYA DEYNEKA DUPRIEZ AND TIM NÖBAUER
LESSMÜLLER LASERTECHNIK GMBH

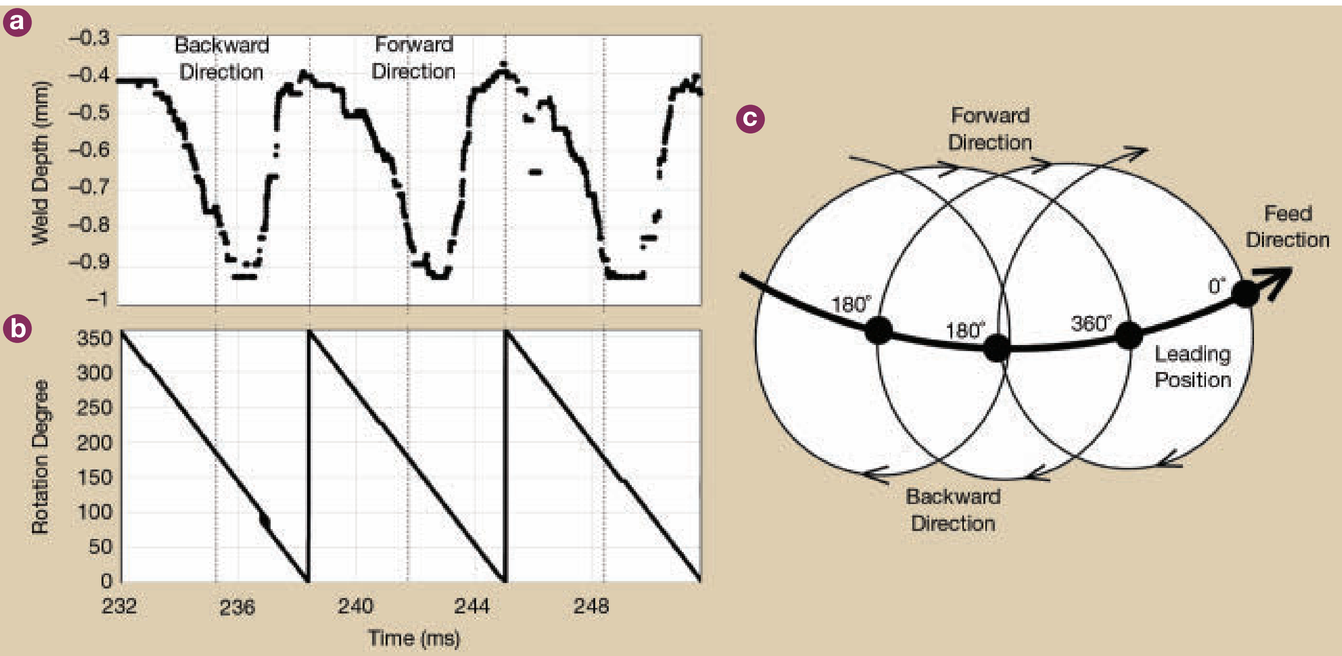
Laser oscillation welding is finding increased popularity in the domain of large-scale industrial production. Through extensive studies examining the welding of aluminum and steel with oscillating laser beams at the commonly used frequencies of 100 to 200 Hz, results showed that oscillation welding is more controllable, offers higher welding speeds, and leads to a reduction in weld defects. The studies have also shown that this process provides significantly reduced weld porosity, a shallower heat-affected zone (HAZ), and an enlarged joining area.

The improved weld quality can be gauged in terms of weld morphology as well as mechanical, electrical, and thermal properties. This improved quality is a prerequisite for series production of battery systems, to achieve high-quality cell connections with minimized electrical and thermal losses and to ensure the highest achievable levels of safety and performance.

For laser oscillation welding, scanning mirrors and lenses are used to manipulate the beam. With these elements, the laser focal point can be moved in a circular or other pattern in conjunction with the welding feed. Additionally, the oscillation shape, amplitude, and frequency can be adjusted.

However, obtaining control of laser penetration at different combinations of welding conditions — as determined by laser power, welding speed, oscillation frequency, and welded material — remains an open issue. An uncontrolled penetration of the laser beam during the joining process poses a safety risk when

Figure 1. Data showing optical coherence tomography (OCT) weld depth measurements **(a)** in relation to rotation degree **(b)** during the laser beam oscillation welding of aluminum alloy. This information is compiled along three oscillation circles **(c)**. The schematic represents the laser beam position within the oscillation circle.



All images courtesy of **Lessmüller Lasertechnik GmbH**.

the welded workpiece is in operation. It is now obvious that a suitable manufacturing process is essential to fulfill the strict necessary technical requirements.

To this end, several technological solutions for real-time monitoring of the weld depth during laser beam oscillation welding have been presented. In many cases, these proposed methodologies have also undergone optimization. For example, x-ray videos along the oscillation path have been used to visualize and analyze the geometry of the keyhole[1]. However, commercial x-ray systems pose too many restrictions for use and application in mass production.

Another study has shown the effect of circular oscillation patterns along the linear feed direction on the keyhole depth measured using in-line coherent imaging during the laser welding of copper and aluminum[2]. Here, a static measurement beam was used to capture measurements at four cardinal points around the circular oscillation pattern, or a beam was rotated in the opposite direction relative to the process beam when the keyhole and measurement beam crossed several times per oscillation period.

Optical coherence tomography (OCT) is the modern technology that has been used to monitor and control the industrial laser welding process. Microsecond-scale temporal resolution and high measurement accuracy at micrometer scale are achievable with OCT. The outstanding precision of OCT can streamline processes, increase overall efficiency and productivity, and lead to cost reductions.

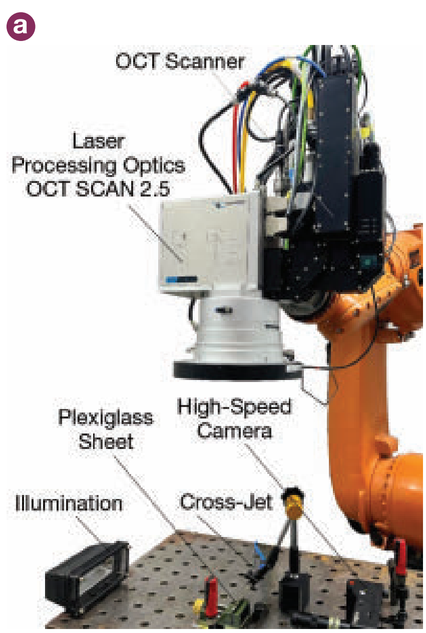
But the major drivers to the intensified use of OCT for this monitoring application during the last decade involve its ease of integration into the welding system, plus its immunity to the process environment. The OCT measuring beam is directed coaxially onto the workpiece surface together with the processing laser beam and used to inspect the surface topography in the pre- and post-welding stages for the seam tracking and quality assessment of the weld bead. OCT also enables direct noncontact in-process measurement of the weld depth to control the consistency of the penetration of the processing laser.

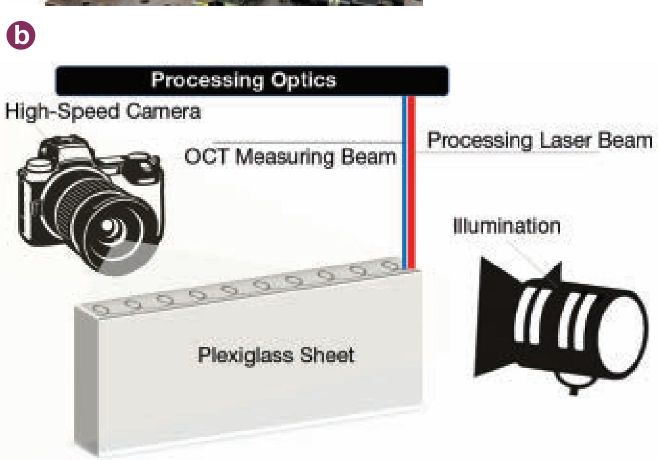
In-process monitoring: Aluminum

In previous work, a true following mode was explored, in which the weld depth was continuously measured with OCT using a newly developed procedure[3,4]. This procedure enabled high-dynamic adjustment of the OCT beam position to the instantaneously modified processing direction, allowing it to follow any welding trajectory and any oscillation geometry.

This was realized via an adjustment of the OCT beam position to the position of the processing laser due to the high-dynamic communication of the control board with both the laser processing optics and an OCT scanner. A 2D galvanometer OCT scanner was used for dynamic beam deflection. The weld depth was measured with OCT in real time during the welding of the as-rolled aluminum workpiece.

The use of an aluminum workpiece is typical for the fabrication of automotive battery components. The processing beam with a laser power of 2.5 kW followed a circular oscillation path in a clockwise direction — with an oscillation frequency





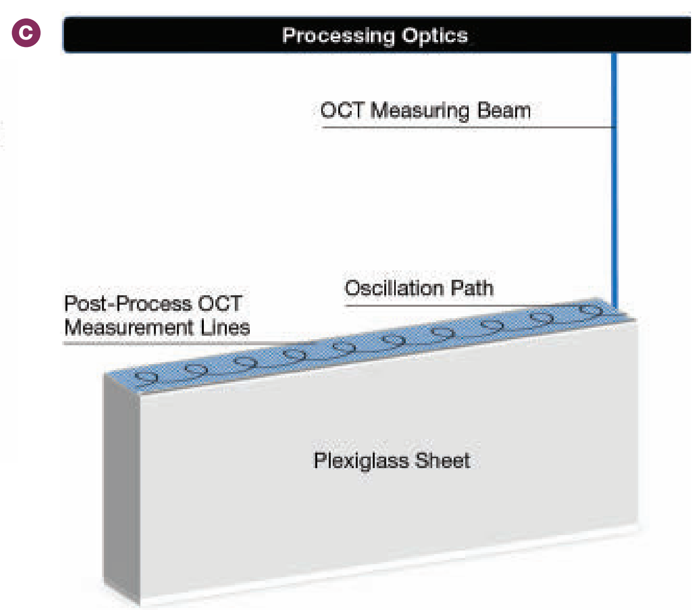


Figure 2. Test setup: welding and testing equipment and installation **(a)**; a schematic presentation of the laser welding and testing setup **(b)**; a schematic presentation of the post-process scanning of the finished seam surface with OCT **(c)**.

of 150 Hz and an oscillation amplitude of 0.8 mm — which was superimposed on the circular feed trajectory with a welding speed of 95 mm/s (see the table).

Exemplary results of weld depth measurements with OCT were obtained during welding along three oscillation loops in the middle time of the entire weld seam (Figure 1). Figure 1 also shows the oscillating behavior of the weld depth as a function of the rotation angle. This behavior is repeated over the entire welding time.

A clear difference in the weld depth was observed at different positions within the oscillation circle. Measurements at the front point (leading position) of the feed direction (radial angle 0° or 360°) showed the shortest keyhole. The deepest keyhole was observed at the beginning of the forward movement, in relation to the feed direction, at a rotation angle between ~90° and 180°.

Monitoring of the PMMA welding

Figure 2 shows a simple and cost-effective test setup used to confirm the OCT weld depth results obtained when welding aluminum with an oscillating processing laser beam and high-dynamic OCT beam. Subsequent processing was performed on the edge surface of a polymethyl methacrylate (PMMA) sheet with a thickness of 3 mm to enable sheet transparency for sideward video recording of the processing. A single-mode laser with a power of 200 W was used; welding speed along the line was 100 mm/s; and the average speed over the entire oscillation path was 262.08 mm/s. An OCT laser welding optic equipped with an f-theta lens, with a focusing distance of $F =$ 400 mm, was used to position the laser beam (Figure 2).

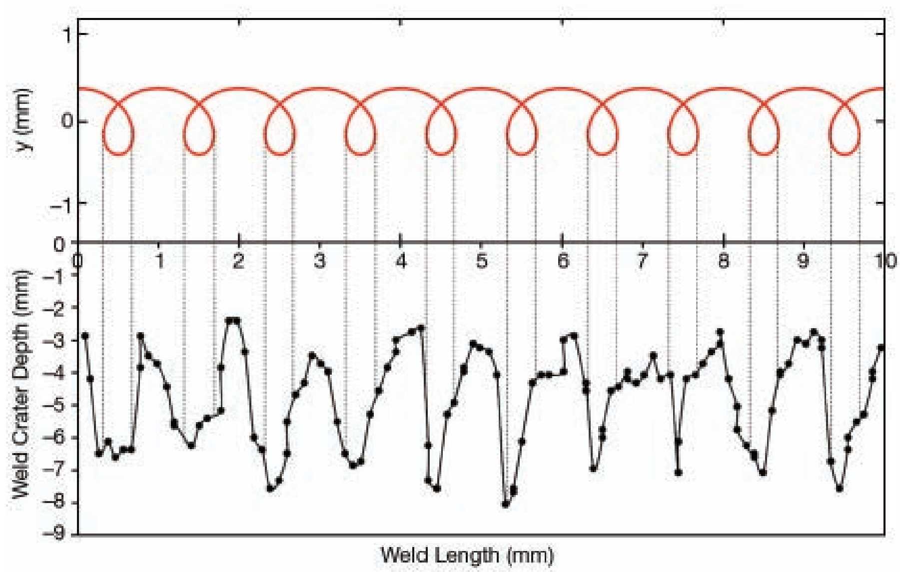


Figure 3. Data showing weld crater topography **(lower diagram)** after the laser beam oscillation welding of polymethyl methacrylate (PMMA) with an oscillation frequency of 100 Hz in relation to the trajectory of the laser beam **(upper diagram)**. From the diagrams, the deepest craters occur when the circular movements overlap.

The process conditions are shown in the table; except for the laser power and oscillation radius, they are similar to those used for aluminum welding with an oscillating laser beam. The laser power was reduced due to the much lower melting temperature of PMMA compared with aluminum, while the oscillation radius had to be adapted to the PMMA sheet thickness.

Laser Oscillation Welding: Process Steps and Results

	Aluminum EN-AW-1050	Polymethyl Methacrylate
Laser Power	2.5 kW	200 W
Oscillation Frequency	150 Hz	100 to 200 Hz
Oscillation Radius	0.8 mm	0.4 mm
Welding Speed Along the Feed Direction	95 mm/s	100 mm/s
Oscillation	Circular	Circular
Rotation Direction	Clockwise	Clockwise
Feed Trajectory	Circular	Circular

A high-speed camera was used to record the welding process, and the video was recorded at a rate of 8986 fps at a resolution of 640 × 120 pixels. The sheet was recorded from the side so that the HAZ could be seen, owing to the transparency of this material.

The cross-jet was used to suppress the bubble formation on the surface of the sheet during laser processing, which occurred as a result of boiling.

The surface topography of the resulting weld was analyzed in the post-process after completion of the weld. OCT measurements with a line rate of up to 250 kHz were performed by taking 100 measurements per line. The length of the OCT scan line across the weld was 2 mm. The theoretically estimated axial resolution of the OCT is ~12 µm.

The melting temperature of the PMMA is 160 °C, and it burns at 460 °C. The application of the high-energy processing laser beam therefore leads to boiling and vaporization of the synthetic polymer. Therefore, the surface scan with OCT over the fully solidified weld seam represents the topography profile of the weld crater (Figure 3).

The topography of the weld craters repeats the oscillating motion of the laser beam; this is similar to that which has been observed previously[2]. Superimposing the crater depth with the oscillation path showed that the crater is deepest when the oscillation circles intersect, and

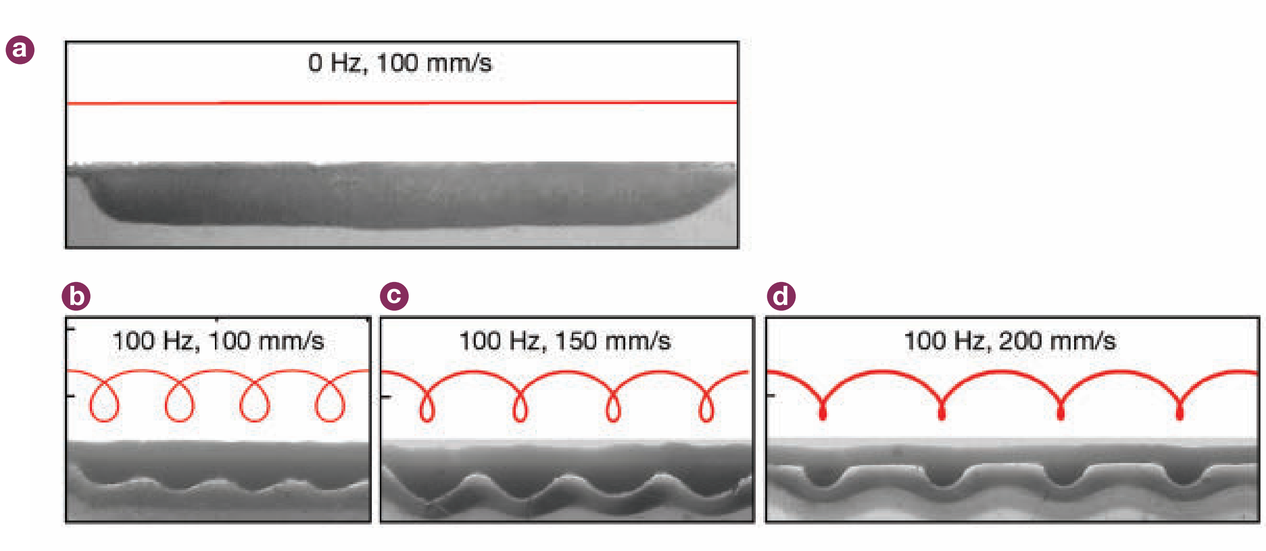


Figure 4. Side-view snapshots of the processed polymethyl methacrylate (PMMA) without **(a)** and with **(b-d)** laser beam oscillation at varying welding speeds.

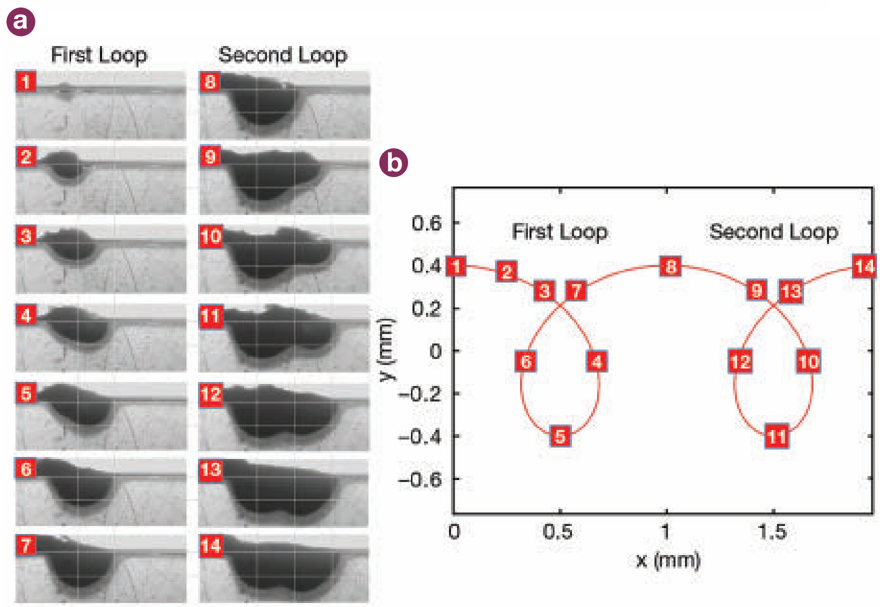


Figure 5. Video snapshots **(a) (stages 1 to 14)** of the successive development of the heat-affected zone (HAZ) within two oscillation loops during the laser beam oscillation welding of the polymethyl methacrylate (PMMA) with an oscillation frequency of 100 Hz. The position of the laser beam at each snapshot time is marked on the schematic to show laser beam trajectory **(b)**.

shallowest when the laser beam moves forward along the feed direction and melts the raw material. A certain discrepancy in the measurement results is due to the scattering of the reflected OCT beam on the rough crater surface. In the circular oscillation pattern, the laser beam moves periodically along and against the welding direction[3]. The crater depth does not provide information about the penetration depth during the forward and backward movement of the processing laser.

Side-view snapshots of the processed PMMA material with and without laser beam oscillation confirm this observation: The almost linear underside of the HAZ is visible after processing without oscillation (Figure 4a). With oscillation welding, the underside of the HAZ shows an oscillating character (Figure 4b-d). It is also noticeable that the welding speed influences the shape of the resulting HAZ. The higher the welding speed, the more the cavity extremes spread out. The resulting data shows that the underside of the HAZ tends toward linearity at lower welding speeds.

The crater topography and the snapshots of the solidified weld seam represent the resulting weld seam in the same way as the metallographic cross-sectional images. It is important to know how the weld forms during the welding process to control and predict the quality of the joint. OCT keyhole depth measurements can shed light on this.

Similar to the x-ray video recording of the metallic workpiece previously referenced, the lateral video recording of the PMMA can track the laser penetration depth and the evolution of the HAZ during processing with the oscillating laser beam and resolve each melting stage (Figure 5). The oscillation frequency, radius, and welding speed differed from those used for welding aluminum. Since lower welding speeds, or higher oscillation frequencies and radius, lead to an almost linear underside of the HAZ, a frequency of 100 Hz, radius of 0.4 mm, and a welding speed of 100 mm/s were chosen to resolve each oscillation cavity individually.

In Figure 5, the sequence of snapshots from the lateral video recording of the weld formation during welding along the first and second oscillation loop is shown. The development of the HAZ in the feed direction can be observed in the first five stages of Figure 5. In these five stages, the HAZ gradually expands in length and depth. When the processing laser moves backward, a further deepening of the already welded portion is noticed (Figure 5, stage 6), which reaches its maximum when the oscillation path overlaps (Figure 5, stage 7). A similar behavior was detected when the laser beam moved along the second oscillation loop (Figure 5, stages 8 to 14).

Analysis of results

A comparison of the results of the video recording of the second loop in Figure 5, with the OCT measurements of the weld penetration depth during oscillation welding of aluminum shown in Figure 1, reveals multiple similarities. Notably, the weld formation during welding with an oscillating laser beam is subject to continuous dynamic changes depending on the temperature and the welding speed.

To cover the longer distance within the oscillation path during forward movement, in relation to the feed direction, the laser beam was advanced onto the aluminum workpiece at a maximum speed of 848.98 mm/s and onto the PMMA at a maximum speed of 351.33 mm/s. Higher welding speeds typically cause shallower welds. However, during the forward movement, the laser beam interacted with molten material due to the crossing of the oscillation circles (except the very first stages 1 to 5), at rotation degrees 180° to 90° and at stages 7 and 13 in Figure 5. The molten material vaporized quickly, resulting in a significant increase in weld depth and HAZ.

When traveling backward in relation to the feed direction, the processing beam covers a shorter distance. On the aluminum workpiece, the minimum speed of the backward movement was 658.98 mm/s, while the laser beam on the PMMA moved backward at a minimum speed of 151.33 mm/s. At lower welding speeds, during backward movement, a deeper weld would be expected. Nevertheless, the shortest keyhole and HAZ were observed in the earlier stages of the backward movement when the laser beam melted the solid material (Figures 1a and 5a). The weld depth and HAZ increased progressively at rotation degrees of 250° to 180° (Figure 1b) in stages 5 and 6 of Figure 5 due to the proximity of the weld pool. A similar 3D model has been previously presented[5].

The results indicate that the proximity of the already-melted areas has the greatest influence on the laser penetration depth. The welding speed during the forward and backward movement of the laser during circular oscillation welding has less influence on the weld formation.

The results additionally emphasize the value of high-dynamic OCT measurements with synchronous online reorientation of the OCT measurement beam in relation to the dynamically changing processing beam position. OCT allows not only control of the consistency of the laser penetration in real time but also the monitoring of the time-resolved weld seam formation. Knowledge of the weld depth dynamics is essential for a stable and controlled weld depth and exceptional weld quality. Moreover, the use of high-dynamic OCT ensures the effective production, high throughput, and optimum performance of the manufactured parts.

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References

1. F. Fetzer et al. (2018). Reduction of pores by means of laser beam oscillation during remote welding of AlMgSi. *Opt Lasers Eng*, Vol. 108, pp. 68-77.
2. C.M. Galbraith et al (October 2018). Wobble-welding of copper and aluminum alloys with inline coherent imaging. *Proc ICALEO*, Vol. 37, Orlando, Florida.
3. N. Deyneka Dupriez et al. (2023). Weld depth dynamics measured with optical coherence tomography during remote laser beam oscillation welding of battery system. *J Laser Appl*, Vol. 35.
4. N. Deyneka Dupriez (June 2023). Measurements of weld quality with OCT during laser beam oscillation welding of aluminum alloy for battery production. *Proc Lasers in Manufacturing Conference 2023*, Munich, Germany.
5. T. Li et al. (2024). Weld formation and porosity in TC4 joint by oscillating laser beam welding with circle trajectory model. *J Mater Res Technol*, Vol. 30, pp. 2680-2689.

Product News

Laser Sensor

The Ophir 70K-W Ultra-High Power Laser Sensor from **MKS Instruments** is a water-cooled calorimetric sensor for industrial and defense applications, such as high-power fiber laser development and testing, industrial cutting, and directed energy systems. The sensor accommodates vertical and horizontal beams and supports the use of tap water or deionized water for cooling. The Ophir 70K-W Ultra-High Power Laser Sensor can measure powers from 2 to 70 kW across a spectral range of 900 to 1100 nm and 10.6 µm, and features real-time laser power monitoring output, Ethernet and RS232 interfaces, a low back reflection of <0.5%, a wide numerical aperture range from collimated beams up to 0.22, a 130-mm aperture, and a <40-kg design.
sales@newport.com

Alignment System

The F-141 from **Physik Instrumente** (**PI**) is an alignment system for testing and assembling photonics arrays and photonic integrated circuits. The alignment system fits inside a space of 5 × 7 × 4 in. while providing 40 mm of xyz travel and 12° of rotation around the optical axis. The F-141 is controlled by an advanced multi-axis EtherCAT-based control system with rapid signal analysis and features pulse width modulation amplifiers and onboard integrated 24-bit analog inputs.
info@pi-usa.us

Power Meter Mobile App

The BLU app from **Gentec-EO** is an Android app that supports the company's INTEGRA UP and XLP thermal laser power meters. Via a USB-A to USB-C cable, the app enables measurements, views of live charts, and creates and share logs among other users.
info@gentec-eo.com

Silicon Avalanche Photodiodes

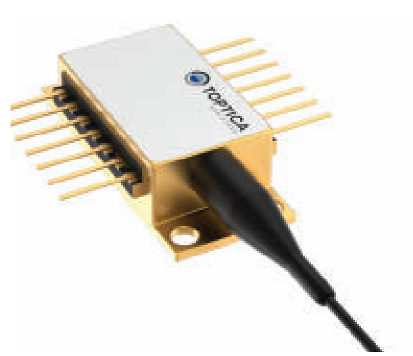
Products in the C30683 Series of silicon avalanche photodiodes from **Excelitas Technologies** offer a discrete transimpedance amplifier for a range of photon detection applications such as lidar, range finding, and laser meters. Hermetically sealed within a TO-8 package, they deliver a spectral response from 400 to 1100 nm with a bandwidth of up to 400 MHz and feature a 500-µm active area.
photonics@excelitas.com

Single-Photon Detection Solutions

The Cricket Pro and PhotonPix from **Photonis** is an image intensifier adapter and high-count rate module, respectively, meant for single-photon detection applications. The plug-and-play Cricket Pro has an expanded 25-mm active detection area, 3-ns high-speed gating, a 3-MHz burst or 30-kHz repetition rate, and an F-mount lens/camera interface. The high-count rate MCP-PMT-based PhotonPix features a Ø8-mm sensitive area, an extreme-low dark count rate as low as 20 counts per second, count rates >200 MHz in burst mode, and a timing resolution of <15 ps.
info@exosens.com

Laser Modules

The Chilas ATLAS, COMET, and POLARIS from **Chilas BV** are laser modules meant for applications such as sensing, quantum technologies, OCT, quantum key distribution, lidar, spectroscopy, telecommunications, and metrology. The Chilas ATLAS broad wavelength tunable laser has an ultra-narrow linewidth and a wide tuning range in wavelength configurations of 685 nm, 850 nm, 1550 nm, 1600 nm, and 1700 nm. The Chilas COMET swept source laser features a fiber output power >10 mW and a sweeping speed of 40 nm/s across the C-band. The Chilas POLARIS frequency-stabilized laser delivers long-term stability in both frequency and power.
info@chilasbv.com

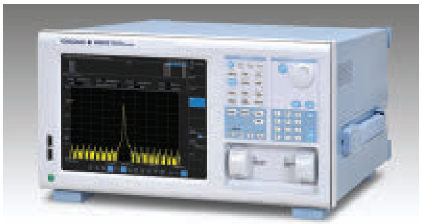


Fiber-Coupled Laser Diode

The miniECL 780 nm from **TOPTICA EAGLEYARD** is a 780-nm fiber-coupled laser diode for spectroscopy, quantum technology, metrology, life sciences, and precision timekeeping applications. The laser diode features an output power of 25 mW, a large mode-hop free tuning range, a typical narrow linewidth of 100 kHz, 20-dB polarization extinction ratio of the fiber, and a hermetically sealed butterfly package.
info@toptica-eagleyard.com

Additive Manufacturing Lens

Coherent's high-power f-theta lens is designed for applications such as additive manufacturing, electric vehicle battery welding, and laser cleaning. The lens is available in 266-, 355-, 532-, and 1070-nm wavelengths for femtosecond to nanosecond pulse durations and high-power fiber lasers.
info@coherent.com

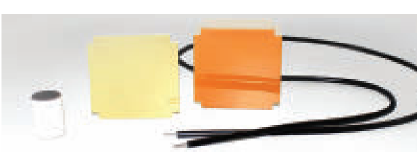


Optical Spectrum Analyzer

The AQ6377E from **Yokogawa Test & Measurement Corporation** is an optical spectrum analyzer for MIR measurements that meets a broader spread of laser application demands, including environmental measurement. The analyzer's built-in chopper operates automatically for light modulation and includes NORMAL/CHOP and MID/CHOP measurement sensitivity settings, which apply the lock-in detection function to the intermediate NORMAL and MID sensitivities.
info@yokogawa.com

BSI CMOS Sensor

The GSENSE1517BSI from **Gpixel** is a back-side illuminated CMOS imaging sensor for applications including astronomy imaging tasks, such as space situational awareness, orbital object tracking, other space-related imaging, and physical sciences research. The sensor uses dual-gain high dynamic range (HDR) and both 12-bit and 14-bit analog-to-digital converters to achieve a variety of imaging modes. Both 12-bit HDR and 14-bit standard are supported at up to 4 fps, using 10 pairs of low voltage differential signaling working at 420 Mbps each. The GSENSE1517BSI also features a 4116 × 4100 (16.8-MP) resolution, 15- × 15-µm pixels, a 61.74- × 61.5-mm imaging area, peak QE of 92%, and a minimum read noise of 1.2 e-.
info@gpixel.com

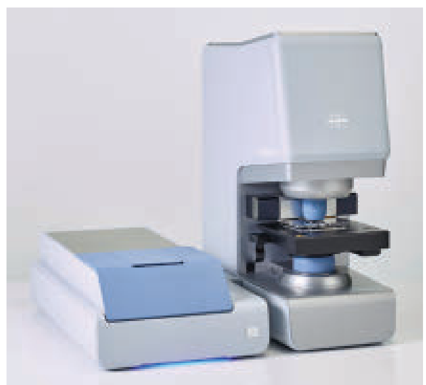


Glass Nano Waveguides

SCHOTT's transverse Anderson localization (TAL)-based glass nano waveguides were designed for applications with ultrahigh-resolution imaging, including medical diagnostics, industrial inspection, and defense, among others. The TAL technology simplifies detector alignment by confining light within sub-camera pixels for accelerating scalability and prototyping for medical devices and in defense manufacturing. The TAL-based glass nano waveguides are manufactured from optical glass types, such as borosilicate or infrared glasses, as well as fused silica to localize light within submicron or nano levels.
info.optics@us.schott.com

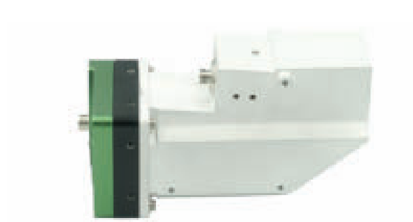
Broadband SLEDs

EXALOS' line of 840-nm broadband superluminescent light-emitting diodes (SLEDs) supports applications such as industrial and biomedical optical coherence tomography. The devices deliver 100 mW of free-space output power at a typical drive current of 300 mA at 25 °C in a TO9 can with an integrated monitor photodiode, as well as a Gaussian-shaped output spectrum with a full width at half maximum of 26 nm at a center wavelength close to 840 nm. The broadband SLEDs are also available as cooled 14-pin butterfly modules with single-mode fiber or polarization-maintaining fiber output, delivering optical power values of 30 mW at operating currents of 230 mA.
sales@exalos.com



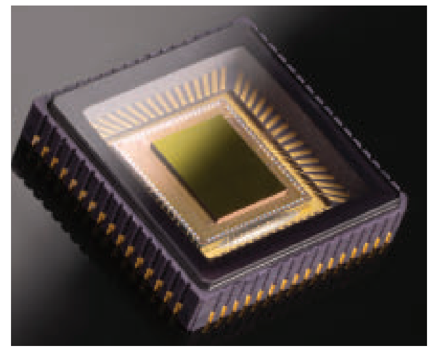
Infrared Imaging Microscope

The LUMOS II ILIM from **Bruker Corporation** is a quantum cascade laser-based infrared imaging microscope meant for applications such as capturing ultrafast infrared images of expansive areas with enhanced spatial resolution in pharmaceutical and life sciences research. Using a coherence reduction method for infrared laser imaging, the microscope is essentially free from artifacts in transmission and reflection modes and offers a large field of view and complete automation capabilities for determining chemical complexity in biological tissues. The LUMOS II ILIM features AI-powered data evaluation and can be integrated with the company's MALDI Imaging methods to enable multimodal imaging for characterizing tissues with analytical depth.
info.bopt.us@bruker.com



OCT Spectrometer

The EAGLE OCT-S 140 from **Ibsen Photonics** is an OCT spectrometer for industrial and biomedical and biopharmaceutical applications. The 140-nm bandwidth spectrometer has a high axial resolution of <3 µm in air, allowing for the capture of higher-resolution OCT images, and is equipped with Teledyne e2v's OCTOPLUS camera. The EAGLE OCT-S 140 features a frame rate of up to 250 kHz and a compact footprint of 143 × 80 × 60 mm.
sales@ibsen.com

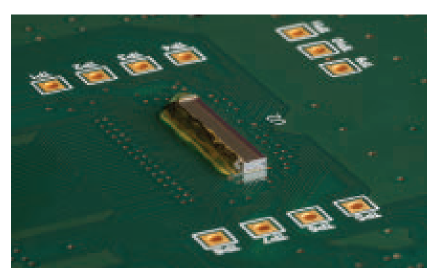


SWIR Sensor

The Eyesential SW from **Lynred** is a SWIR sensor for applications in machine vision, scientific imaging, and spectroscopy. The sensor uses a high frame rate of 300 Hz full frame/1200 Hz 1/4 full frame and low noise for automation and data exchange trends in industry 4.0 manufacturing. The Eyesential SW also features a resolution of 640 × 512, a pixel pitch of 10 µm, 14-bit digital output, commercial off-the-shelf packaging, and wavelength detection from 0.9 to 1.7 µm.
info@lynred.com

Optical Engine

The Z-30 from **Lumus** is an optical engine built for AR applications. Built with the company's Z-Lens 2D waveguide, the engine offers a 30° field of view to fit with standard glasses sizes as well as micro-LED projectors. The Z-30 has a weight of 14.5 g, full color 720- × 720-pixel resolution, and a brightness of >3000 nits/W.
info@lumusvision.com



SPAD Line Sensor

The Sirona from **Singular Photonics** is a single-photon avalanche diode (SPAD)-based line sensor meant for Raman spectroscopy, fluorescence lifetime imaging microscopy, time-of-flight, and quantum applications. The 512-pixel line sensor is capable of time-correlated single-photon counting.
info@singularphotonics.com

Industry Events

APRIL

○ PIC International Conference
(April 7-9) Brussels.
Contact Angel Business Communications, +44 0-24-76718970, **info@picinternational.net**; www.picinternational.net.

SPIE Optics + Optoelectronics
(April 7-11) Prague.
Contact SPIE, +1 360-676-3290, **customer service@spie.org**; https://spie.org/conferences-and-exhibitions/optics-and-optoelectronics.

AeroDef Manufacturing
(April 8-10) Detroit.
Contact SME, +1 800-733-4763, **aerodef@ xpressreg.net**; www.aerodefevent.com.

○ SPIE Defense + Commercial Sensing
(April 13-17) Orlando, Fla.
Contact SPIE, +1 360-676-3290, **customer service@spie.org**; www.spie.org/conferences-and-exhibitions/defense-and-commercial-sensing.

Optica Biophotonics Congress: Optics in the Life Sciences
(April 20-24) Coronado, Calif.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/biophotonics_congress.

○ OPIE
(April 23-25) Yokohama, Japan.
Contact OPIE, **event@optronics.co.jp**; www.opie.jp/en.

○ ASLMS Annual Conference
(April 24-26) Orlando, Fla.
Contact ASLMS, +1 715-845-9283 / +1 877-258-6028, **information@aslms.org**; www.aslms.org/home.

MAY

○ CLEO 2025
(May 4-9) Long Beach, Calif.
Contact CLEO, +1 800-766-4672, **info@cleoconference.org**; www.cleoconference.org/home.

○ SENSOR + TEST
(May 6-8) Nuremberg, Germany.
Contact AMA Service GmbH, +49 0-5033-9639-0, **info@ama-service.com**; www.sensor-test.de/en.

CONTROL
(May 6-9) Stuttgart, Germany.
Contact P.E. Schall GmbH & Co. KG, +49-0-7025-9206-0, **info@schall-messen.de**; www.control-messe.de/en.

○ Automation UK
(May 7-8) Coventry, England.
Contact Automate UK, +44 (0)20-8773-8111, **sales@automation-uk.co.uk**; www.automation-uk.co.uk.

25th China (Guangzhou) Int'l Laser Equipment and Sheet Metal Industry Exhibition
(May 10-12) Guangzhou, China.
Contact Zheng Lisy, +86 135-7059-8541, **julang@julang.com.cn**; www.julang.com.cn/english/banjin.

○ SID Display Week
(May 11-16) San Jose, Calif.
Contact Mari Ramirez, +1 813-381-3667, **registration@sid.org**; www.displayweek.org.

○ Automate 2025
(May 12-15) Detroit.
Contact the Association for Advancing Automation, +1 734-994-6088, **info@automate show.com**; www.automateshow.com.

EASTEC
(May 13-15) West Springfield, Mass.
Contact SME, +1 800-733-4763; www.easteconline.com.

Optica OIC — Optical Interference Coatings
(May 18-23) Tucson, Ariz.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/topical_meetings/optical_interference_coatings.

○ Embedded Vision Summit
(May 20-22) Santa Clara, Calif.
Contact Edge AI + Vision Alliance; www.embeddedvisionsummit.com.

○ MD&M East
(May 20-22) New York.
Contact Informa Markets +1 310-445-4273, **registration.ime@informa.com**; www.mdmeast.com/en/attend/show-sectors/automation.html.

○ Indicates shows **Photonics Media** will be attending.
Complete listings at **www.photonics.com/calendar**.
Submit your event online at **www.photonics.com/eventsubmit**.

Photonics North
(May 20-23) Ottawa, Ontario.
Contact Photonics North, +1 418-522-8182, **pn.info@conferium.com**; www.photonicsnorth.com/en.

23rd EMVA Business Conference
(May 22-24) Rome.
Contact European Machine Vision Association, +34 93-220-7201, **info@emva.org**; www.emva.org/events/business-conference/23rd-emva-business-conference.

5th Annual Conference on Lasers, Optics, Photonics Sensors, Bio Photonics, Ultrafast Nonlinear Optics & Structured Light 2025
(May 31-June 2) Hollywood Beach, Fla.
Contact Keerthi Rajana, +1 647-952-4467, **support@lopsnews.com**; www.exceleve.com/photonoptics.

JUNE

Optica Quantum 2.0 Conference and Exhibition
(June 1-5) San Francisco.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/topical_meetings/quantum.

PAPERS

ECOC
(Sept. 28-Oct. 2) Copenhagen, Denmark.
Deadline: Abstracts, April 22
Contact +45 70-20-03-05, **info@cap-partner.eu**; www.ecoc2025.org.

SPIE Optifab
(Oct. 20-23) Rochester, N.Y.
Deadline: Abstracts, May 7
Contact SPIE, +1 360 676 3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/optifab.

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.

AutoSens USA
(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.

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

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.

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sales.ophir.usa@mksinst.com **tinyurl.com/2r94cppf**

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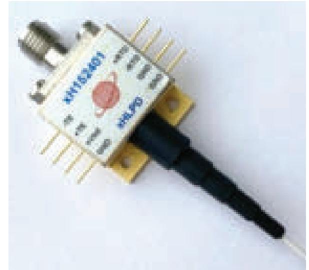

The xHLPD photodiodes provide high power operation up to 10 GHz bandwidth, and deliver up to 4 V peak-to-peak (+16 dBm CW) RF output power with exceptional phase linearity < 5 rad/W. The thermo-electrically cooled modules enable reliable device operation with multiple biasing options. Applications include ultra-low noise optical clocks, photonic time transfer, antenna remoting, and RF-over-Fiber.

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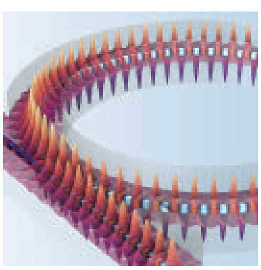

COMSOL Multiphysics® is a software environment for creating physics-based models and standalone simulation apps. Add-on products provide specialized functionality for electromagnetics, structural, acoustics, fluid flow, heat transfer, and chemical simulations. Interfacing products offer a unified workflow with all major technical computing and CAD tools. COMSOL Compiler™ and COMSOL Server™ are used for deploying simulation applications to colleagues and customers.

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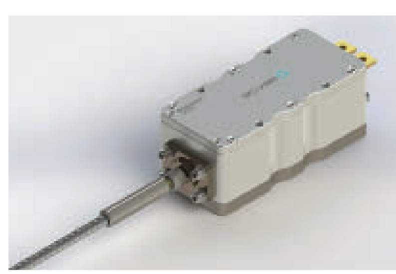
Diode Lasers for SWIR Illumination



QPC Lasers offers high power lasers for SWIR illumination. Wavelengths range from 780 to 2000 nm and powers from single Watts to over 100 W. Fiber-coupled and free-space versions are available, as are integrated modules supplying multiple wavelengths. Lasers can be supplied with integrated thermoelectric cooling and matching power supplies.

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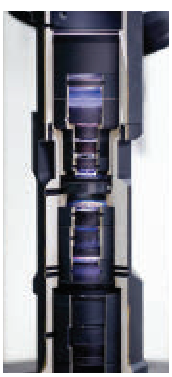

Hyperion specializes in custom objective lenses engineered for quantum applications. Achieve high NA in a compact design with metrology-backed precision, including 2-5 µm decenter & tilt correction per surface and 20 µm air gap control between each element. We support extended wavelengths in the UV range (CaF_2, Quartz). Our Active Alignment assembly process ensures unmatched resolution. Enhance your quantum performance with custom engineering.

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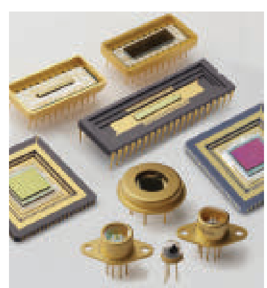
InGaAs Sensors: Advanced Solutions



Teledyne Judson InGaAs sensors offer enhanced sensitivity, superior QE, and minimal dark current, providing researchers and engineers with advanced capabilities to tackle photonic challenges. They feature a stable response vs. temperature, a wide dynamic range, high linearity, and require no bias or cooling. Cut-off wavelength range of 1.7 µm to 2.6 µm, these sensors are versatile for gas analysis, NIR-FTIR, spectroscopy, and medical imaging.

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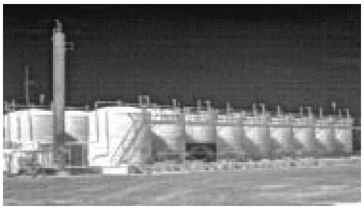
world-of-photonics.com/tickets

Photonics Showcase

Uncooled Optical Gas Imaging



LightPath Technologies OGI (Optical Gas Imaging) camera provides a low cost, effective solution to visualize Methane and VOC's (volatile organic compounds). Traditionally only cooled sensors have been utilized, this has been a road-block to mass deployment due to cost. Our high-sensitivity uncooled LWIR camera provides a unique cost effective path to mass deployment and remote monitoring for gas detection and additional applications.

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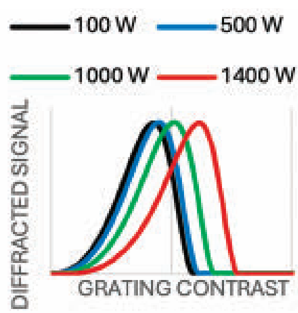

The newest SLM from Meadowlark Optics boasts CW power handling of ≥ 1 kW at 1070 nm. In tests at SPICA, the SLM retained its full >1 wave range of phase modulation at powers up to 1.4 kW. With sapphire coverglass, built-in water cooling, and a suite of calibration tools, the high-power SLM can maintain calibrated performance under extreme laser power loads.

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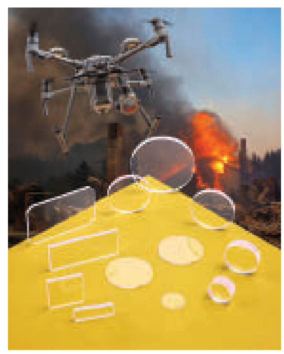
Sapphire Windows for Drones



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.

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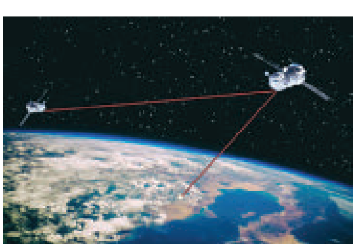

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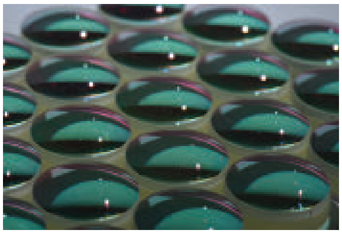

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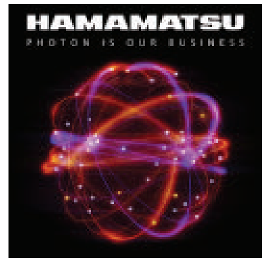
Photonics in Quantum Technologies



Quantum technologies are changing the future of technology and society. All emerging quantum technology fields, including quantum computing and quantum communication and networking, rely on photonics innovations, and we're proud to be empowering the next generation of quantum advancements with our wide range of photonic devices and solutions. From lasers and detectors to cameras and modulators, we can help you realize your next discovery.

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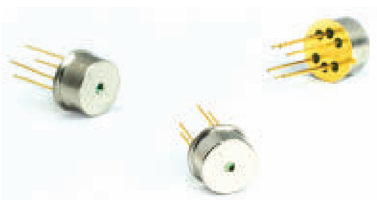
EP760 DFB & VCSEL — Oxygen Sensing



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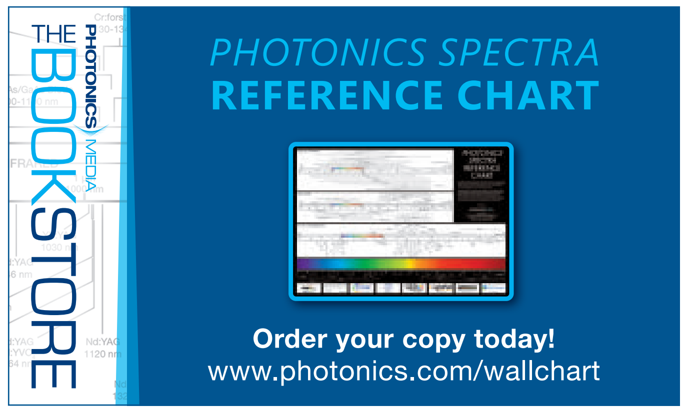

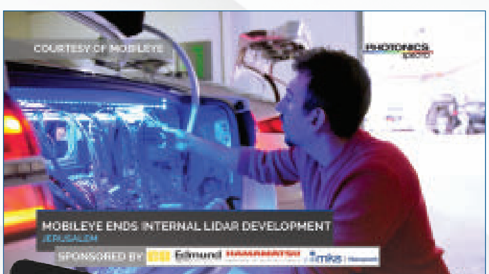

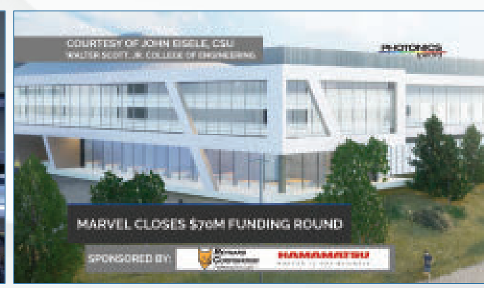

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The curious case of the quantum grape

Whether used as a decoration on your charcuterie spread, as a quick snack for the peckish photonics luminary, or as a fake eyeball to gross out trick-or-treaters on Halloween night, the value of a grape should not be understated.

To expand on the fruit's roles beyond set dressing and sustenance, researchers from Macquarie University have demonstrated how ordinary supermarket grapes can enhance the performance of quantum sensors, potentially leading to more efficient quantum technologies.

Where did these mad researchers get the idea to use grapes in their research? Well, social media of course! Specifically, viral videos showing the interaction between two grapes placed into a microwave side by side. In the videos, the fruits sent sparks flying while generating plasma between each other, not only captivating scientists everywhere but almost assuredly voiding the warranty on everyone's favorite kitchen appliance as content creators tested this theory themselves in the quest for more views. Other studies had been performed to investigate the electric fields produced from the interaction, but this team decided instead to focus on the magnetic field effects that are crucial for quantum applications.

The team used specialized nanodiamonds containing nitrogen-vacancy centers that act as quantum sensors. These defects (one of the many defects giving diamonds their color), behave like tiny magnets that can detect the presence of magnetic fields.

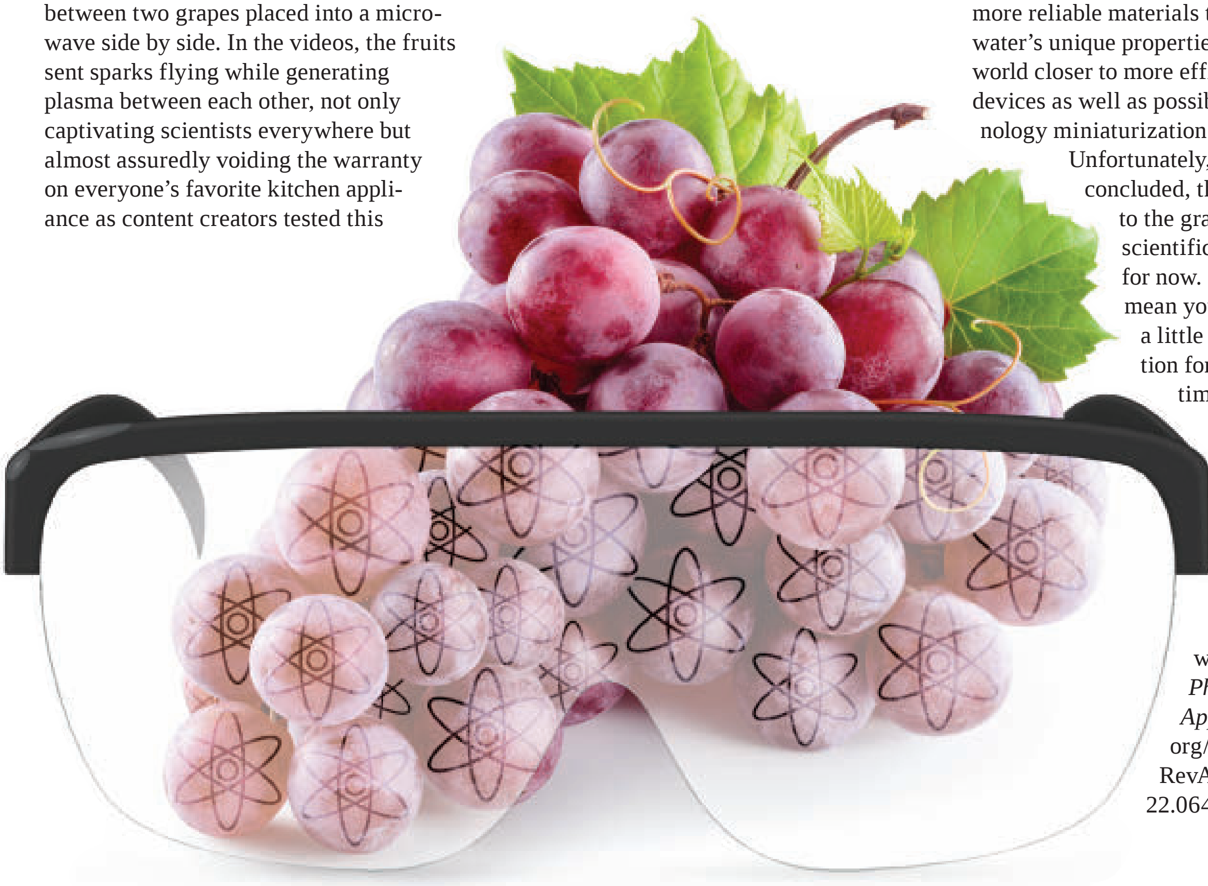
The researchers placed their quantum sensor on the tip of a thin glass fiber and positioned it between two grapes. By shining green laser light through the fiber, they could make these atoms glow red. The brightness of this red glow revealed the strength of the microwave field around the grapes.

The size and shape of the grapes proved to be crucial to the experiment's success. The team's experiments relied on grapes ~27 mm long to concentrate microwave energy at approximately the right frequency of the diamond quantum sensor. Quantum sensing devices traditionally use sapphire for this purpose, but the Macquarie team theorized that water might work even better, though they conceded that it's less stable and is apt to lose more energy in the process. This made grapes, which are mostly water enclosed in a thin skin, perfect for testing their theory.

The researchers are now developing more reliable materials that could harness water's unique properties, bringing the world closer to more efficient sensing devices as well as possible quantum technology miniaturization.

Unfortunately, with this study concluded, the end has come to the grape's time in the scientific spotlight, at least for now. But that doesn't mean you shouldn't feel a little more appreciation for the fruit the next time you peel a bunch of them in a bowl with the aim of scaring the ever-living plasma out of a few kids next Halloween.

The research was published in *Physical Review Applied* (www.doi.org/10.1103/PhysRevApplied.22.064078).



Grapes courtesy of iStock.com/Tim UR, safety glasses courtesy of iStock.com/VikiVector, and atom molecule icon courtesy of iStock.com/designer29.