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January 2025

# PHOTONICS spectra®

# 2025 Trends

- Silicon Photonics
- Micro-Optics
- PICs
- Laser Microprocessing
- Optical Materials
- Nonvisible Imaging

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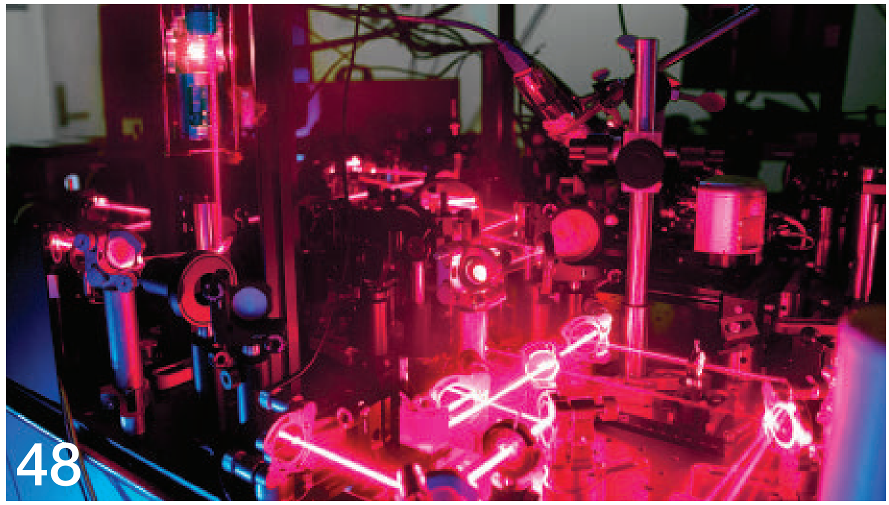
# Inside This Issue

January 2025 volume 59 issue 1

## Features













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## Departments



**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.

## Columns




## The Cover

Trends in the domains of imaging, optical materials, lasers, optical communications, and sensors and detectors are converging into high-powered tailwinds, ushering the photonics industry into 2025. Image courtesy of iStock.com/gleitfrosch. Cover design by Senior Art Director Lisa N. Comstock.

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***Photonics Spectra* Editor** Jake E. Saltzman



### Editorial Offices

100 West Street, PO Box 4949
Pittsfield, MA 01202-4949
+1 413-499-0514; fax: +1 413-442-3180
www.photonics.com

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+1 413-499-0514
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advertising@photonics.com

**Japan** Sakae Shibasaki
The Optronics Co. Ltd.
Sanken Bldg., 5-5 Shin Ogawamachi
Shinjuku-ku, Tokyo 162-0814, Japan
+81 3-3269-3550
Fax: +81 3-5229-7253
s_shiba@optronics.co.jp

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Circulation Offices

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# Editor's Note

## The more we know

January issues of *Photonics Spectra* offer more; in addition to more material, it is our hope that the content that features in our annual "Trends" edition encourages readers to ponder what they've read even after finishing an article. More content, to empower our readership to be more actively informed on major themes in and for our industry, is the ultimate reward for members of our staff who have made this issue possible.

This idea of more — and of more information — is especially topical right now. Here in the U.S., the vast and considerable changes that each new year promises feel particularly close as we greet 2025. Undoubtedly, the line that separates politics and society has been blurred in the recent past. But if the developments of this past December are any indication — with appointments to governmental positions that rattle the status quo — this demarcation between our government and our day-by-day is apt to undergo a profound transformation in the immediate future.

Change is, of course, never without context. Developments of the past often catalyze the forces that trigger change and spark the trends that define the present. The information that we have acquired in the past doesn't go away. Rather, it expands. More information and more context open opportunities to make valuable connections that shape our ability to perceive and make more sense of the world.

This is true in our governments and our societies. It is just as true in this year's "Trends" issue. Many of the trends that this issue explores — such as a photonic integrated circuits supply chain, alternative optical materials, and qualifying micro-optics for specialty applications — are best understood by placing them in a context that looks back, even with the promise of new opportunities that loom ahead.

In the pages that follow, industry contributions from Intel, Corning Incorporated, PhotonDelta, and MKS Newport explore topics in silicon and integrated photonics, materials science, and positioning equipment. Contributing editor Andreas Thoss offers a firsthand report on Lithuania's dynamic laser ecosystem. And Michael Eisenstein's survey of the current drone-based remote sensing landscape reveals how engineering, integration, and application challenges are commanding the attention of firms in and on the periphery of photonics.

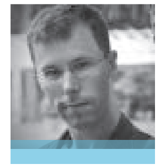
One hundred thirty-two pages allows us only to begin to identify some of the industry trends worth exploring. So, consider this an open invitation to peel back the layers on the topics spotlighted in this magazine. They are likely to open the door to trends that are not yet established but no doubt forthcoming. And if they do, remember that more information is likely already accessible.

jake.saltzman@photonics.com

## Contributors

### Erik Beckert
Erik Beckert earned his diploma in precision engineering and a doctorate in optoelectronics system integration from Technical University of Ilmenau, Germany. He heads the Opto-Mechatronical Components and Systems Department at Fraunhofer IOF. Page 90.

### Faisal Kamran
Faisal Kamran, Ph.D., serves as principal technology analyst at Sony. He is a photonics and business expert with experience in technology evaluation, global collaboration, sustainable business strategies, and mentoring startups. Page 62.



### James Schlett
Contributing editor James Schlett is an award-winning author, poet, and journalist. He is the former editor of *BioPhotonics*. Page 48.

### Indrajit Dutta
Indrajit Dutta is the Laser Optics Product Line manager at Corning Incorporated. He spent 12 years in Corning R&D, where his work resulted in 17 patents, more than 25 journal papers, and numerous technical presentations. Page 100.

### Sunil Priyadarshi
Sunil Priyadarshi is director of engineering for integrated photonics solutions at Intel Corporation. In his more than 25 years in optical connectivity product design, he has held positions at Broadcom (Avago), Coherent (Finisar), Source Photonics, NEC, and more. Page 38.

### Christopher Spiess
Christopher Spiess is a research associate and photonics innovator at Fraunhofer IOF, specializing in advanced quantum communication systems and their technological implementations. Spiess earned a Ph.D. from Friedrich-Schiller University Jena. Page 90.

### Michael Eisenstein
Michael Eisenstein studied biology at Brown University and Rockefeller University. He has worked as a freelance science journalist and as an editor for the past 10 years. Page 78.

### Abdul Rahim
Abdul Rahim, Ph.D., is ecosystem manager at PhotonDelta, where he is developing an innovative integrated photonics ecosystem. He is dedicated to fostering collaboration among Dutch, European, and global stakeholders. Page 62.

### Andreas Thoss
Andreas Thoss, Ph.D., is a laser physicist, founder of THOSS Media, and a contributing editor to *Photonics Spectra*. He has been writing and editing technical texts, with a focus on the field of photonics, for two decades. Pages 54, 90, and 96.

### Marie Freebody
Contributing editor Marie Freebody is a freelance science and technology journalist with a master's degree in physics from the University of Surrey in England. Page 70.

### Marc Schenkelberger
Marc Schenkelberger, Ph.D., is Newport sales manager for Newport Spectra-Physics GmbH. Page 84.

### Jue Wang
Jue Wang, Ph.D., is a leading scientist in surfaces, thin films, and coating technologies for Corning Incorporated. His work has resulted in more than 30 U.S. patents and more than 100 technical publications. He served as a full professor of physics at Tongji University. Page 100.

### Knut Hauke
Knut Hauke is Newport senior sales territory manager at Newport Spectra-Physics GmbH, based in Darmstadt, Germany. Page 84.

# Photonics Spectra Webinars

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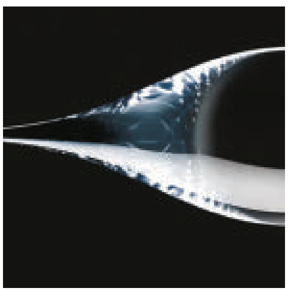
### Fused Silica Step Index Fibers: Advanced Preform and Fiber Metrology



This webinar discusses advanced preform and fiber measurement techniques for specialty fibers, with a focus on fibers produced using the plasma outside deposition (POD) process. Key analytical techniques, such as refractive index profile analysis, as well as focal ratio degradation, characterization of attenuation, and metrological challenges that arise during product characterization will also be discussed. Participants will gain insights into state-of-the-art measurement technologies and methods for the precise development and implementation of specialty fibers for advanced applications. The presentation will provide a comprehensive understanding of the metrology required to evaluate and improve the performance and quality of specialty fiber preforms.
Presented by Heraeus Conamic.
To view, visit **www.photonics.com/w1089**.

Heraeus Conamic

### Design Considerations for Automated Manufacturing of Optical Assemblies

As the demand for efficient production of optical systems grows in industries ranging from aerospace and defense to medical imaging, the automation of optical assembly processes becomes increasingly critical. This webinar discusses strategies for optimizing optical assembly designs for automated manufacturing, providing an in-depth exploration of how the latest innovations in optical design, materials selection, and component placement are transforming assembly methods. Zach Klassen discusses how effective optical design software can simulate and predict the performance of manufactured optical assemblies, allowing for adjustments that maximize alignment and tolerances before production begins. Whether focused on stand-alone assemblies or the integration of optical components into larger systems, this webinar is a gateway to mastering the complexities inherent in optical assembly automation. Presented by Benchmark.
To view, visit **www.photonics.com/w1145**.

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SUMMIT

# Integrated Photonics Summit


PI
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Luceda Photonics
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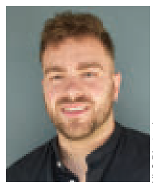
VLC Photonics
Minguillon.


vario-optics
Flöry.

The editors of *Photonics Spectra* magazine invite you to the Integrated Photonics Summit, a one-day virtual event premiering on Feb. 12, 2025. This summit dives into the future of integrated photonics and addresses challenges in PIC development. All presentations will be available on demand following the premiere.

Innovators from PI (Physik Instrumente), COMSOL, vario-optics, Luceda Photonics, and VLC Photonics discuss developments in integrated photonics, focusing on optical waveguide design and managing variability in PICs by bridging the gap between designers and foundries. Sessions also detail how modern, scalable manufacturing methods can bolster the industry and enhance traditional processes.

Registration for the summit is free and provides access to expert presentations that explore the challenges and opportunities of shaping integrated photonics.

**Website**

For more information and to register, visit **www.photonics.com/IPS2025**.

**Everything Old is New Again: Photonics Repeating Semiconductor Manufacturing's Script**
Scott Jordan, PI (Physik Instrumente)

**Bridging Designers and Foundries: Managing Variability in PICs**
Martin Fiers, Luceda Photonics

**Simulating Optical Waveguides: Construction, Analysis, and Modeling**
Yuanshen Li, COMSOL

**Challenges in PIC Development**
Miquel Minguillon, VLC Photonics

**From Photonic Interposers to Embedded Optical Interconnects: Solving the PIC Packaging Bottleneck**
Nikolaus Flöry, vario-optics

## Upcoming Summits

**Spectroscopy** — *March 12*

**Infrared Imaging** — *April 16*

**Microscopy** — *May 14*

**Laser Optics** — *June 11*

**Optical Design** — *August 13*

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# The Best in Photonic Innovations to be Celebrated at 2025 Prism Awards

SPIE has named 24 finalists for the 2025 Prism Awards, which honors breakthrough photonics products and commercial offerings. Companies ranging from emerging innovators to industry stalwarts have been selected as finalists across eight categories. The annual event, celebrating its 17th year, takes place Jan. 29 during a gala evening at Photonics West and recognizes industrial-level advancements in the photonics industry and companies that are bringing transformative products to market.

Rapidly developing technology areas — encompassing augmented and virtual reality hardware, sensors, quantum, test and measurement, and lasers — showcase the range and variety of this year's entries and finalists. Newer companies such as Eoptic, Delta Life Science, Ki3 Photonics Technologies, FlulDect, and 2023 SPIE Prism Award winner Qunnect, will share the stage alongside established companies such as Thorlabs, Leonardo, TRIOPTICS, and NIL Technology.

SPIE

## The Finalists by Category

### Biomedical

**Delta Life Science**
(Rotterdam, Netherlands)
The **inQuiQ** is a label-free biosensing solution for research and laboratory applications, including measurements in serum, plasma, and supernatant. The technology uses a combination of silicon chips and polycarboxylate hydrogel, allowing for more data points from a small sample on a reusable sensor. inQuiQ supports sample volumes from 25 µL to 2 mL. The use of nanophotonic evanescent field sensing technology enables analyses taking up limited space (30 × 40 cm) on the lab bench.

**Enspectra Health**
(Mountain View, Calif.)
**VIO** is a skin imaging system that combines multiphoton laser scanning with reflectance confocal microscopy to deliver actionable cellular information noninvasively in real time. The technology captures in vivo images of tissue, including blood vessels, collagen, and solar elastosis, among others, in and through the epidermis, to assist physicians in forming a clinical judgment.

**Norlase** (Ballerup, Denmark)
Ophthalmic medical device company Norlase develops next-generation laser solutions for the treatment of retina and glaucoma disease. Its product offerings

include ECHO, a multi-spot pattern laser; LION, an indirect ophthalmoscope integrated with a green laser source; and LEAF, a green laser photocoagulator. The company is nominated for its newly developed **LYNX** product technology.

## Cameras and Imaging Systems

**Eoptic** (Rochester, N.Y.)
The **Cambrian Edge** camera enables synchronized, multichannel image acquisitions, along with real-time data fusion and customizable spectral and polarimetric options. AI-enabled processing trains and deploys models directly on the device. Cambrian Edge features a three-channel optical engine, full-resolution capture at 240 fps, and visible, SWIR, and polarization sensor options.

**NIL Technology**
(Kongens Lyngby, Denmark)
The **metaEye Ultra-Compact Camera** can be used for applications such as eye-tracking, iris tracking, and automotive safety. The camera uses metalenses rather than refractive lenses to reduce stray light and for reduced dust and water system contamination in supported applications. The metaEye Ultra-Compact Camera's architecture allows for NIR sensing and features a 1.64- × 1.64- × 2.17-mm form factor and LED illumination of the eye at 850 nm.

**Thorlabs Inc.** (Newton, N.J.)
**Mini2P** is a high-resolution two-photon microscope designed for in vivo imaging of nonstationary specimens. Excited by a 920-nm femtosecond pulsed laser (for green fluorescent proteins), the product's head-mounted design allows for stable calcium imaging without impediment to the sample. The Mini2P allows for hundreds of neurons to be monitored in a single field of view, while visualization of up to a thousand cells is achievable through multiplane imaging controlled through the built-in microtunable lens.

## Lasers

**n2-Photonics Technologies Inc.**
(Hamburg, Germany)
The **MIKS1_M** is a single-stage unit that is compatible with any repetition rate and pulse-on-demand laser system. The unit does not require active optical elements or mechanically moving components and features >100 W of average power, pulses $<$20 to 50 fs, and input energy between 200 and 500 μJ.

**Scantinel Photonics GmbH**
(Ulm, Germany)
The **Narrow Linewidth Hybrid-Integrated Laser** is a hybrid laser source on a PIC. The laser's narrow linewidth and high modulation linearity enables long-range detection and high-precision velocity data, while powering Scantinel's single-chip frequency-modulated continuous-wave lidar.

**Thorlabs Inc.** (Newton, N.J.)
The **Long-Wave Infrared Supercontinuum Laser** (**LWIRSC**) can be used in applications such as absorption spectroscopy, environmental sensing, and infrared spectromicroscopy, among others. The laser's emission spectral range of 3.5 to 11 μm complements >20 mW of average output power and a single-mode, achromatically collimated beam. The LWIRSC architecture is based on the all-fiber femtosecond mid-infrared laser technology developed by Thorlabs.

## Optical Materials and Components

**LightPath Technologies**
(Orlando, Fla.)
LightPath's **BDNL Materials** envelop the company's BlackDiamond-NRL infrared glass, BDNL. The materials support defense and aerospace applications. BDNL, a chalcogenide glass, includes BDNL-4. This glass exhibits a negative thermo-optic coefficient that enables the design of devices that are unaffected by temperature changes and is a true multispectral material that can be used across SWIR, MWIR, and LWIR imaging bands.

**Omega Optical** (Brattleboro, Vt.)
Omega Optical's **DeepUV Transmission Gratings** can be used in applications such as spectrometer instrumentation, capillary analysis, and high-performance liquid chromatography. The

gratings demonstrate excellent transmission from 190 to 400 nm, environmental stability, and solarization resistance. They are available in sawtooth and holographic grating structures, and in sizes from 4 × 4 mm to 30 × 30 mm, and larger.

**xolo GmbH** (Berlin)
The **Xube² Lens 3D Printer** is a volumetric 3D-printing solution designed for both academic and industrial applications. The printer uses a quick-change cuvette holder for various standard cuvettes along with a fully adjustable three-channel LED projector for resolution per container size down to 5 µm. The Xube² Lens 3D Printer features a switchable light sheet module for 375 and 405 nm.

## Quantum Tech

**Ki3 Photonics Technologies Inc.** (Montréal)
**Q-COMB** technology uses Ki3 Photonics Technologies' photonics hardware to support the generation and processing of broadband quantum signals. The company's sources target the generation of entangled photons over an optical frequency comb spanning the S, C, and L telecommunications bands. Supported applications include quantum cryptography, quantum metrology, and quantum information processing.

**Leonardo DRS Daylight Solutions** (Arlington, Va.)
The **Stretto** family of high-precision external-cavity diode lasers covers the ultraviolet, visible, and infrared spectra. The lasers are geared toward applications in quantum information science, including computing, sensing, timing, and networking. Stretto is designed for seamless OEM integration and efficient volume production scaling.

**Qunnect** (Brooklyn, N.Y.)
Qunnect, a quantum-secure networking technology company targeting scalable quantum networks, is the developer of the GothamQ network. This network, using existing commercial fiber optic cable, can support high-quality entanglement distribution networking protocols. Qunnect is a Prism Award finalist for its **QU-RACK Gotham** solution. The company's hardware portfolio comprises multiple entangled photon source offerings.

## Sensors

**EXALOS** (Schlieren, Switzerland)
EXALOS' **HOPP 3-fiber 1550-nm SLED transceiver** is a 14-pin Butterfly module that emits an optical spectrum with 3-dB bandwidth of 33 nm around a center wavelength of 1549 nm. The output is collimated into three output beams that are propagating through an optical circulator before being focused into an array of three polarization-maintaining output fibers. Efficient beam collimation and low-loss beam propagation on the optical bench in combination with high-efficiency coupling to the polarization-maintaining output fibers yield output power values of ~1 mW per fiber channel at low drive currents of only 150 mA.

**FluIDect GmbH** (Jena, Germany)
The **SpheroScan Explorer** is a semi-automatic device that uses biofunctionalized microparticles µBeads sensor technology to enable the detection of pathogens in a sample. The device is suitable for both laboratory and production environment use, while eliminating the need for time-consuming sample preparation and reducing measurement time. The device is loaded manually and features numerous measurement modes.

**Interherence GmbH** (Erlangen, Germany)
**QuScite** is a waveguide-based total internal reflection system for high- and superresolution microscopy. Samples are optically excited via different waveguides on QuChips, which replace the coverslip. In this way, several square millimeters at a time can be illuminated simultaneously at select excitations. Samples are illuminated with a highly

# SPIE Catalyst Award Finalists

In addition to the 2025 Prism Awards, SPIE will present the second SPIE Catalyst Award at Photonics West. This recognition honors for-profit companies with specific socially or environmentally focused programs that have had significant positive impact, either within their workplace, on society at large, or on the environment.

## The Finalists

**SCHOTT AG** (Mainz, Germany)
To meet climate-friendly specialty glass production, SCHOTT AG has completed testing of its **100% hydrogen optical glass production** capabilities. The tests were completed using gray hydrogen rather than green hydrogen as it is not yet available in sufficient quantities. Green hydrogen is produced solely from renewable energy sources. If the glass meets the high product requirements, it will be sent to the customer, though the lack of green hydrogen infrastructure is delaying industrial use.

**Thorlabs Inc.** (Newton, N.J.)
The **Thorlabs Photonics Learning** group is Thorlabs' educational outreach arm. The group aims to accelerate the development of the photonics community through immersive educational platforms that cultivate awareness, access, and advancement to a workforce qualified to research, design, and manufacture future technologies. The group runs the Thorlabs Mobile Photonics Lab, a finalist for the inaugural Catalyst Award in 2024. This photonics lab visits universities, high schools, and public events to provide access to the photonics community.

**Vacuum Innovations** (Dansville, N.Y.)
Vacuum Innovations provides **Optical Coating Design & Technology Education** through workshops and courses. Its inaugural three-day Optical Coating Design & Technology Workshop, held in March 2024, enabled attendees to learn about coating uniformity, stresses, and laser damage capabilities with coatings. Topics in these workshops include thin-film stress and mitigation, optical coating design, optical characterization and testing, and more.

homogeneous field reaching a field flatness of more than 1000:1, with most total internal reflection fluorescence microscopes achieving 30:1.

## Software

**BRELYON** (San Mateo, Calif.)
**BRELYON Visual Engine** is a universal generative software tool that allows users of any display system to interact with existing visual content. The shader-level layer in the rendering pipeline provides content to amplify immersion and productivity as well as entertainment experiences. Visual Engine operates directly on the video input streams and is both hardware agnostic and backward compatible with existing computers and display systems.

**HyperSpectral Corp.** (Alexandria, Va.)
**SpecAI** is an AI-powered spectral intelligence solution for industries including food safety, health care, and defense. The technology combines the capabilities of spectroscopic identification and AI to enable the detection of harmful gases and pathogens, and the identification of spectral signatures of threats such as *E. Coli*, methane, salmonella, ethylene, and listeria.

**PlanOpSim** (Melle, Belgium)
**PlanOpSim** software unites the different stages of metasurface and planar optics components design in one tool. The software calculates and models the key steps in metalens design, including nanostructure modeling, component design, and system integration. PlanOpSim runs on any standard desktop or laptop computer, with no need for cluster setups or supercomputers.

## Test and Measurement

**Innovations in Optics Inc.**
(Woburn, Mass.)
The **LumiSun-50** compact LED solar simulator achieves an irradiance of 0.1 to 1.2 suns and a spectral range of 350 to 1250 nm over a highly uniform area of 50 × 50 mm. The device is suitable for applications including photovoltaic cell testing and research, photochemistry and biology research, phototherapy research, materials testing, weathering tests, and more.

**Quartus Engineering Inc.** (San Diego)
The **OptiQuiver** metrology tool combines high dynamic range wavefront sensing with the precision angular measurement and internal reference source of an electronic collimator. The metrology tool provides surface figure measurements for multiple flat or curved optics simultaneously. It is compatible with coherent lasers and broad spectral sources, and the software supports both Windows and MacOS for live results, data logging, and application programming interfaces.

**TRIOPTICS GmbH** (Wedel, Germany)
The **OptiCentric Bonding 5D Multi-Align** system is part of OptiCentric family of high precision centration test devices, alignment, cementing, and bonding systems. OptiCentric systems offer extremely high centration accuracy and integrated operation. The devices are modular, allowing a wide range of different applications and samples for optimum composition.

## Samsung Display develops quantum dot recycling technology


A technique to restore the purity of quantum dot (QD) ink will allow Samsung Display to save $7.2 million annually.

Samsung Display developed a quantum dot ink recycling technology that it said greatly increases the efficiency of the manufacturing process for its quantum dot (QD)-OLED displays. Using the technology, which collects and recycles quantum dot ink that would otherwise be wasted during the QD-OLED manufacturing process, the company said that it can recover and reprocess 80% of the ink that had been unused in the production of the quantum dot emissive layer.

Samsung anticipates that this technology will result in annual cost savings of more than KRW 10 billion ($7.2 million).

The quantum dot light-emitting layer, the key structure of QD-OLED displays, is formed using an inkjet printing process that densely sprays red and green quantum dot ink through micro nozzles in micrometer sizes. Previously, any quantum dot ink left in the nozzles was discarded, accounting for ~20% of the total quantum dot ink used in the process.

In Samsung Display's process, the remaining ink is recycled in-house, and the regenerated ink undergoes advanced synthesis technology that revives its purity and optical properties, resulting in the same performance levels as the original ink in quality tests. The company said that it has adopted the process into its production lines and plans to undertake additional measures to further enhance its competitiveness in QD-OLED manufacturing. This will be done not only through quantum dot ink regeneration technology but also by improving equipment performance and process capabilities to increase productivity and yield, the company said.

## Celestial AI acquires Rockley's silicon photonics portfolio

Optical computing technologies developer Celestial AI acquired silicon photonics intellectual property from Rockley Photonics. The acquired portfolio, which includes issued and pending patents, comprises the technology categories of optoelectronic systems-in-package, electro-absorption modulators, and optical switch technology, Celestial AI said.

All three categories are relevant to AI data center infrastructure applications. Celestial AI is focused on delivering solutions to hyperscale data center customers, both directly and through its ecosystem partners. These solutions, the company said, enable performance, scalability, and energy efficiency advantages at the forefront of next-generation AI compute and network connectivity.

Celestial AI said that the acquired intellectual property aligns with its core technology road map and complements its existing portfolio, which spans advanced packaging, thermally stable silicon photonics, and system architectures for optical compute interconnect.

Celestial AI's Photonic Fabric platform targets applications in AI and data centers by addressing constraints in utility power availability, memory capacity, and operational costs. The technology allows the disaggregation of compute and memory, enabling each component to be leveraged and scaled with greater efficiency. According to Celestial AI, Photonic Fabric delivers >25× greater bandwidth and memory capacity while reducing latency and power consumption by up to 10× compared with existing optical interconnect alternatives and copper.

Rockley Photonics previously filed for Chapter 11 bankruptcy protection at the beginning of 2023.

## Upstate N.Y. to house CHIPS for America EUV Accelerator Complex

NY CREATES' Albany NanoTech Complex will be home to a CHIPS for America EUV Accelerator, the first of three National Semiconductor Technology Center (NSTC) facilities. The project will be funded with an estimated $825 million from the U.S. Department of Commerce and is expected to spark a significant investment in extreme-ultraviolet (EUV) lithography R&D under the CHIPS and Science Act.

The EUV Accelerator will serve as a focal point for advanced semiconductor R&D initiatives and support programs to bolster the necessary workforce. Research at the facility will focus on innovation in semiconductor technologies with the aim of supporting the U.S. domestic supply chain and the development of next-generation chips.

The selection of the site follows the signing of a memorandum of understanding between NY CREATES and Natcast, a nonprofit entity established through the CHIPS and Science Act, to operate the NSTC consortium. The EUV Accelerator will be accessible to NSTC members and Natcast researchers who will be able to leverage more than $25 billion in public-private investments that have been made since the site's inception, including access to standard numerical aperture (NA) EUV lithography, and access to high NA EUV lithography by 2026.

The Albany NanoTech Complex is a publicly owned and accessible 300-mm semiconductor R&D facility. It received a $10 billion investment last year to support the acquisition of high NA EUV lithography equipment and the construction of a 50,000-sq-ft facility. The facility's construction is currently underway.

The high NA EUV lithography tool, built by ASML, supports the creation of chips with 7- and 5-nm channels and has the potential to produce chips with nodes <2 nm, a barrier broken by IBM, a partner and investor to the NanoTech Complex, in 2021.

During the last two years, chip companies have announced more than $112 billion in planned capital investments in New York. These include planned expansions from Micron, GlobalFoundries, AMD, Edwards Vacuum, Menlo Micro, and TTM Technologies, among others.

**$150M**

— expected size of the global supercontinuum laser market by 2032, according to Business Research Insights

## This month in history

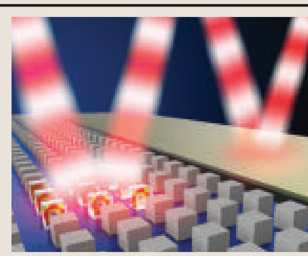
What were you working on five, 10, 20, or even 30 years ago? *Photonics Spectra* editors have perused past January issues and unearthed the following:

**1995**

Theodore Moustakas at Boston University's Center for Photonics Research developed a method for making a gallium nitride LED that emits in the UV to blue. The device was the first of its kind to be made in the U.S. and was a step toward the creation of a low-cost, durable blue laser diode, according to Moustakas.

**2005**

Researchers at the University of Bristol and the U.S. Naval Academy employed geometric singularity theory to describe the pattern and intensity of the polarization of sunlight in terms of the contours of elliptical integrals. The work replaced pages of formulas and calculations with a single, simple solution.



**2015**

Scientists from Sandia National Laboratory developed a magnetic mirror that used nonmetallic metamaterial properties to reflect IR light. The mirror was created by placing nanoscale antennas at or very near the mirror's surface, allowing the researchers to harness IR radiation.

**2020**

A team from Harvard University's John A. Paulson School of Engineering and Applied Sciences developed rewritable optical components for surface light-waves. Using near-field microscopy, the researchers demonstrated the ability to erase and rewrite the optical components they created.

## Teledyne to acquire Excelitas' defense electronics businesses

Teledyne Technologies Inc. entered into an agreement to acquire select aerospace and defense electronics businesses from Excelitas Technologies Corp. in a deal valued at $710 million in cash. The acquisition includes the Optical Systems business, which is based in Northern Wales and known under the Qioptiq brand, as well as the U.S.-based Advanced Electronic Systems business.

The U.K.-based Optical Signals business provides advanced optics for head-up and helmet-mounted displays, dismounted tactical night-vision systems, and proprietary glass used in space and satellite applications. In the U.S., the Advanced Electronics Systems business provides custom energetics, such as electronic safe and arm devices, high-voltage semiconductor switches, and rubidium frequency standards.

"Our respective products are highly complementary and not competitive, and we generally serve customers in complementary geographies," said Robert Mehrabian, Teledyne's executive chairman.

Last year, Excelitas announced and completed the relocation of its corporate headquarters, and the company also said in January 2024 that it had begun the groundwork to pursue an initial public offering.

The Teledyne businesses transaction is anticipated to be completed in early 2025 and is subject to customary closing conditions, including regulatory approvals. Teledyne acquired micro- and optoelectronics producer Micropac in a separate deal announced in November 2024.

## IonQ will acquire Qubitekk, partners with NKT Photonics, Ansys

Trapped ion quantum computing company IonQ will acquire quantum networking company Qubitekk, in a deal that IonQ said will drive its expansion into the quantum networking market. The combination of the companies, said IonQ president and CEO Peter Chapman, will join synergetic technology areas. Qubitekk's offerings include optical components and systems for quantum networks, quantum security, and quantum information science.

Per the deal, IonQ will specifically acquire 118 patents in the areas of quantum networking hardware and quantum network security and protection. The Qubitekk team that will join IonQ, includes Qubitekk cofounder and CEO Stan Ellis, cofounder and CTO Duncan Earl, chief revenue officer Corey McClelland, and president Keith Clark.

## People in the News

Sydor Technologies, a developer of advanced diagnostics and high-speed imaging for defense, research, and industrial applications, named **Nicholas West** president. West will oversee daily operations of Sydor's U.S. and U.K. businesses, reporting to company founder **Michael Pavia**, who will transition to chairman of the board.

Fiber optics developer art photonics GmbH appointed **Stefanie Foerster** CEO. Foerster has held previous senior leadership roles at thyssenkrupp and Siemens.

art photonics

Foerster.

Instrument Systems GmbH, a manufacturer of light measurement solutions, appointed **Daniel Winters** vice president of R&D. Winters has more than 20 years of professional experience in the development of optical measurement technologies. He has additional prior experience as CEO and CTO of Trioptics USA.

Instrument Systems

Winters.

Brewer Science

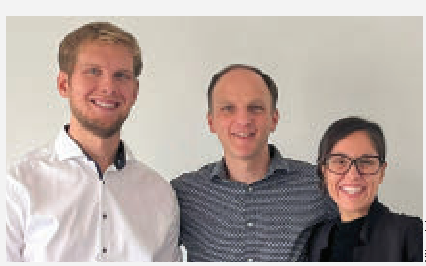
Srikanth Kommu **(left)** and Dan Brewer.

Computing materials manufacturer Brewer Science Inc. appointed **Dan Brewer** and **Srikanth Kommu** co-CEOs of the company. **Terry Brewer**, founder and chairman, will continue to be involved in the company and will serve in an advisory role to Brewer and Kommu.

Optical interconnect technology solutions provider Avicena added **Greg Dougherty** to its board of directors. Dougherty currently serves as a director at Infinera and MaxLinear and previously served as CEO of Oclaro from June 2013 until its acquisition by Lumentum in December 2018.

asphericon, a provider of optical systems, appointed **Sebastian Henkel** vice president of global sales and procurement and **Sebastian Steffenhagen** product manager of the company's BeamTuning brand. Henkel previously served as head of sales and procurement for the company. Prior to joining asphericon, Steffenhagen was part of the sales and construction/design team at Gero GmbH.

Vitrealab, a developer of display technology for AR/VR, appointed **Ronny Timmreck** CEO. Timmreck serves as chairman of Sixonia Tech GmbH's board and has prior leadership experience as CEO of companies including Bahama Invest & Consult, leXsolar GmbH, deepXscan, and Senorics.



Vitrealab

**(From left)** Vitrealab CTO Jonas Zeuner, Ronny Timmreck, and chief research officer Chiara Greganti.

According to IonQ, the deal will close by spring 2025.

In addition to the acquisition, IonQ established separate partnerships with NKT Photonics and Ansys. Both moves serve to strengthen the company's position within the quantum market.

IonQ's partnership with NKT Photonics serves to supply the company with next-generation laser systems for its trapped-ion quantum computers and networking equipment. NKT will develop and deliver three prototype optical subsystems to IonQ in 2025, designed to support the commercialization of IonQ's data center-ready quantum computers, such as IonQ Tempo and future barium-based systems.

With Ansys, IonQ aims to accelerate simulation, expand high-fidelity design exploration, and reduce product development timelines by integrating quantum computing into the computer-aided engineering industry. The partnership will integrate IonQ's quantum computers with Ansys' technology for complex simulations to accelerate discovery and innovation.

IonQ will additionally use Ansys' multiphysics technology, including structural, optical, photonic, and electromagnetic simulation software, to design and optimize key components for scalable, high-performance next-generation quantum computers.

IonQ's acquisition of Qubitekk follows a series of recent quantum networking announcements from the company. In September 2024, IonQ announced a $54.5 million contract award with United States Air Force Research Lab (AFRL) to design, develop, and deliver quantum networking technology. Recently, IonQ demonstrated remote ion-ion entanglement as a key milestone toward scaling its compute across multiple quantum processors using photonic interconnects. And earlier in 2024, IonQ announced its selection by the Applied Research Laboratory for Intelligence and Security (ARLIS) for a quantum networking contract to design a networked system for blind quantum computing. This technology enables quantum computing systems to be operational while they remain "blind" as to what information is being processed.

## Hamamatsu acquires BAE Systems Imaging

Through its subsidiary Photonics Management Corp., Hamamatsu Photonics KK acquired BAE Systems Imaging, a semiconductor manufacturer specializing in high-performance CMOS image sensors in the visible to NIR and x-ray regions. Based in San Jose, Calif., BAE Systems Imaging is currently a subsidiary to its parent company BAE Systems. Following the transaction, BAE Systems Imaging will be known as Fairchild Imaging and will become Hamamatsu's North American design center for 2D, low-noise image sensors, according to Hamamatsu.

BAE Systems Imaging's (Fairchild Imaging's) core products include scientific CMOS (sCMOS) image sensors as well as x-ray CMOS image sensors for dental and medical diagnostic applications. Hamamatsu said that it expects the acquisition to strengthen and expand its position in the dental market. Hamamatsu Photonics' dental business serves the European and Asian regions, while Fairchild Imaging will increase the company's access to the North American market.

More broadly, Fairchild's 2D CMOS image sensors complement Hamamatsu's existing 1D CMOS image sensor offerings, which are used for analytical instruments and factory automation applications, such as displacement meters and encoders.

Per the deal, BAE Systems will retain the aerospace and defense segment of the BAE Systems Imaging Solution's portfolio, which was transferred to the BAE Systems Inc. Electronic Systems sector prior to the closing of the stock purchase transaction with the Hamamatsu subsidiary.

Hamamatsu finalized its acquisition of NKT Photonics in May 2024, in a deal also completed with Photonics Management Corp.

## Briefs

**OptoSigma Corporation**, a developer of precision optical components and systems, relocated its headquarters to a new facility in Costa Mesa, Calif. The company said the move will allow for an increase in production capacity and manufacturing capabilities to meet the demands of its customers, including a new 8000-sq-ft cleanroom, system integration, optical design and assembly, optical coatings, and planar optics, such as waveplates, wedges, and prisms.

Microelectromechanical systems (MEMS)-based solid-state lidar developer **MicroVision** secured $75 million in financing as the company prepares to ramp up production of its MOVIA L 3D industrial lidar sensor.

**Comptek Solutions**, a developer of advanced passivation technology, installed a 200-mm wafer pilot line with funding from the European Innovation Council. The line integrates the company's Kontrox passivation technology with other techniques, such as atomic layer deposition, for a scalable solution for industrial manufacturing specifically targeting optoelectronic and power electronics applications. The pilot line will also be used to maximize chip performance and optimize yields in semiconductor applications, from sidewall passivation layers for micro-LEDs to complex gate stack dielectrics for power transistors.

**Hamamatsu Ventures**, the corporate venture capital arm of **Hamamatsu Photonics**, invested in laser technology company **SuperLight Photonics**. Hamamatsu's European Union Corporate Venture Capital business development manager David Castrillo will join SuperLight's advisory board to serve as a liaison, per the investment deal, which will allow SuperLight to focus on growing its team, scaling production capacity, expanding into new markets, and establishing stronger partnerships with global distributors. Separately, Hamamatsu Ventures invested in deep tech digital health company **iLoF**, to accelerate the deployment of iLoF's Optomics AI-powered medical photonics platform technology and expand its presence in the U.S. and Japanese markets. The companies will also drive the development of new AI methodologies through optical data analysis, advancing precision diagnostics and patient stratification.

**ZEISS** opened its **ZEISS Microscopy** semiconductor applications lab in Dresden, Germany. The facility is located within the ZEISS Innovation Hub, which opened last year. The company said that the lab will address increased automation of microscopy workflows and techniques to help the semiconductor industry accelerate root cause analysis and pathfinding for challenges in microelectronics.

The Israeli Ministry of Defense committed more than $500 million to expand serial production of the country's first domestically developed weapon system, the **Iron Beam**, with lead developers **Rafael Advanced Defense Systems** and **Elbit Systems**. Iron Beam is a ground-based 100-kW-class high-energy laser air defense system designed to counter aerial threats, including rockets, mortars, uncrewed aerial vehicles, and cruise missiles. Per the newly signed contract, Elbit will supply its high-powered laser solution as well as ongoing support services.

**Amkor Technology Inc.**, an outsourced semiconductor assembly and test service provider, signed a memorandum of understanding with **TSMC** to collaborate and bring packaging and test capabilities to Arizona. Under the agreement, TSMC will contract turnkey packaging and test services from Amkor in their planned facility in Peoria, Ariz., outside Phoenix. TSMC will leverage these services to support its customers, particularly those using TSMC's wafer fabrication facilities in Phoenix. The companies will jointly define the specific packaging technologies, such as TSMC's integrated fan-out and chip-on-wafer-on-substrate that will be employed to address common customers' needs.

**AllFocal Optics**, a nanophotonic display company, secured $5.3 million in seed funding. The funding will go toward commercialization of the company's optics offerings. The company is a spinout of the University of Cambridge, developing technologies for AR, VR, and mixed reality (MR) applications.

**Bruker Corporation**, an analytical solutions developer, formed a division for solutions in spatial biology. **Bruker Spatial Biology** brings together **NanoString Technologies** and **Canopy Biosciences** in operational coordination, along with its subsidiary **Bruker Spatial Genomics Inc.**, and will focus on advancing biomedical research with a suite of spatial biology instruments, assays, software, data analytics, and contract research organization services.

**Meridian Innovation Pte. Ltd.**, a developer of thermal imaging sensors, raised $12.5 million to scale its operations, accelerate product development, and expand its reach into broader consumer and commercial markets. The funding brings Meridian's total investment to date to more than $30 million. Meridian's product offerings include thermal imaging camera modules, camera module evaluation kits, a thermal image processor, and a smartphone thermal camera attachment.

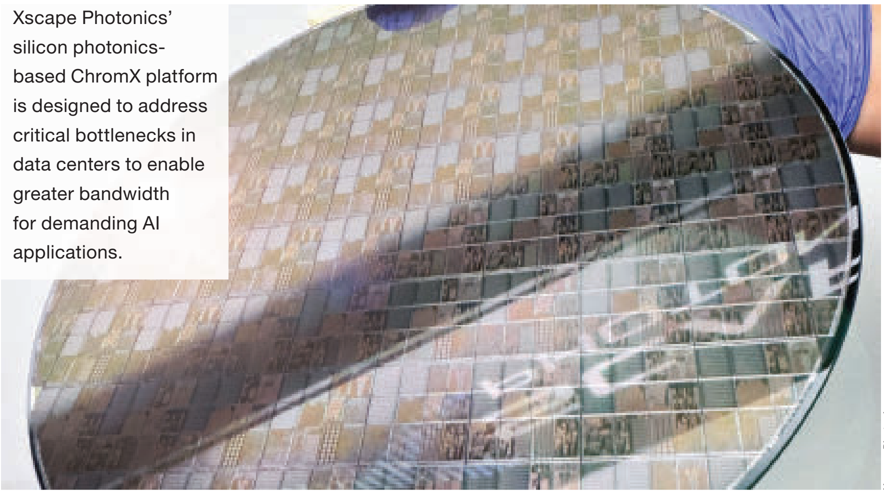
## Silicon photonics company Xscape Photonics raises $44M

Silicon photonics startup Xscape Photonics raised $44 million in funding that the company said will accelerate development of its ChromX platform. The scalable, multicolor, programmable photonics platform is designed for AI data center fabrics.

The company has now raised $57 million following the recent series A close.

Xscape Photonics' technology will address bottlenecks in AI and data centers related to bandwidth demand and features a platform capable of handling hundreds of colors on a single fiber. Data centers have traditionally been constrained to transmit data streams over four colors on a single fiber.

"Historically, performance and scalability challenges have been addressed by building bigger data centers to train large language models," said Vivek Raghunathan, company cofounder and CEO. "This approach is not sustainable and unlocks a myriad of additional issues around energy consumption and cost."



Xscape Photonics' silicon photonics-based ChromX platform is designed to address critical bottlenecks in data centers to enable greater bandwidth for demanding AI applications.

Xscape Photonics

The recent financing was led by IAG Capital Partners. The round additionally received investments from Altair, Cisco Investments, Fathom Fund, Kyra Ventures, LifeX Ventures, NVIDIA, and OUP.

Xscape was founded in 2022 by silicon photonics luminaries and laser specialists Raghunathan, Alexander Gaeta, Yoshi Okawachi, Michal Lipson, and Keren Bergman.

## Photonic computing leader Lightmatter raises $400M

Photonic computing company Lightmatter raised $400 million in series D funding. The company plans to use these funds to prepare its reconfigurable optical interposer, called Passage, for mass deployment in partner data centers.

According to the company, the Passage photonic engine technology addresses bottlenecks presented by traditional electronic interconnects by leveraging 3D-stacked photonics chips to move data, increasing AI cluster bandwidth and performance while reducing power consumption.

In 2024, the MIT spinout named former NVIDIA executive Simona Jankowski as its CFO and added semiconductor and computing specialists Richard Beyer and Robin Washington to its board of directors. Since its previous funding announcement in December 2023, Lightmatter has expanded its footprint with an office in Toronto and has continued to grow its workforce.

The company has raised $850 million to date and is currently valued at $4.4 billion.

## Lumibird to acquire nanosecond laser line from Amplitude

Lumibird entered into an agreement with Amplitude Laser Group to acquire its nanosecond laser product line under the Continuum brand, as well as its associated service business. Amplitude said that the sale aligns with its strategy to concentrate on its core strengths in femtosecond and high-energy advanced laser solutions.

"The acquisition of the Continuum brand, which is highly recognized by universities, will enable Lumibird to strengthen its product range and increase its share of the nanosecond solid-state laser market," said Marc Le Flohic, chairman and CEO of Lumibird. "This operation is not only profitable, [but] it is also in line with the group's strategy of strengthening our position in a recurring market and accelerating the optimization of the group's industrial tools."

Damien Buet, chairman and CEO of Amplitude Laser Group, said that the subsidiary Amplitude Laser Inc. will now be entirely dedicated to the key

## Mergers & Acquistions

**IPG Photonics** signed a definitive agreement to acquire **Clean-Lasersysteme GmbH (clean-LASER)**, which serves customers across the automotive, industrial, aerospace, medical, and food markets, offering process-safe laser technology for the cleaning and processing of industrial surfaces. The company, founded in 1997, generates approximately $30 million in annual revenue. The acquisition follows IPG's divestment of its Russian subsidiary, IRE-Polus.

Solid-state lidar technology developer **XenomatiX** entered into a collaboration with cloud-based sound recognition technologies company **ASAsense** to combine the companies' portfolios for infrastructure management solutions. The collaboration will leverage technologies including edge AI, lidar, and sound and vibration analysis for comprehensive detection and localization solutions for pavement inspection, infrastructure digitization, soundscape monitoring, object classification, event detection, and source localization. The collaboration will operate under the name **XenomatiX Group**.

**Exosens** reached an agreement to acquire **Night Vision Laser Spain (NVLS)**, a developer and manufacturer of portable night-vision and thermal devices. Terms of the transaction were not disclosed. Exosens acquired LR Tech, a specialist developer and manufacturer of Fourier transform infrared devices, in September 2024, after the group acquired Centronic Ltd earlier last year.

**Teledyne Technologies** and **Micropac Industries** entered into a definitive merger agreement under which Micropac will be merged with a wholly owned subsidiary of Teledyne. The transaction values Micropac, a designer and manufacturer of microelectronic circuits, optoelectronic components, and sensor and display assemblies primarily for military, aerospace, and medical applications, at approximately $57.3 million.

**Onto Innovation Inc.**, a provider of process control and packaging lithography solutions, acquired **Lumina Instruments Inc.**, a supplier of optical inspection systems, as well as the lithography business from **Kulicke and Soffa Industries Inc.**, including 24 issued patents.

**Laser Photonics Corporation (LPC)**, a developer of industrial cleaning laser systems, signed a definitive agreement to acquire **Control Micro Systems Inc. (CMS)**, a provider of laser solutions for the pharmaceutical industry. The acquisition of CMS' assets, in a deal worth $1 million, is expected to provide an opportunity for Laser Photonics to strategically broaden its market reach, engineering talent, and technology portfolio for the medical and pharmaceuticals industries.

**Gooch & Housego (G&H)** acquired **Phoenix Optical Technologies**, a manufacturer of precision optics technology based in Saint Asaph, Wales. The acquisition, valued at up to £6.75 million (approximately $8.8 million), strengthens G&H's position in aerospace and defense while expanding its presence in the U.K. and European markets as a supplier to defense primes. G&H said that the acquisition is also poised to support industrial and life sciences market customers.

**Addtech Electrification**, a subsidiary of **Addtech**, signed an agreement to acquire 100% of the shares outstanding in **nanosystec GmbH**, a developer of equipment primarily for manufacturing optoelectronics. The parent company said that nanosystec complements and strengthens Addtech's existing operations within its connectivity solutions business unit. Addtech Electrification companies provide battery solutions and components and subsystems in mechatronics, among other offerings.

growth initiatives of the parent company. Meanwhile, Lumibird's acquisition, he said, will accelerate the development of the Continuum line of products and provide customers with enhanced solid-state nanosecond laser offerings.

Lumibird acquired Convergent Photonics from Prima Industrie in 2023. In December 2022, Amplitude acquired ultrafast-pulse shaping, characterization, and optical parametric amplifier technology developer Fastlite.

**$12.8B**

— estimated size of the global fiber laser market by 2029, according to MarketsandMarkets

## Lumenuity emerges from stealth with Qualcomm collaboration

Lumenuity, a mobile optics startup, has received $1.2 million in seed funding and launched a collaboration with Qualcomm Technologies. Lumenuity's Light Unfolding technology boosts the zoom capabilities of mobile device cameras, such as those found in smartphones, bringing them up to par with the performance of digital single-lens reflex cameras, Lumenuity said.

Benjamin Shapiro, cofounder and CEO of Lumenuity, said that the solution aims to virtually eliminate the need for bulky, high-end cameras. Currently, smartphones rely on separate cameras for primary, wide-angle, and zoom functions. Lumenuity's optical system, the company said, can deliver the performance of two cameras in one, streamlining design and reducing production costs.

Its partnership with Qualcomm will focus on optimizing the company's technologies for use in smartphones that contain the latest Snapdragon mobile platforms.

"Lumenuity's technology allows higher-performance optics in a more efficient form factor," said Judd Heape, vice president of product management at Qualcomm. "Qualcomm will be able to support phone makers that will be implementing this new technology on the Snapdragon platform, by providing complementary advanced image processing and AI features to further increase image quality."

Lumenuity has developed prototypes that deliver double the zoom capability of existing smartphone cameras, while maintaining industry-standard size and form. In addition to Qualcomm, Lumenuity said that it has been collaborating with DXOMARK to refine and validate its technology.

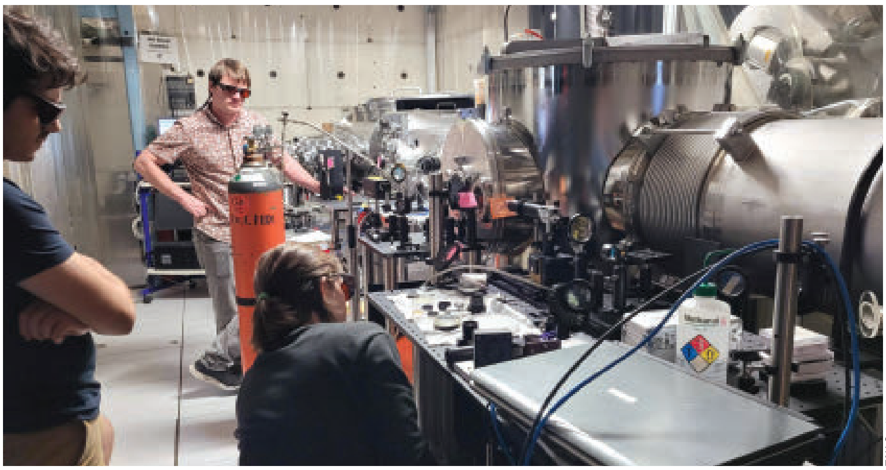
## TAU Systems and partners pursue laser wakefield acceleration

TAU Systems, a producer of ultrafast, compact laser-plasma accelerators and secondary radiation sources, entered into a research collaboration with the Extreme Light Infrastructure (ELI ERIC) and the University of Texas at Austin (UT Austin). The collaboration will support work on a series of experiments based on laser wakefield acceleration using the Texas Petawatt laser system, housed at UT Austin. The collaborators seek to generate multi-gigaelectron volt beams, supporting applications such as radiography and muon production.

Per the collaboration, the scientists will use the nanoparticle-assisted laser wakefield acceleration technique, which recently allowed researchers from TAU Systems and UT Austin as well as several U.S. national laboratories and European Universities, to generate and accelerate electrons to record energy of 10 GeV over a distance as short as 10 cm.

Experiments at UT Austin will serve to test an upgrade at the Texas Petawatt Laser Facility, under which the repetition rate of the system was increased 3×, up to a shot every 20 min. Further experiments will use ELI's Petawatt beamlines available in Czechia at the ELI-Beamlines facility.

The collaboration, which began this past June, will take place over the course



TAU Systems

A collaboration between TAU Systems, University of Texas at Austin (UT Austin), and ELI-Beamlines will take advantage of new acceleration techniques to further develop laser-driven particle acceleration.

of one year and consist of several campaigns at the Texas Petawatt facility. The stakeholders anticipate that the collaboration will accelerate the path to democratized laser-driven particle and radiation sources, from both electrons and neutrons to x-rays and Gamma rays. The development of these products, along with innovative pay-to-play beam access at TAU Labs application centers, will accelerate research into areas such as radiation testing for space-bound electronics, higher resolution 3D materials imaging, battery development, biomolecules structure determination and engineering, material testing for nuclear fusion reactors, and nuclear waste reduction, TAU Systems said.

## Optical networking startup Oriole Networks raises $22M

Oriole Networks, a spinout of University College London that focuses on networked photonic AI chips, raised $22 million in a series A funding round to accelerate growth, expand its workforce, and engage with high-volume suppliers.

Oriole Networks, which said at the time of the funding announcement that it planned to deliver early-stage products to customers before the end of 2025, develops optical technology that it uses to create networks of AI chips and combine their processing power to train large language models (LLMs). With this approach, LLMs can be trained up to 100× faster, while consuming a fraction of the power, allowing algorithms to run with much lower latency, according to the company.

The company's platform is based on 20 years of research conducted at University College London by founding scientists George Zervas, Alessandro Ottino, and Joshua Benjamin.

Oriole Networks was founded in 2023 and is led by former EFFECT Photonics CEO James Regan. It raised $13 million in an earlier 2023 seed round. The current funding was led by Plural, with all existing investors returning.

As part of the current financing, Ian Hogarth, who led the investment on behalf of Plural, will join Oriole's board of directors.

**8.9%**

— expected compound annual growth rate of the global infrared detectors market by 2031, according to Verified Market Research

## Optical memory breakthrough holds promise for compute capabilities

PITTSBURGH — Until recently, researchers have been limited in their development of photonic memory solutions for AI processing: Gaining an important attribute, such as speed, has meant sacrificing another, such as energy usage.

In response to this dynamic, an international team of researchers demonstrated a solution that addresses current limitations of optical memory, which have yet to combine nonvolatility, multibit storage, high switching speed, low switching energy, and high endurance in a single platform. The researchers' proposal is a resonance-based photonic architecture that leverages the nonreciprocal phase shift in magneto-optical materials to implement photonic in-memory computing.

According to Nathan Youngblood, an assistant professor of electrical and computer engineering at the University of Pittsburgh, the discovery represents a key enabling technology toward a faster, more efficient, and more scalable optical computing architecture that can be directly programmed with CMOS circuitry — a quality that makes it compatible with conventional computer technologies.

"The materials we use in developing these cells have been available for decades. However, they have primarily been used for static optical applications, such as on-chip isolators, rather than a platform for high-performance photonic memory," Youngblood said.

"Additionally, our technology showed three orders of magnitude better endurance than other nonvolatile approaches, with 2.4 billion switching cycles and nanosecond speeds," he said.

A typical approach to photonic processing is to multiply a rapidly changing optical input vector with a matrix of fixed optical weights. However, encoding these weights on-chip using traditional methods and materials has proved to be challenging. By using magneto-optic memory cells composed of heterogeneously integrated cerium-substituted yttrium iron garnet (Ce:YIG) on silicon micro-ring resonators, the cells cause light to propagate bidirectionally, like sprinters running in opposite directions on a track.

University of California, Santa Barbara/Brian Long

A conceptual image depicting a photonic in-memory computing scheme leveraging the nonreciprocal phase shift in magneto-optical materials.

"It's like the wind is blowing against one sprinter while helping the other run faster," said Paolo Pintus, who led the work at the University of California, Santa Barbara. "By applying a magnetic field to the memory cells, we can control the speed of light differently depending on whether the light is flowing clockwise or counterclockwise around the ring resonator. This provides an additional level of control [that is impossible] in more conventional nonmagnetic materials."

The team is working to scale up from a single memory cell to a large-scale memory array that can support even more data for computing applications. According to their research, the nonreciprocal magneto-optic memory cell offers an efficient, nonvolatile storage solution that could provide unlimited read/write endurance at sub-nanosecond programming speeds.

"We also believe that future advances of this technology could use different effects to improve the switching efficiency," said Yuya Shoji, an associate professor on the research effort based at the Institute of Science Tokyo, "and that new fabrication techniques with materials other than Ce:YIG and more precise deposition can further advance the potential of nonreciprocal optical computing."

The developing team comprises researchers from the University of Pittsburgh Swanson School of Engineering; University of California, Santa Barbara; the University of Cagliari; and the Tokyo Institute of Technology (now the Institute of Science Tokyo).

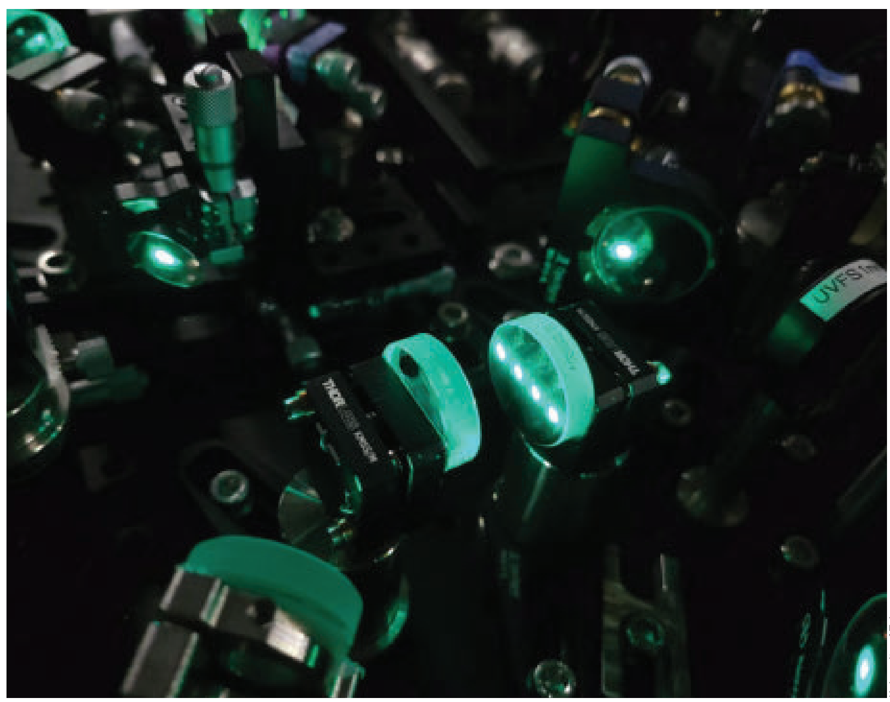
The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-024-01549-1).

## Raman spectroscopy undergoes a major speed upgrade

TOKYO — Researchers at the University of Tokyo increased the measurement rate of Raman spectroscopy by 100-fold, in a development that addresses what has been considered a major limitation to the technique. The improvement, according to the Tokyo researchers, is expected to aid advancements in multiple fields relying on the identification of molecules and cells, such as biomedical diagnostics and materials analytics.

As a mode of identification for cells and molecules, Raman spectroscopy is widely used, though it is limited in its ability to "keep up" with the speed of changes in certain chemical and physical reactions due to the low scattering cross section. During the last decade, various broadband-coherent Raman scattering spectroscopy techniques have been developed to address the limitation, achieving a measurement of 500 kSpectra/s (kilospectra per second).

To further improve the measurement rate, the University of Tokyo researchers built a system from scratch that uses a mode-locked ytterbium laser system. They combined coherent Raman spectroscopy — a variant of Raman spectroscopy that produces stronger signals than the conventional, spontaneous Raman spectroscopy— with their previously developed specifically designed ultrashort-pulse laser and time-stretch technology using optical fibers. The newly developed system provided a 50-MSpectra/s




University of Tokyo

A Raman spectroscopy technique developed at the University of Tokyo combines coherent Raman spectroscopy, an ultrashort-pulse laser, and time-stretch technology to achieve a reported 100-fold increase in measurement rate compared with previous methods.

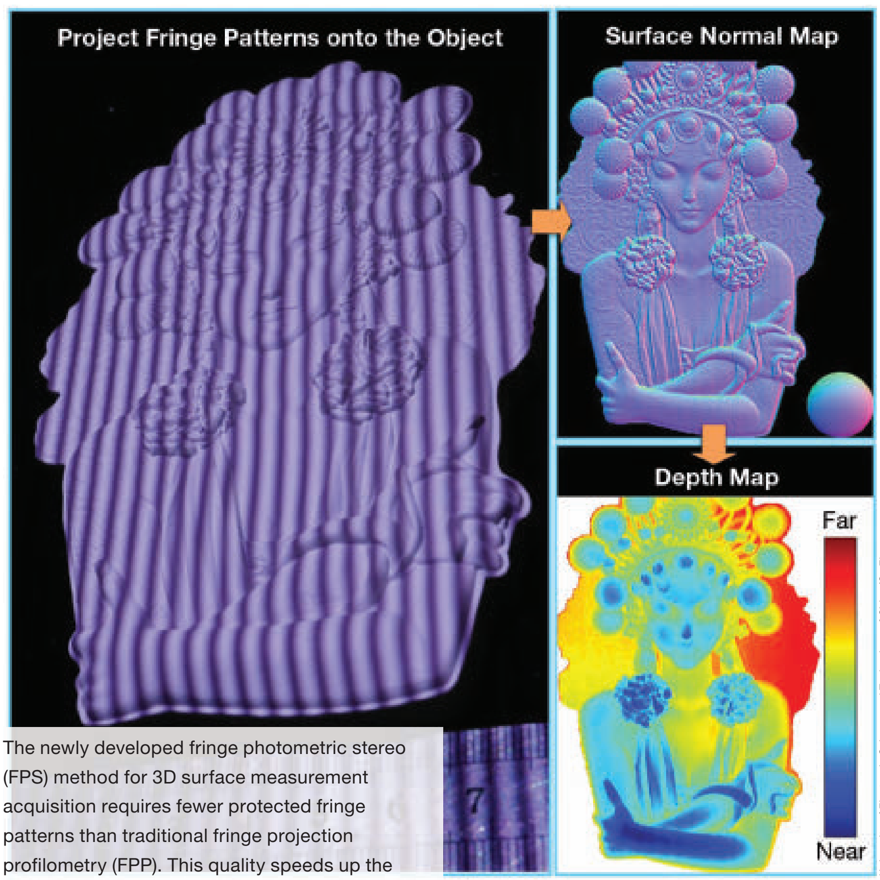
(megaspectra per second) measurement rate, which represents a 100-fold increase compared with the previous fastest rate of 500 kSpectra/s, the researchers said. The developed system enabled highly efficient Raman scattering with an ultrashort femtosecond pulse and sensitive time-stretch detection with a picosecond probe pulse at a high repetition of the laser.

As a proof-of-concept, the researchers measured broadband coherent Stokes Raman scattering spectra of organic compounds covering the molecular fingerprint region from 200 to 1200 $cm^{-1}$. The researchers are currently aiming to apply their spectrometer to microscopy, which could enable the researchers to capture 2D or 3D images with Raman scattering spectra, researcher Takuro Ideguchi said.

"Additionally, we envision [the system's] use in flow cytometry by combining this technology with microfluidics. These systems will enable high-throughput, label-free chemical imaging and spectroscopy of biomolecules in cells or tissues," Ideguchi said.

The research was published in *Ultrafast Science* (www.doi.org/10.34133/ultrafast-science.0076).

## Method improves scanning speed for precise 3D surface measurement




The newly developed fringe photometric stereo (FPS) method for 3D surface measurement acquisition requires fewer protected fringe patterns than traditional fringe projection profilometry (FPP). This quality speeds up the scanning process.

University of Electronic Science and Technology of China/Ce Zhu

CHENGDU, China — Researchers at the University of Electronic Science and Technology of China developed a technique for 3D surface measurement, called fringe photometric stereo (FPS), that could improve the speed and accuracy of surface measurements taken for industrial inspection, medical applications, robotic vision, and other purposes. FPS accelerates the image scanning process and enables high-quality, unambiguous 3D reconstruction by requiring fewer fringe patterns than traditional fringe projection profilometry (FPP).

To measure and reconstruct 3D surfaces using traditional FPP, a series of phase-shifted light patterns are projected onto an object's surface. The reflected images are then captured and the phase differences analyzed to create a 3D map of the surface. The long scanning time required for FPP comes primarily from the high number of multiple-frequency fringe images required to analyze phase differences. FPP uses triangulation to convert the phase data into continuous values for an accurate representation of the shape or surface.

FPS bypasses the need for phase unwrapping and reduces the number of fringe images required by using single-frequency fringe patterns. It analytically relates the depth gradient to the phase gradient, which allows it to retrieve the continuous 3D surface directly from the high-frequency wrapped phase.

In this way, FPS enables 3D reconstruction for continuous objects without the need for phase unwrapping.

"Traditional 3D imaging works by comparing two viewpoints, similar to how our eyes work together to judge depth," said professor Ce Zhu, who led the research. "In contrast, our new approach 'feels' the surface by projecting light patterns, almost like running a hand over it to detect changes. This can reduce the number of patterns used by more than two-thirds, which greatly speeds up the scanning process, and surprisingly, is even more accurate than the old technique."

Additionally, FPS requires only a camera and a projector. There is no need for dual, multiple, or light-field cameras.

To test the technique, the researchers set up an experimental system to take measurements of single objects and groups of objects with continuous surfaces, including a human hand, a paper mask, a cloth toy, gypsum geometries, and clay handicrafts. In experiments, the FPS technique was found to mitigate additive Gaussian noise better than traditional temporal phase unwrapping. The researchers also validated the FPS approach using standard plane and sphere models, demonstrating that FPS effectively suppresses noise compared to traditional FPP.

The rapid scanning speed and high precision make FPS a promising technique for high-precision industrial inspection. For example, it could be used for surface-mount inspection in printed circuit board manufacturing, defect detection in new energy batteries, corrosion inspection of oil pipelines, or speaker diaphragm deformation measurement.

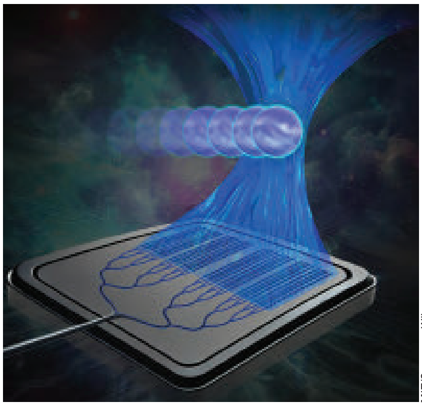
Also, according to Zhu, FPS could be particularly useful for customizing prosthetics. “It can quickly acquire high-precision surface information from the residual limb, reducing errors associated with manual measurements and improving the fit of the prosthesis,” he said. “This would also eliminate the need to apply plaster or other materials to the skin, making the experience much more comfortable for the patient.”

Although the FPS method has been found to improve scanning speed and accuracy for scenes with continuous surfaces, its utility to reconstruct objects with sudden changes in depth requires further development. The researchers are addressing this challenge by incorporating established surface reconstruction techniques from photometric stereo into FPS. This enhancement could enable FPS to analyze more complex scenes, further widening its reach as a 3D-surface imaging and image reconstruction tool.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.531601).

## Silicon photonics holds a key to optical tweezer innovation

CAMBRIDGE, Mass. — Compared with bulk optical tweezers, integrated optical tweezers are compact and low-cost, making them practical for most research organizations. But so far, integrated optical tweezers have been of limited use in biological research, as a result of the very small standoff distances that they provide.



MIT/Sampson Wilcox

Chip-based optical tweezers use an intensely focused beam of light to capture and manipulate biological particles without damaging the cells. These devices could help biologists better study the mechanisms of diseases.

To increase the standoff distance, researchers at MIT used an integrated optical phased array (OPA) that enabled trapping and tweezing of biological particles at 5 mm above the chip surface, enlarging the standoff distance by more than two orders of magnitude. The silicon photonics-based OPA tweezers captured and manipulated biological particles from a safe distance while the particles remained inside a sterile cover slip. In this process, both the chip and the particles were protected from contamination.

The OPA optical tweezers offer the same advantages of integrated tweezers along with much of the functionality of bulk optical systems, the researchers said. The OPA tweezers could be used to study DNA, classify cells, investigate disease mechanisms, and perform experiments that are not possible with prior implementations of integrated tweezers.

In the tweezer system, the OPA focuses the light emitted by the chip at a specific point in the radiative near field of the chip. It provides a steerable, potential energy well in the plane of the sample that can be used to trap and tweeze microscale particles. The OPA consists of a series of microscale antennas fabricated on a chip using semiconductor manufacturing processes. By electronically controlling the optical signal emitted by each antenna, the researchers directed the OPA to shape and steer the beam emitted by the chip.

Most integrated OPAs developed to date are not designed to generate the tightly focused beams needed for optical tweezing. The team found that, by creating specific phase patterns for each antenna, it could form an intensely focused beam suitable for trapping and tweezing several millimeters from the chip’s surface. By varying the wavelength of the optical signal that powers the chip, the researchers steered the focused beam over a range >1 mm with microscale accuracy.

In demonstrations, the researchers

used the OPA optical tweezers to trap polystyrene microspheres 5 mm above the surface of the chip and calibrated the optical trap system. They nonmechanically steered the focal spot of the beam by varying the input laser wavelength. They changed the system from a static optical trap to dynamic optical tweezers and demonstrated tweezing of polystyrene microspheres in 1D patterns with high fidelity and at submicron levels of precision.

Another advantage to the developed tweezers involves bypassing the use of a large microscope setup in a lab and multiple devices to form and control light. These elements are typically required of traditional optical tweezers. Chip-based optical tweezers, on the other hand, offer a compact, mass-manufacturable, broadly accessible, high-throughput alternative to bulk systems for optical manipulation.

Given the natural scalability and design flexibility of the CMOS-compatible fabrication platform used to produce the OPA tweezers, the researchers envision numerous ways to evolve the system to improve its performance and enable new functionality. Specifically, the team wants to refine the system to support an adjustable focal height for the light beam. It also plans to apply the device to different biological systems and use multiple trap sites simultaneously to manipulate biological particles in increasingly complex ways.

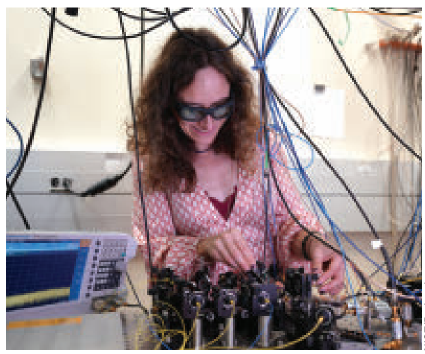
The research was published in *Nature Methods* (www.doi.org/10.1038/s41467-024-52273-x).

## Dual-comb spectroscopy technology improves gas leak detection

GAITHERSBURG, Md. — National Institute of Standards and Technology (NIST) researchers developed a dual-comb spectroscopy technique that enables the detection of gases and other substances with more speed and sensitivity than traditional dual-comb methods. The free-form dual-comb spectroscopy method quickly identifies the most information-rich parts of a sample's fingerprint, making both detection and measurement of substances more efficient. In the future, the researchers said, it could be key to locating small leaks or emissions that might otherwise go unnoticed and could contribute to climate change.

Dual-comb spectroscopy is a high-resolution technology that allows many colors of light to be examined in detail simultaneously. The frequency combs in dual-comb spectroscopy analyze how a substance interacts with the light from both combs. The two-comb approach enables substances to be measured faster than with a single comb and provides more detailed information than many other spectroscopy methods.

Time-programmable frequency combs enable measurement techniques that are less constrained than traditional dual-comb measurement methods; instead of fixing the repetition rate offset between combs, free-form dual-comb spectroscopy provides full control of the temporal offset between the dual-comb pulse trains. This makes it possible to select different sampling patterns to optimize resolution, signal-to-noise ratio, species selectivity, or acquisition time, allowing for highly flexible, precise control of the frequency combs.



NIST/R. Jacobson

Esther Baumann, a National Institute of Standards and Technology (NIST) scientist, works in the lab where a team of researchers has developed an improved version of a laser-based measurement technique called dual-comb spectroscopy.

The combs in the free-form dual-comb spectroscopy technique emitted pulses that are 100 fs in duration. Inside each pulse, an electric field vibrates trillions of times per second. The timing of these laser pulses can be controlled with a high degree of precision, compared to pulses emitted by conventional dual-comb techniques.

Using the developed technique, in the event that the type of gas detected is unknown, researchers can use compressive sampling, a smart measurement technique, to focus on areas that are likely to have important information about the substance, while taking fewer measurements elsewhere. With compressive sampling, the process of identifying and measuring a substance is 10 to 100× more efficient than with traditional methods, the researchers said.

The NIST team demonstrated compressive sensing with free-form dual-comb spectroscopy and obtained compression factors of up to 155, with an up to sixty-fold reduction in acquisition time. During the demonstration, the free-form system maintained identical spectral point spacing and comparable signal-to-noise ratio to traditional dual-comb spectroscopy.

The researchers also demonstrated molecular recurrence sampling for methane detection using free-form dual-comb spectroscopy. This sampling technique exhibited 22× higher sensitivity than traditional dual-comb spectroscopy sampling techniques, but required the researchers to have prior knowledge about the specific characteristics of the substance being analyzed.

In addition to detecting greenhouse gases, such as methane, users could deploy the developed technology to identify and measure other types of gases.

"The flexibility of our system means it could be adapted for a wide range of applications," researcher Esther Baumann said. "In the future, we might see more versatile and efficient sensors based on this technology in everything from air quality monitors to food safety detectors to studying how materials burn or assessing muscle health noninvasively."

The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-024-01530-y).

## Mode filtering using metal apertures improves VCSEL performance

CHANGCHUN, China — VCSEL light sources are used in optical storage, laser printing, 3D sensing, and other critical applications. Conventional oxide-confined VCSELs typically operate in single-transverse mode, with an oxide aperture of <4 µm. This can lead to increased series resistance and low output power in the VCSEL.

To overcome these limitations, researchers at the Changchun Institute of Optics, Fine Mechanics, and Physics of the Chinese Academy of Sciences developed a mode filtering technique that uses metal apertures to flexibly regulate transverse modes in VCSELs. The metal-dielectric film mode filter structure demonstrates the broad potential of metal apertures to enhance optical mode control and improve the performance of single-mode VCSELs.

The researchers began by creating a finite element simulation model of a metal mode-filtered VCSEL (MMF-VCSEL). They simulated variations in the position of the metal layer, the metal apertures, and oxide apertures on the fundamental mode optical spot of the MMF-VCSEL, and the effect of the variations on modal control. The researchers systematically calculated the modal loss and optical confinement factor variations with different metal apertures and metal layer positioning.

Next, they defined the optical gain, making it possible to describe the modal discrimination and provide alternative computational schemes and parameter ranges to achieve optimal device performance according to specific requirements.

From simulation results, the researchers showed that the modal control performance of the MMF-VCSEL was significantly influenced by the number of P-distributed Bragg reflector pairs, the metal aperture size, and the oxide aperture size. The transverse optical field was strongly confined within the metal aperture when the number of P-distributed Bragg reflector pairs was low, but the confinement weakened as the number of pairs increased. Also, the researchers found that when the metal aperture was smaller than the oxide aperture, the optical scattering effect intensified as the distance between the two apertures shrank. The mode discrimination and modal loss of the VCSEL increased, improving single-mode stability.

Continued study revealed that when the metal aperture exceeded the size of the oxide aperture, the optical mode in the VCSEL was controlled primarily by the oxide aperture. This finding shows how the complex relationship between the metal and oxide apertures can affect optical field confinement and mode discrimination in the VCSEL. By selecting the appropriate metal aperture and oxidation aperture values, the VCSEL can maintain favorable single-mode stability while retaining low threshold characteristics.

The research and test results enabled the team members to introduce a new parameter, optical gain, which in turn allowed them to characterize the change in the threshold gain of the different transverse modes due to optical scattering. By balancing the difference in optical gain between modes and the optical gain of the fundamental mode, they could identify the optimal structural parameters needed to enhance both the single-mode stability and the slope efficiency of the MMF-VCSEL.

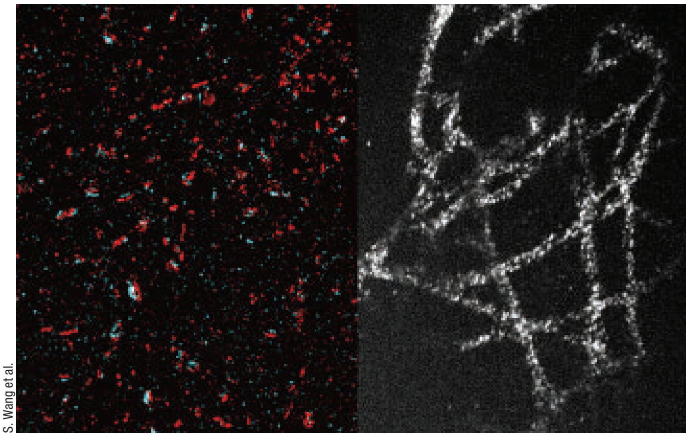
The researchers said that this study shows that the number, volume, and stability of transverse modes inside the VCSEL can be adjusted according to three key parameters — the oxide aperture, the metal aperture, and the distance between the oxide aperture and the metal aperture — to form a flexible window.

Now, a new parameter, optical gain, can be defined to describe the mode identification.

The researchers said additionally that the work underscores the critical role of metal apertures in enhancing mode control in VCSELs. Also, the work could lead to new approaches for developing high-performance VCSELs, the researchers said. This would support a broad range of potential applications.

The research was published in *Sensors* (www.doi.org/10.3390/s24144700).

## Boost to microscopy method ups performance, cuts cost



S. Wang et al.

A novel expansion microscopy technique enabled MIT researchers to use a conventional light microscope to generate high-resolution images of synapses **(left)** and microtubules. In the image at left, presynaptic proteins are labeled in red, and postsynaptic proteins are labeled in blue. Each blue-red ‘sandwich’ represents a synapse.

CAMBRIDGE, Mass. — An expansion microscopy technique from MIT enables a conventional light microscope to generate high-resolution images at the nanoscale, by expanding specimens twentyfold before imaging them. Historically, scientists have used high-powered and expensive superresolution microscopes to image nanoscale structures in cells. The developed protocol, in addition to achieving twentyfold expansion in a single step, provides an inexpensive method that most biology labs can use to perform imaging at a resolution of ~20 nm, according to the researchers.

MIT professor Edward Boyden and his team developed the original version of the expansion microscopy technique in 2015, which expanded tissue about fourfold and provided images with a resolution of ~70 nm. In 2017, Boyden's lab modified the process to include a second expansion step, achieving an overall twentyfold expansion.

“We've developed several twentyfold expansion technologies in the past, but they require multiple expansion steps,” Boyden said. “If you could do that amount of expansion in a single step, that could simplify things quite a bit.”

The newly demonstrated method reaches the same level of performance possible with iterative expansion methods, but with the simplicity of a single-shot protocol.

To implement the method, the researchers embedded a tissue specimen in an absorbent polymer and added water, creating a hydrogel that expands the polymer and pulls the biomolecules in the specimen apart. This gel is extremely absorbent and mechanically stable to ensure that the gel does not fall apart when the specimen is expanded by 20×.

To further stabilize the gel and enhance its reproducibility, the researchers removed oxygen from the polymer solution prior to gelation. This prevented side reactions that could interfere with crosslinking. Unlike previous expansion gels, which require another molecule to be added to form crosslinks between the polymer strands, the gel used for the single-shot, twentyfold expansion microscopy technique forms crosslinks spontaneously.

“This approach may require more sample preparation compared to other superresolution techniques, but it's much simpler when it comes to the actual imaging process, especially for 3D imaging,” researcher Tay Won Shin said.

In one round of expansion, the technique, which the team members called 20ExM, enabled the researchers to image hollow microtubule structures in cultured cells and synaptic nanocolumns in the mouse somatosensory cortex on a conventional confocal microscope. The team could also visualize mitochondria and the organization of individual nuclear pore complexes in the cells.

The 20ExM technique could be used for a variety of experiments in which high resolution and single-step simplicity are desired. The researchers are currently using the technique to image glycans — carbohydrates that can be found on the surface of a cell, among other locations, that help control how the cell interacts with its environment. The 20ExM method could additionally be used to image tumor cells, providing insight into how proteins are organized within these cells. And in principle, the technique could be used to simplify or enhance the resolution of other expansion-based technologies. These technologies include such in situ RNA detection and sequencing as well as genome imaging.

The research was published in *Nature Methods* (www.doi.org/10.1038/s41592-024-02454-9).

## Broadband UV combs will enhance molecular spectroscopy

ORLANDO, Fla. — Researchers at the University of Central Florida College of Optics and Photonics (UCF CREOL) developed an ultrafast laser platform that generates ultra-broadband UV frequency combs with an unprecedented 1 million comb lines. The solution provides exceptional spectral resolution, using an approach that also produces extremely accurate and stable frequencies.

According to the researchers, the development could enhance high-resolution molecular spectroscopy as well as atomic spectroscopy.

Optical frequency combs emit thousands of regularly spaced spectral lines, and have been essential to fields such as metrology, spectroscopy, and precision timekeeping using optical atomic clocks. The first frequency combs operated within the visible to near-infrared range, and their spectral range was extended to the UV region through optical harmonic generation shortly after their introduction. This extension unlocked a spectral domain for precision laser spectroscopy.

"Nevertheless, achieving both broadband coverage and high spectral resolution in the UV range has remained a considerable challenge," said research team leader Konstantin Vodopyanov.

"Broadband, high-resolution UV spectroscopy provides unique insights into electronic transitions in atoms and molecules, making it invaluable for applications such as chemical analysis, photochemistry, atmospheric trace gas sensing, and exoplanet exploration, where the simultaneous detection of numerous absorption features is essential," Vodopyanov said.

The researchers' high-resolution dual-comb spectroscopy system generates light across two ultra-broad UV spectral regions. With a line spacing of just 80 MHz, the frequency combs exhibit a resolving power of up to 10 million.

To use UV frequency combs containing a million closely spaced spectral lines for spectroscopy applications, the researchers sought a method capable of achieving high spectral resolution, beyond the capabilities of existing spectrometers. They turned to dual-comb spectroscopy, which combines two frequency combs with slightly different line spacings on a single detector to produce interferograms. By applying a Fourier transform, the entire spectrum can be reconstructed with exceptionally high spectral resolution and rapid data acquisition.

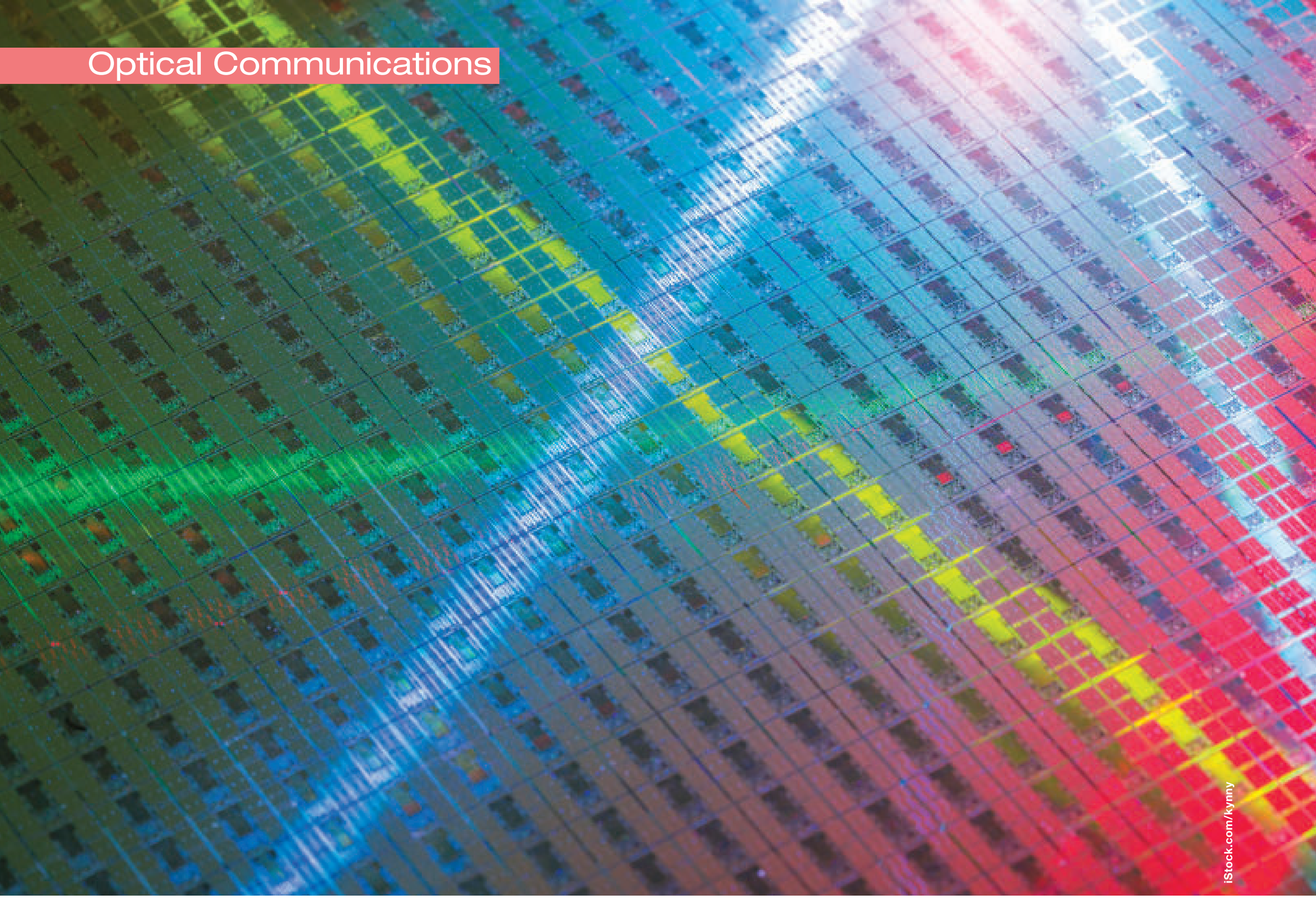
"Although, over the past decade, dual-comb spectroscopy has made significant progress in the mid-infrared and terahertz regions, a notable gap remains in the UV spectral range, where existing demonstrations fall short in terms of resolution, bandwidth, or both," Vodopyanov said.

The researchers developed a laser platform that generates highly coherent ultrafast infrared pulses at 2.4 µm. Using a nonlinear crystal, they produced the sixth and seventh harmonics, resulting in two UV bands: the sixth harmonic covering ~1 million spectrally resolved comb lines and the 7th harmonic containing ~550,000. This yielded two UV ranges spanning 372 to 410 nm and 325 to 342 nm. Then, they replicated the broadband UV comb system, allowing for further refinement of the UV comb's structure to enable dual-comb spectroscopy.

As a demonstration, they used the dual-comb system to measure the narrow reflection spectrum of a volume Bragg grating mirror. The system achieved a resolving power of 10 million, which the researchers said is far superior to existing grating and Fourier spectrometers.

Next, the researchers aim to extend the technology to even deeper UV regions, potentially down to a wavelength of 100 nm.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.536971).




# Charting the Path Toward 1.6T and 3.2T Optical Module Solutions

Exponential growth in data communication is driving bandwidth demands in hyperscale data centers.



Image this page, courtesy of iStock.com/kynny.
All other images, courtesy of Intel Corporation.

BY SUNIL PRIYADARSHI
INTEL CORPORATION

The relentless expansion of data communication, propelled by advancements in artificial intelligence (AI) and machine learning workloads, as well as cloud computing, cloud storage, AR/VR, video on demand, 5G technology, the Internet of Things, and autonomous vehicles, demands a substantial increase in bandwidth. Hyperscale data centers are under continuous pressure to enhance and augment their network capacity. This is achieved through hardware upgrades, including more advanced switches, routers, and servers, which offer higher bandwidth via increased port speeds and higher port counts relative to previous generations.

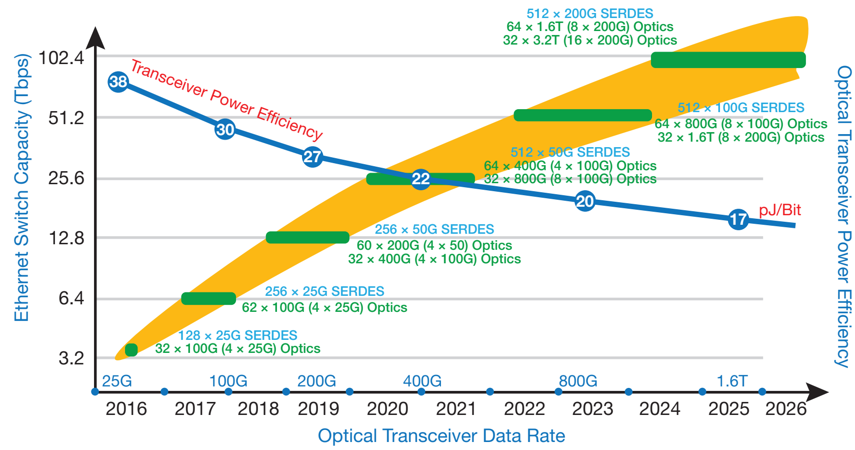
In parallel, the optical interconnects that link these network devices must also scale their bandwidth capabilities. Over the years, this scaling has been accomplished through advancements in lane speeds, modulation techniques, and the number of lanes (Figure 1).

Pluggable optical transceiver modules are essential components in data communication systems, widely used as optical interconnects at the termination of fiber optic links. These modules perform the critical function of converting electrical signals into optical signals, and vice versa. They are designed to insert into networking equipment, such as switches, routers, and servers, in which they interface with the fiber optic cabling that interconnects hyperscale data centers and enterprise networks.

These transceiver modules are engineered for hot swapping, which means that the transceivers can insert or be removed from their network ports without interrupting operation or powering down the network equipment. This allows for easy maintenance, upgrades, and installation.

These pluggable optical transceivers conform to standards defined by multisource agreements (MSAs), such as Small Form Factor Pluggable (SFP), Quad SFP (QSFP), QSFP-Double Density (QSFP-DD), Octal SFP (OSFP), and Common Management Interface Specification (CMIS). These standards specify the connector pinouts, dimensions of the transceiver(s), power consumption, and communication protocols with the host board. A single optical transceiver definition under an MSA can support a multitude of transceiver types, which may vary in the number of lanes, optical wavelengths, signal formats, and link reach.

This standardized approach affords network architects the flexibility to select from a wide range of optical transceivers without the need to alter the underlying electrical switch design(s) (Figure 2). For example, a variety of optical transceivers are supported within the QSFP-DD form factor, including 400GBASE-SR8, 400GBASE-DR4, 400GBASE-FR4, 400GBASE-LR4, and 400GBASE-ZR4. These products differ in their connector types, carrier wavelengths, modulation



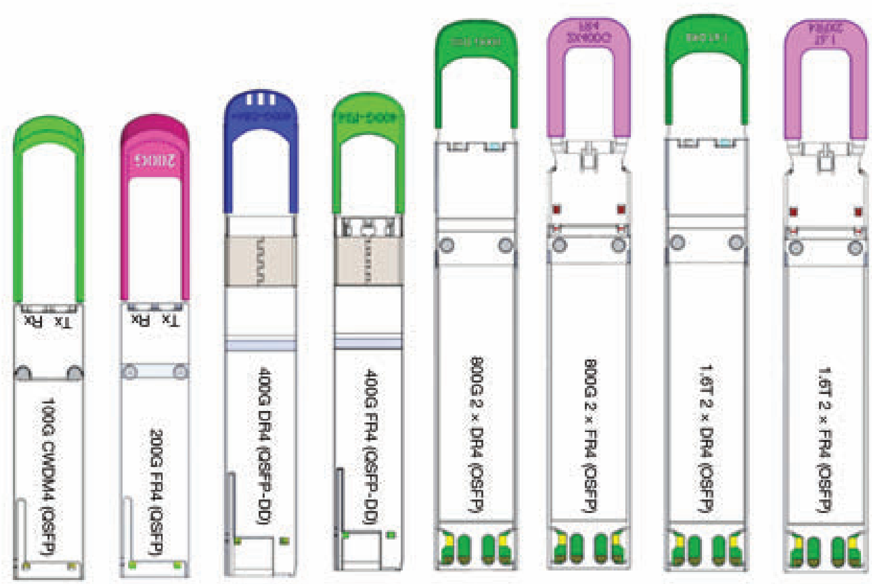




**Figure 1.** The evolution of Ethernet switch bandwidth and optical pluggable transceiver bandwidth based on vendor disclosures and public announcements **(top)**. SERDES: serializer/deserializer.

**Figure 2.** An example of different form factor and data-rate pluggable optical transceivers **(bottom)**.

formats, and maximum transmission distances.

And, while MSAs ensure interoperability among devices, they also provide network architects the freedom to choose product architectures that meet specific requirements and enable cost reductions. Amid the current surge of data and telecom demands, this variance in architectures is particularly relevant for

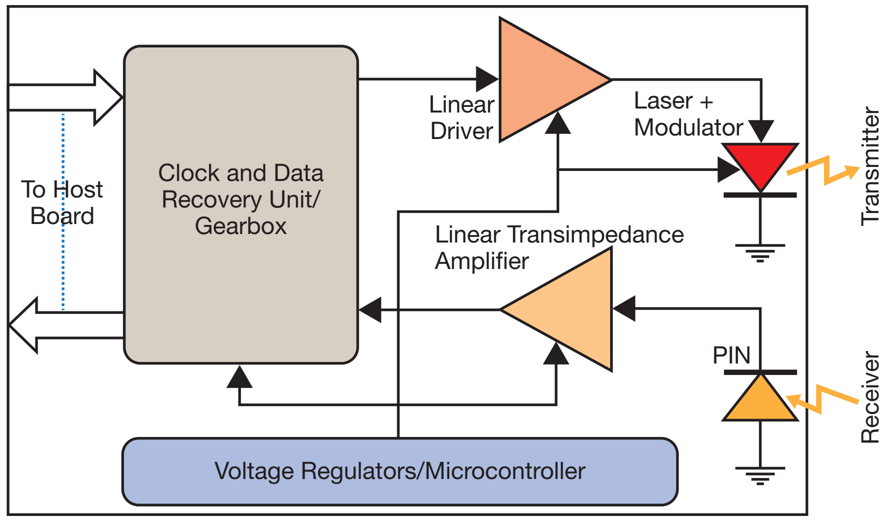



**Figure 3.** A diagram of an optical transceiver.

**Table 1.**
**Transmit (Tx) Specification for 800GBASE-2 × DR4**

| Tx Parameter | Minimum | Typical | Maximum | Unit |
|---|---|---|---|---|
| Wavelength range | 1304.5 | 1311 | 1317.5 | nm |
| Operating link reach | 2 | | 500 | m |
| Side mode suppression ratio | 30 | | | dB |
| Average launch power per lane | −2.9 | | 4 | dBm |
| Optical modulation amplitude ($OMA_{outer}$), each lane | −0.8 | | 4.2 | dBm |
| Tx and dispersion eye closer for PAM4 (TDECQ) | | | 3.4 | dB |
| Optical modulation amplitude -TDECQ, each lane | −1.9 | | | dB |
| TDECQ-10*log10($C_{eq}$) | | | 3.4 | dB |
| Average launch power of OFF Tx per lane | | | −15 | dBm |
| Extinction ratio | 3.5 | | — | dB |
| Tx transition (rise/fall) time | | | 17 | ps |
| Relative intensity noise (RIN)17.1 OMA | | | −136 | dB/Hz |
| Optical return loss tolerance | | | 15.5 | dB |
| Tx reflectance (defined looking into the Tx) | | | −26 | dB |

TDECQ (metric): transmitter dispersion eye closure quaternary.

Figure 4. A 400GBASE-DR4 transmitter (Tx) subassembly with discrete components **(right)**. EMLs: electro-absorption modulated lasers.

Figure 5. An 800GBASE-2 × FR4 transmitter (Tx) photonic integrated circuit **(middle)**.

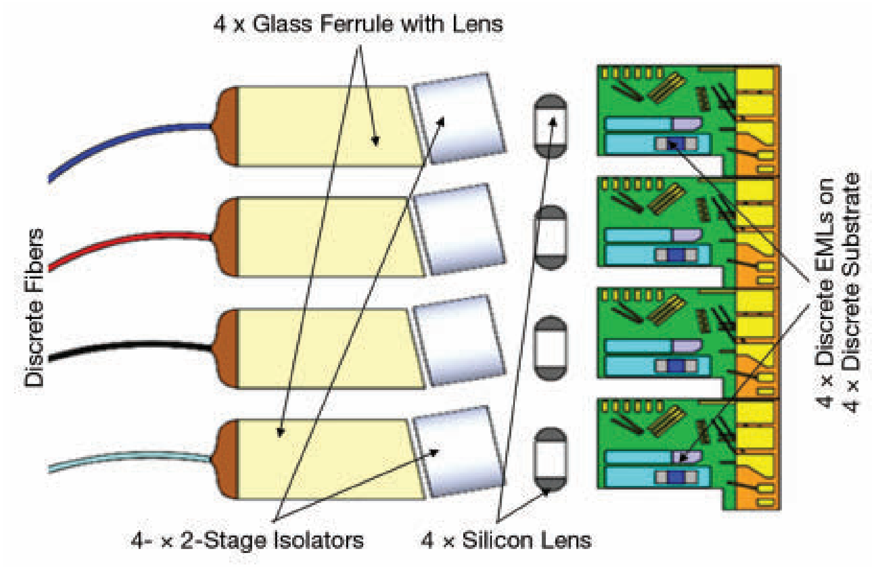
high-volume deployments in hyperscale data centers.

## Pluggable transceiver design

As the bandwidth of optical transceiver modules increases, technical challenges are emerging for members of the engineering community tasked with the design of pluggable optical transceiver modules. This complex design process requires the integration of multiple technological disciplines. Challenges relate to high-speed operation, an increased number of host channels, power constraints, thermal management requirements, and electrical specifications. Electrical, mechanical, optical, and firmware engineering must collaborate precisely to deliver the required electro-optical performance.

A pluggable optical transceiver module architecture consists of several critical components: a laser light source capable of high-speed modulation, a modulator driver, a photodetector, a transimpedance amplifier (TIA), clock and data recovery units (CDRs), digital signal processors ((DSPs) or gearboxes), a microcontroller, and voltage regulators that power various power rails. These components are essential for the module's operation (Figure 3).

In a pluggable optical transceiver, the input electrical signal received from the host board is first processed using a retimer. The purpose of a retimer mechanism is to eliminate jitter that has been introduced by the host's serializer/deserializer (SERDES) and to correct any other signal impairments that may be introduced while the signal is transmitted from the host board to the module PCB. For example, in an OSFP-800GBASE-2 × DR4 transceiver, eight lanes of 53.125 Gbaud PAM4 signals are retimed to remove jitter. The retimed and amplified signals are then used to modulate the intensity of the output laser. A variety of optical modulators, such as directly modulated lasers (DMLs) and electro-absorption modulated lasers (EMLs), can be implemented to achieve this modulation. The modulated



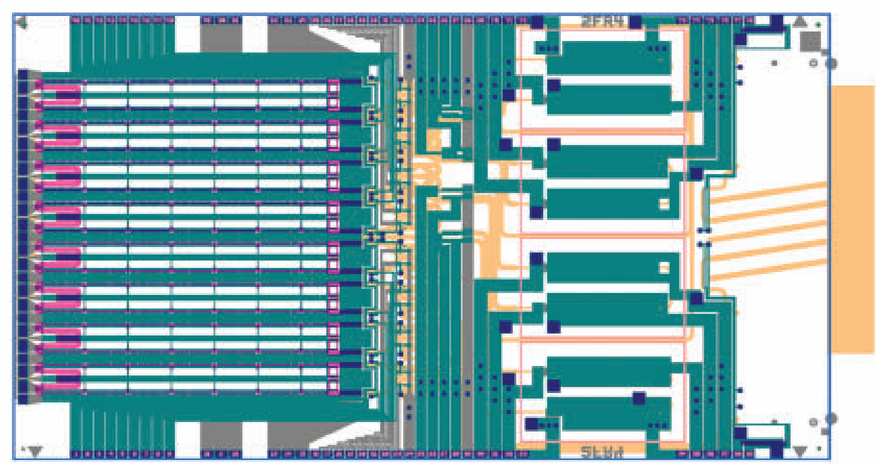
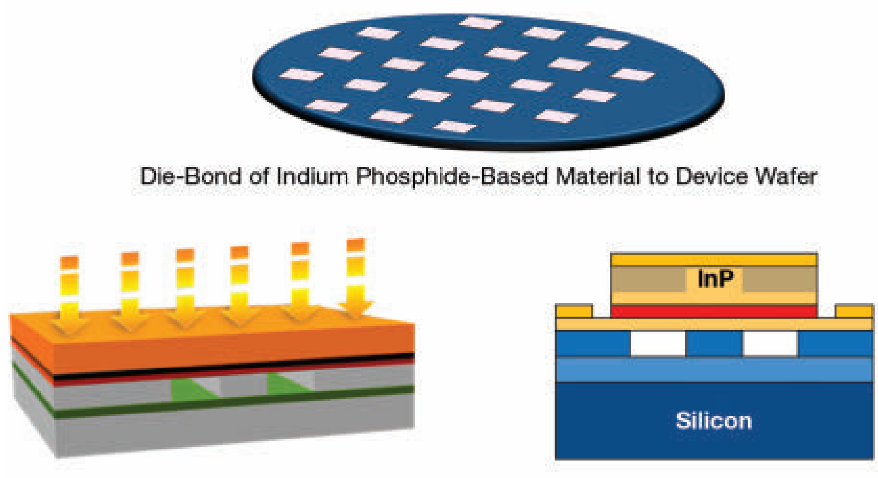



**Table 2.
Receiver (Rx) Specification for 800GBASE-2 × DR4**

| Rx Parameter | Minimum | Typical | Maximum | Unit |
|---|---|---|---|---|
| Lane wavelengths: meet sensitivity and overload as below | 1304.5 | 1311 | 1317.5 | nm |
| Average Rx power, each lane (informative) | −5.9 | | 4 | dBm |
| Rx power, OMA each lane: BER of 2.4e-4 or better | | | 4.2 | dBm |
| Rx reflectance | | | −26 | dB |
| Rx damage threshold | 5 | | | |
| Unstressed Rx sensitivity at BER = 2.4e-4 (OMA) | max. (−3.9, SECQ −5.3) | | | dBm |
| Stressed sensitivity at BER = 2.4e-4 (OMA, per lane) | | | −1.9 | dBm |

BER: bit error rate; OMA: optical modulation amplitude; SECQ (metric): stress eye closure quaternary.



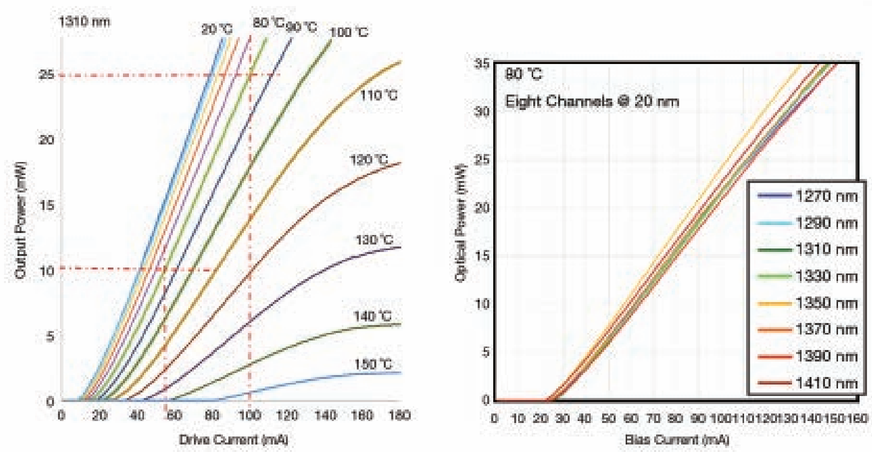




**Figure 6.** An integrated laser/semiconductor optical amplifier (SOA) at wafer scale **(left)**. InP: indium phosphide.

**Figure 7.** Integrated laser characteristics over temperature **(below, left)** and bias current **(below, right)**, as well as the flexibility of incorporating multiple coarse wavelength division multiplexing (CWDM) wavelengths within a single photonic integrated circuit.

light is then coupled into the optical fiber using lenses.

Silicon photonics-based Mach-Zehnder and ring modulators can also be used. Mach-Zehnder modulators (MZMs) and ring modulators both use interferometric structures to translate refractive index changes into optical intensity modulations. Both are key components in silicon photonics-based transceivers, offering distinct advantages and trade-offs, including between one another. MZMs are favored for their high extinction ratios, higher linearity, thermal stability, and ease of fabrication, though they suffer from high power consumption and a larger footprint. In contrast, ring modulators offer small footprints, favorable bandwidth, and low optical loss, though they have high thermal sensitivity, which means that they require accurate temperature control to achieve optimal performance. They also have a limited operational optical bandwidth. Fabrication techniques, such as *p-n* junction-based MZMs, are straightforward but less modulation-efficient compared with carrier injection and accumulation methods. Power consumption in these devices is primarily determined by the voltage required to achieve a phase shift of $\pi$ radians. Ultimately, the choice between MZMs and ring modulators depends on specific application requirements influencing performance, thermal stability, power consumption, and fabrication complexity.

On the receiver side of a pluggable optical transceiver, if the incoming light signal contains more than one wavelength, it is first demultiplexed. In operation a photodetector then converts the optical signal into an electrical current waveform. This current is subsequently converted into a voltage waveform by a TIA. The voltage waveform is then processed through a retimer to mitigate any impairments introduced by the fiber, such as dispersion or jitter. If necessary, the signal is passed through a gearbox to adjust the data rate before it is transmitted back to the host board.

## Optical transceiver specifications

Optical transceivers must adhere to all relevant specifications to ensure interoperability among devices produced by different vendors. IEEE 802.3 task forces typically define the electrical and optical specifications without specifying form factors. The IEEE specifications encompass the optical link budget, transmit (Tx) and receive (Rx) specifications at the physical layer, and the media access control at the data link layer.

Complementarily, MSA groups (such as OSFP) specify form factor-related requirements, including power supply voltage, connector pinout, mechanical dimensions, optical connector definitions, and the host control interface. For instance, the 800GBASE-2 × DR4 is a single-mode fiber-based optical transceiver that features eight parallel Tx/Rx optical lanes with a center carrier wavelength of 1310 nm. Each lane is required to operate at 100 Gbps and support a minimum link reach of 500 m. Tables 1 and 2 list the specifications for the Tx and Rx as defined in IEEE 802.3ck-2022 and IEEE P802.3df, respectively.

In addition to optical, electrical, mechanical, and reliability specifications, optical transceiver modules are also required to meet environmental and safety compliance standards. And, they must be designed with manufacture and test in mind — concepts known as design for manufacture (DFM) and design for test (DFT) optimize manufacturing throughput and yield with the ultimate aim to minimize production costs. Given the diversity of optical transceivers available on the market, each produced by different vendors with their own distinct technological approaches, there is no one-size-fits-all design methodology or workflow that is applicable to all types of optical transceivers or vendors.

### Discrete vs. silicon photonics

Silicon photonics technology has gained significant traction within hyperscale data centers in recent years, and it is increasingly prevalent as the demand for larger volumes of pluggable optical modules increases within these facilities. Traditionally, the manufacture of optical transceivers has involved the use of discrete optical components. This process entails the manual assembly of free space DMLs, EMLs, photodetectors, isolators, optical multiplexers and demultiplexers, lenses, and fiber termination connectors. These components are typically integrated into gold-box or ceramic substrate assemblies. Figure 4 shows an example of such a Tx subassembly, for a 400GBASE-DR4 transceiver using EMLs.

As shown in Figure 4, the necessity for multiple active and passive optical alignments during manufacturing that characterizes this subassembly process makes it quite labor-intensive and costly. In the case of a 400GBASE-DR4 Tx subassembly, for example, EMLs mounted on a substrate must first undergo a burn-in process and subsequent testing to eliminate any of these components that fail. Following this, four discrete EML substrates are individually mounted onto a ceramic substrate, which serves as an optical bench. Four discrete lenses are then positioned on the bench, followed by four pieces of two-stage isolators, and finally, four discrete glass ferrules with polarization lenses are aligned, resulting in a total of 16 discrete component alignments.

A 400GBASE-FR4 transceiver requires the incorporation of an additional discrete optical multiplexer. The complexity of this manufacture increases significantly in doubling (or quadrupling) for 800G and 1.6T 2 × DR4/FR4 Tx subassemblies when using discrete components.

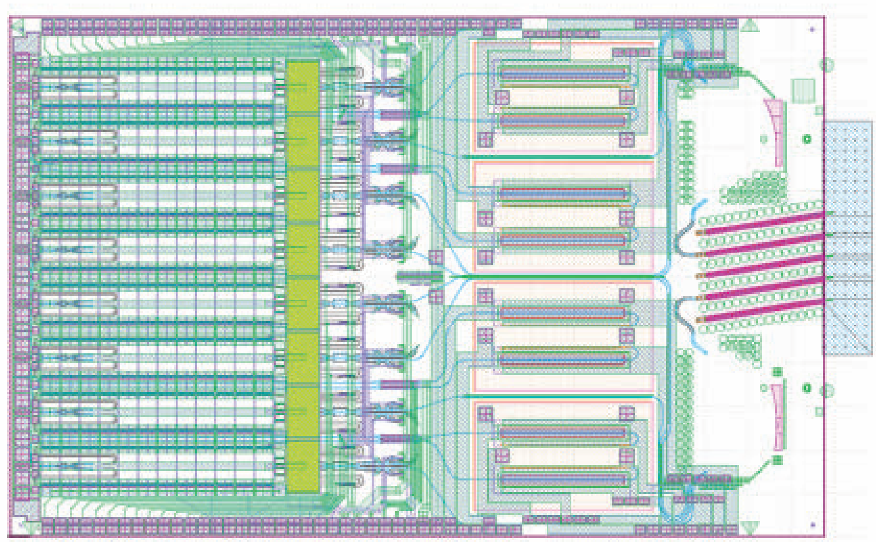


**Figure 8.** A 1.6TBASE-DR8 photonic integrated circuit.

Owing to the complexity of these design requirements, industry-led innovations, including those pioneered at Intel, have targeted simplifications — as well as performance improvements — for the manufacture of optical transceivers. For example, Figure 5 shows an 800G 2 × FR4 Tx PIC with dimensions of 5.77 × 10.72 mm. This Tx PIC, based on Intel silicon photonics technology, integrates 8× DFB lasers (2 × 4 coarse wave division multiplexing (CWDM)) 4 λs, 8× MZMs,

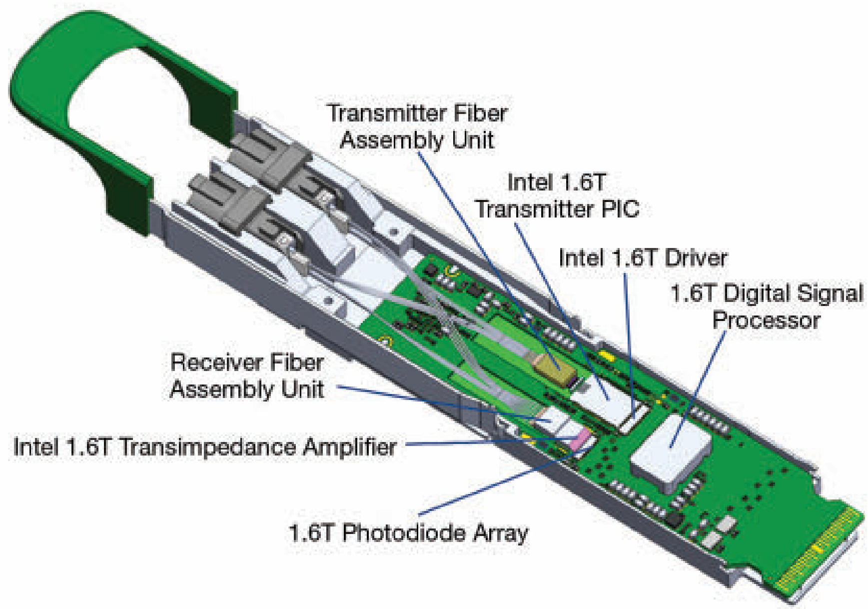



**Figure 9.** An architecture of a 1.6TBASE-DR8 module, using an Intel photonic integrated circuit.

16× quadrature bias heater/monitor photo detector, 8× variable optical attenuator, 2× temperatures diodes, 8× MZM biasing terminations, 2× edge inverted taper optical out, and 2× quad optical multiplexers, both optical active and passive components, totaling more than 50-plus individual components.

Consequently, this technology eliminates the laborious assembly process involved with discrete fabrications. In fact, the PIC in this system necessitates only a single active alignment to couple it with the fiber assembly unit (Figure 5). Intel's silicon photonics technology enables the integration of the complete Tx and Rx optical systems within a PIC, which can significantly reduce the number of assembly steps, manufacturing time, and production costs.

## Heterogeneous integration

There are additional necessities to consider beyond design and development, and many are located downstream from fabrication. Wafer integration — targeting the development of integrated hybrid lasers — as well as delivery to customers are two additional requirements that Intel is meeting. The company has shipped its integrated solution in mass volume, and more than 8 million PICs and more than 32 million on-chip lasers have been deployed in the field. A critical advantage involves the use of a process that enables monolithic integration — in this case, of indium phosphide (InP) and germanium onto silicon wafers. This process is used to create integrated lasers, as well as optical amplifiers and photodetectors, which offer integrated laser sources inside the PIC. This integration eliminates the need for external laser sources, semiconductor optical amplifiers (SOAs), and/or photodetectors, which represents a requirement that can add design complexity and increase costs.

As shown in Figure 6, InP epitaxial-material chiplets are placed onto a 300-mm silicon-on-insulator (SOI) wafer. Then, the lasers are patterned and created at wafer level, including the inscription of gratings into the silicon material. This process enables the fabrication of highly complex chips that integrate multiple lasers with different wavelengths, along with numerous other passive and active components.

Integrating optical gain directly onto the photonics chip offers a significant advantage in simplicity, performance, and cost. Consider that chip-scale laser integration using conventional discrete lasers is often plagued by reliability issues. Using DFB lasers, the absence of exposed facets, and the elimination of mechanical stress from grinding, polishing, and singulation — all of which are common in the production of discrete lasers — characterize the integration designs. Figure 7 displays the laser characteristics over temperature and bias current as well as the flexibility of incorporating multiple CWDM wavelengths within a single PIC.

These integration approaches aim to streamline manufacturing efficiency and automation by reducing discrete components and manual processes. As a result, the technology serves to increase overall factory output. Additionally, wafer-level burn-in and testing allow for extensive automation and high production rates, making the mass production and adoption of leading-edge optical transceivers more attainable. Silicon photonics also enhances product yield through consistent and reliable component performance, due to the precision of lithography and wafer etching techniques. Early detection and correction of design-related issues are possible through statistical modeling and simulations, which predict transceiver performance before manufacturing.

Further, economies of scale are realized as the up-front investment in chip design is amortized over increasing production volumes, enabling efficient, high-volume production. As optical modules proliferate in data centers, the benefits of silicon photonics will be amplified, making high-speed optics more widely available in the market.

### The path to 1.6T and 3.2T

Transitioning from 800G to 1.6T optical modules as AI workloads in data centers escalate will effectively double the bandwidth capacity per 1 rack unit (RU) without requiring modifications to the existing infrastructure. With the current use of 800G pluggable modules, a 2RU rack is necessary to support a 51.2T switching capacity across 64 ports.

On the other hand, the adoption of 1.6T pluggable modules would allow the same 51.2T capacity to be achieved within a single 1RU rack using only 32 ports. Furthermore, the shift toward 200G/lane optical links in data centers sets the stage for 1.6T and 3.2T optical module solutions with 200G/lane serial electrical interfaces. This is essential for supporting next-generation 102.4T switches and expansive AI clusters, such as the NVIDIA GB200. Also, the direct 1:1 mapping between electrical and optical I/O speeds enabled by 200G/lane signaling from the application-specific integrated circuit (ASIC) eliminates the need for gearboxes or multiplexers, and thereby streamlining the implementation of 1.6T or 3.2T optical modules.

Figure 8 shows a 1.6T 2 × FR4 PIC. This architecture is similar to that of the 800G 2 × FR4, but this solution features eight high-speed MZMs operating at 200 Gbps, simplifying the design of 1.6T optical modules on an OSFP platform. A 3.2T capacity could be achieved using two such PICs on an OSFP-extended density (OSFP-XD) platform. Figure 9 depicts the implementation of a 1.6T optical module in an OSFP platform using Intel's PICs and integrated electronic circuits. Intel's 1.6T optical module solution, for example, enhances bandwidth density by 2×, optimizing the space in data centers.

## Co-packaging and compute interconnect

In current iterations of switch systems, signal speed increases are creating a challenge related to routing electrical traces from the switch chip to the front panel ports for pluggable optics. By integrating optics more closely with the ASIC, the length of electrical traces between the switch silicon and the optical I/O can be minimized, because the signals no longer need to be routed to a front panel. This change replaces the formerly high-loss channel with a shorter-length, lower-power interface (<5 pJ/bit) to offer a solution to these power and cooling challenges.



The pursuit of tighter integration between optics and electronic chips in this context, including ASICs, is paving the way for a future that demands cost-effective optical I/O, reduced system power, and consistently higher bandwidth density. The technological components and processes required for this integrated optics approach are increasingly dependent on the maturation of silicon photonics, heralding a promising direction for direct optical I/O.

Already, silicon photonics is enabling high-bandwidth optical interfaces for chip-to-chip interconnects, marking an exciting frontier in technology development. Indeed, there have been several demonstrations of this trend. In 2020, for example, Intel showcased the integration of its 1.6 Tbps silicon photonics engine with a 12.8 Tbps programmable Ethernet switch. More recently, it demonstrated the fully integrated optical compute interconnect (OCI) chiplet, co-packaged with an Intel CPU and running live data. This OCI chiplet — enabling co-packaged optical I/O for emerging AI infrastructure in data centers and high-performance computing applications — represents a significant advancement in high-bandwidth interconnect technology.

Silicon photonics is leading the charge for denser, more efficient bandwidth usages. The technology introduced by industry players, including Intel's silicon photonics, is paving the way for innovations such as co-packaged optics and OCI, which promise to overcome current power and cooling limitations. These advancements not only enhance current data transmission capabilities, but also pave the way for future breakthroughs in optical interconnects, ensuring that the infrastructure of data centers evolves to meet current and forthcoming data communication needs.

## Meet the author

Sunil Priyadarshi is director of engineering for integrated photonics solutions at Intel Corporation. In more than 25 years in optical connectivity product design, he has held positions at Broadcom (Avago Technologies), Coherent (Finisar), Source Photonics, Lucent Technologies, and NEC; email: sunil.priyadarshi@intel.com.

Infrared and ultraviolet imaging are extending beyond the biomedical and chemical settings in which they are strongly established.

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# Nonvisible Imaging

## Streamlines Nano and Advanced Manufacturing

Higher throughputs, wider fields, and lower temperatures are broadening microscopy's industrial applications in the infrared, ultraviolet, and terahertz ranges.

BY JAMES SCHLETT
CONTRIBUTING EDITOR

To produce faux marble kitchen countertops, a manufacturer places a piece of solarized polypropylene — a thermoplastic polymer material — on top of white stone. To ensure that a successful bond is created, the stone must contact the nonsolarized side of the polypropylene.

The challenge: The visible eye cannot differentiate which side is which.

To make this distinction, the manufacturer in a recent use case used Shimadzu Scientific Instruments' infrared microscopy solution to determine where oxidation had occurred. Oxidation is an indication of the solarization and is therefore a useful gauge for the manufacturer.

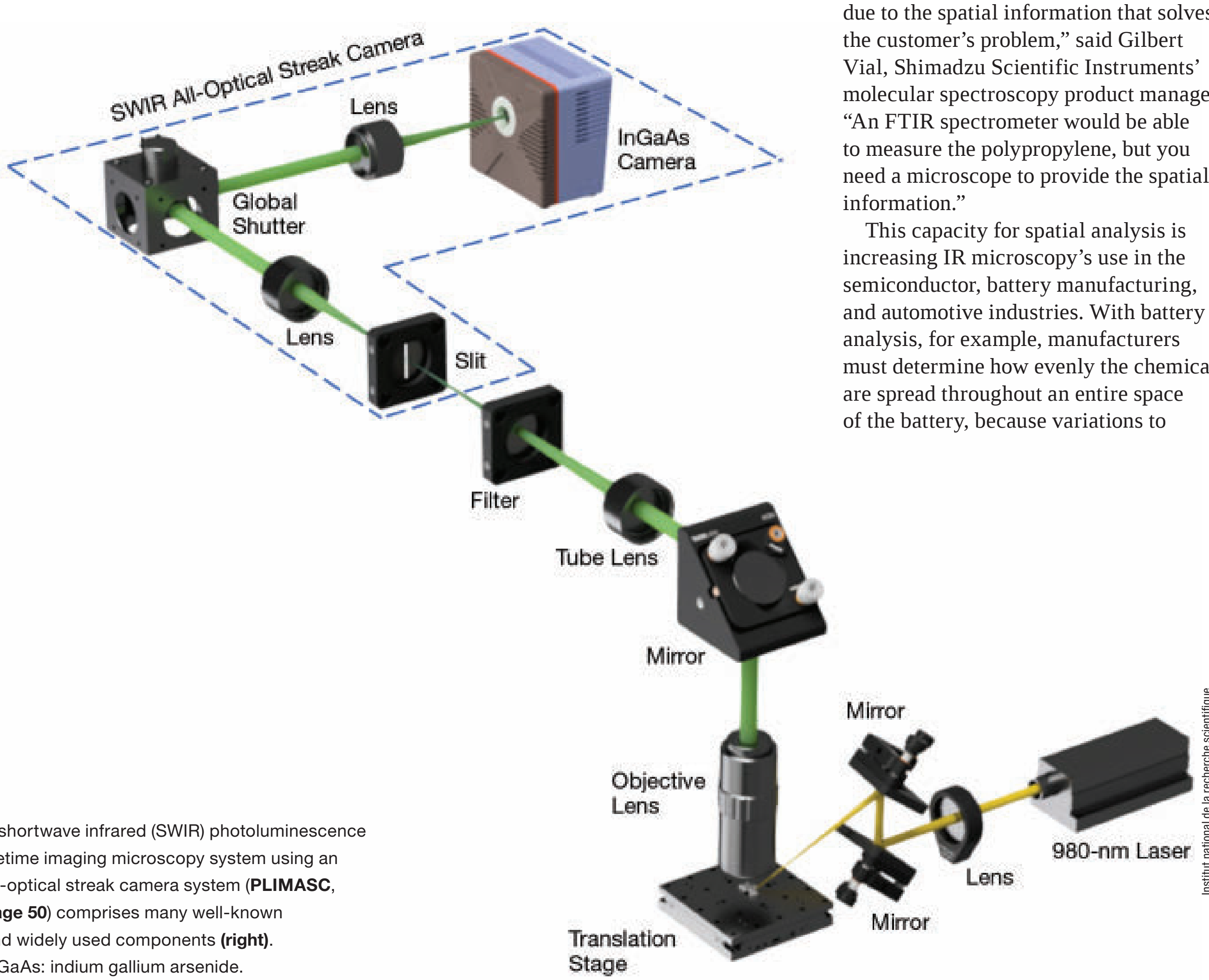
The manufacture of faux marble countertops is one of the nontraditional — but growing —industrial applications for nonvisible microscopy, in which uses of infrared (IR), ultraviolet (UV), and terahertz wavelengths are each finding expanded adoption. Many of these applications and use cases require additional components and instrumentation that are themselves emerging. The prevalence of other applications can be attributed to the growing demand to perform functions in support of sophisticated technology areas, ranging from quantum science (computing) to materials research (semiconductor manufacturing).

## Fourier transform

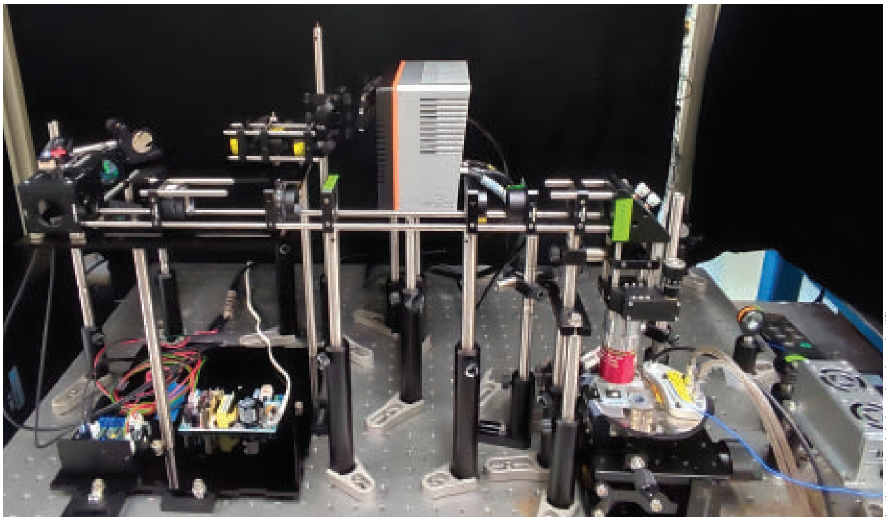
Certain nonvisible microscopy imaging modalities provide established options for end users in many fields, including those in the life sciences. Particle analysis, for example, is a common application in biomedical and biology research. Although industrial examples are less widespread, functions in industrial settings also commonly require particle and failure analyses, which can be performed using IR, UV, and terahertz imaging.

In the aforementioned case of the faux marble countertop, the IR microscope connects to a Fourier transform infrared (FTIR) spectrophotometer. "The IR microscope is needed for this [application] due to the spatial information that solves the customer's problem," said Gilbert Vial, Shimadzu Scientific Instruments' molecular spectroscopy product manager. "An FTIR spectrometer would be able to measure the polypropylene, but you need a microscope to provide the spatial information."

This capacity for spatial analysis is increasing IR microscopy's use in the semiconductor, battery manufacturing, and automotive industries. With battery analysis, for example, manufacturers must determine how evenly the chemicals are spread throughout an entire space of the battery, because variations to




A shortwave infrared (SWIR) photoluminescence lifetime imaging microscopy system using an all-optical streak camera system (**PLIMASC**, **page 50**) comprises many well-known and widely used components **(right)**. InGaAs: indium gallium arsenide.




A shortwave infrared (SWIR) photoluminescence lifetime imaging microscopy system using an all-optical streak camera system.

the distribution influence the battery's efficiency. "The IR microscope has the ability, with most manufacturers, to stitch together multiple measurement points, which allow a chemical change to be tracked over a surface. Performing this type of measurement on a sample can show how widespread the contamination is, and it can potentially show if there's a way to salvage the product or if the entire piece needs to be discarded," Vial said.

Kitchen countertop production is obviously not required at the volumes or scales that are demanded by semiconductors and pharmaceuticals; in these fields, FTIR microscopes are used in higher throughput applications. And for such high-throughput functions, the instruments may incorporate quantum cascade laser (QCL) sources and wide-field cameras. Classical Fourier transform relies on a thermal IR source and enables broadband IR spectroscopy, though the amount of light intensity limits its microscopic applications. The integration of QCL sources in FTIR microscopes dramatically increases light intensity. In combination with wide-field camera detectors, large areas can be illuminated and imaging measurements can be conducted at unprecedented speeds, according to Hans-Christian Koch, Bruker Switzerland's microscopy manager.

An IR microscope solution from Bruker combines Fourier transform and QCL technology in a single device. "Using QCL technology, measurement speeds can be dramatically increased. For many applications, such as pharmaceutical tablet imaging or particle screening, this is a game changer," Koch said. Additional applications for this FTIR microscopy augmented by QCLs include the analysis of the amounts of silk, cotton, and wool fibers in tissue fabric, as well as the quality control of adhesive sealing used for tea bags, to prevent them from disassembling in a cup.

Bruker's combination of FTIR microscopy with QCL sources supports a trio of measure modes: transmission, reflectance, and attenuated total reflectance (ATR). While high-throughput capabilities may not be a top priority for all materials analysis, or for all testing laboratories that serve small-batch research applications, the ability to combine FTIR microscopy with microscope ATR offers distinct advantages. Covalent Metrology Services of Sunnyvale, Calif., has combined FTIR microscopy with microscope ATR to identify the source of small foreign particles in packaged medical devices. "This enabled the customer to isolate the elements of the manufacturing process that were introducing the particles and [to] fix them," said Xiang Li, an engineer with Covalent Metrology. This resulted in significant savings in both in time and cost, Li said.

Failure analysis involving small particle contamination is a fast-growing application for FTIR microscopy services. Still, particles sized <100 µm are difficult to identify, as are inorganic materials with little IR absorption or nonspecific bands. The submicron size of nanoplastics, for example, would traditionally place their analysis outside the scope of IR microscopy's capabilities.

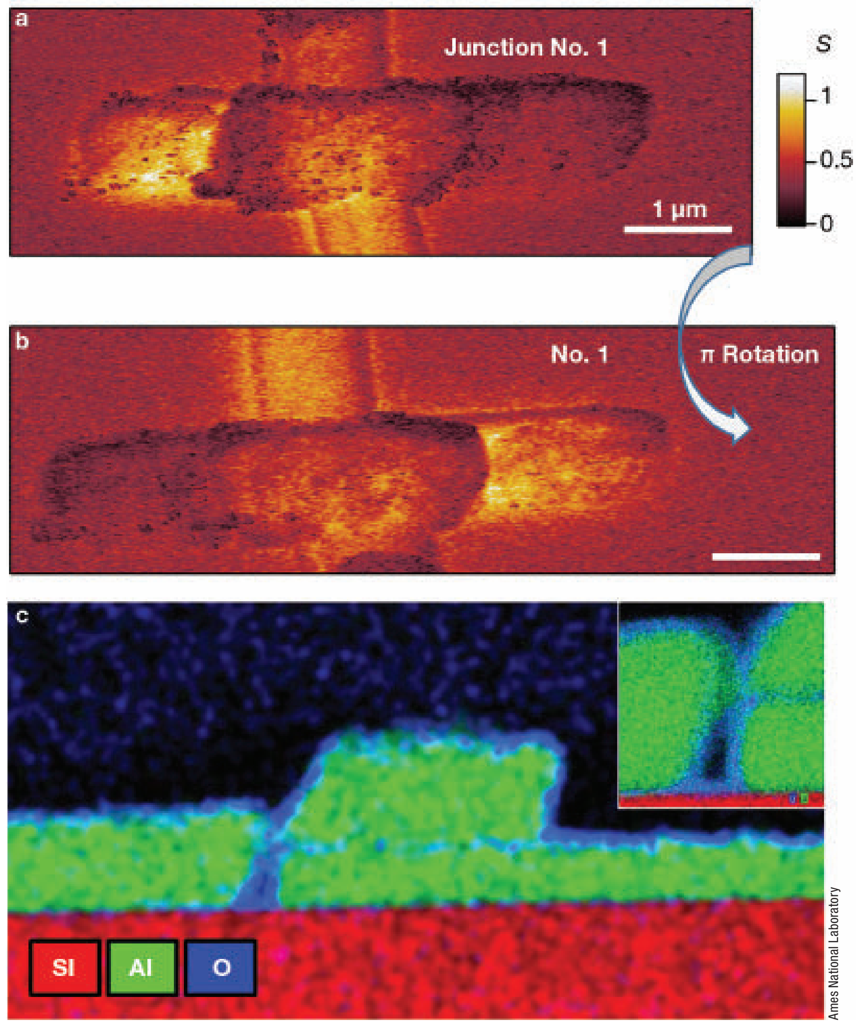
Shimadzu is addressing the bottleneck with an FTIR microscope that can be used to obtain measurements as small as 10- × 10-µm spots, using its 15× aperture and Raman objectives that enable measurements of 3-µm spots on samples. This aperture supports the focus on small locations. Traditional FTIR benchtop systems require larger samples, close to 3 to 5 mm.

Additional limiting factors for FTIR microscopy include the slowness of mapping and low resolution, when compared with visible light optical microscopy, confocal Raman, and electron microscopy. According to Li, full-field detectors could support a viable solution, because these components enable faster mapping. And users can also improve resolutions with nano-IR, optical photothermal infrared spectroscopy, and atomic force microscope-IR spectroscopy, Li said.

In addition to QCL sources and wide-field imagers, systems designers are also incorporating AI and/or machine learning elements with FTIR microscopy. Often, this enhancement is introduced to customize post-processing results in FTIR microscopy. Vial cited the example of AI automatically producing a report on microplastics that details which microplastics are present in samples and quantifying them.

But AI's confidence metrics are much more complex than those in conventional systems, for which the common library matching confidence metric is the overlap of sample and reference spectra as calculated with an inner product, Li said.

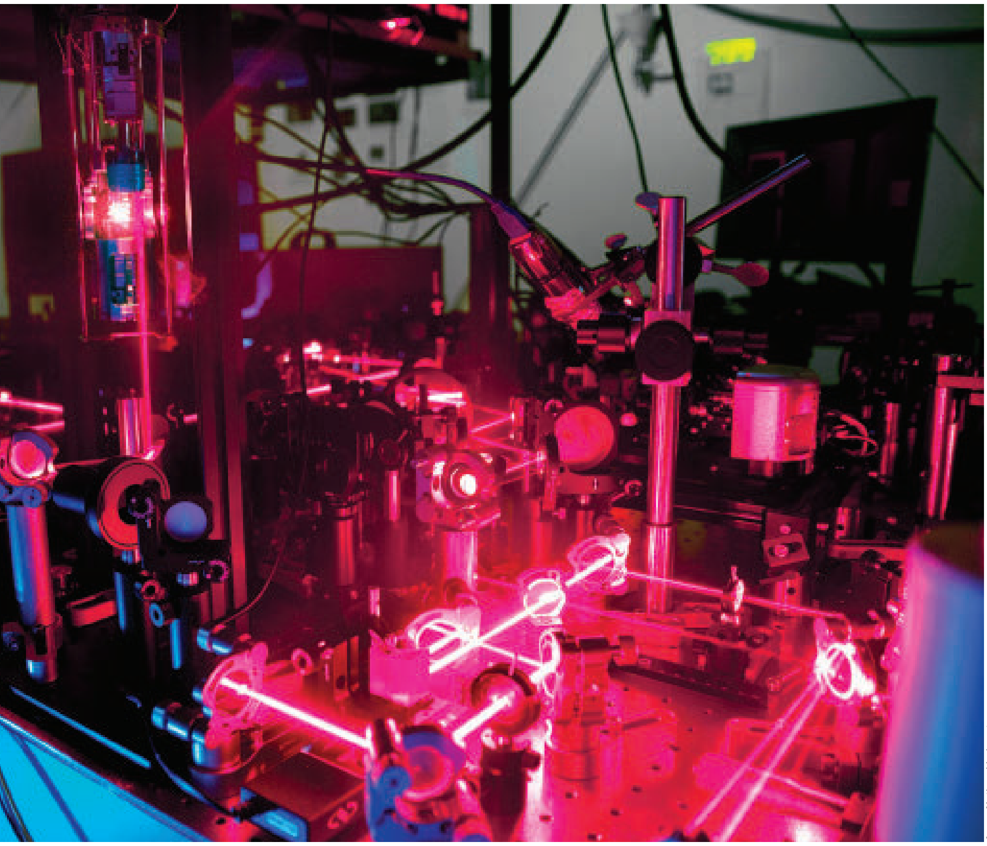
"Ultimately, to assess accuracy, what we would want to know is the rate of true positive matches, false positives, true negatives, and false negatives, and the efficacy of confidence or matching metrics in each of those scenarios," Li said.




This terahertz scanning near-field optical microscope (SNOM) image of representative terahertz near-field images of nano-dipole fields across Josephson junction structures indicates a connectivity issue by showing electrical field concentration and asymmetry. See Reference 3. Al: aluminum; O: oxide; s: scattering amplitude; Si: silicon.

## Advancing SWIR use cases

Anti-counterfeiting for high-security and luxury items is another application for IR microscopy. This application has com-



Ames National Laboratory

Ames National Laboratory scientists' terahertz scanning near-field optical microscope (SNOM) enables measurements of frequency-dependent dielectric and conductivity responses, with sub-20-nm resolution and 100-fs time resolution at 0.1 to 3 THz frequency, operating at 1.8 K and under a magnetic field of 5 T.

manded increased attention from institutions that handle and process these items as well as solution providers and members of the R&D community.

At the Institut national de la recherche scientifique (INRS) in Québec City, researchers developed a shortwave infrared (SWIR) imaging technique capable of capturing the photoluminescence lifetimes of rare-earth doped nanoparticles at the microsecond timescale. The technique combines wide-field SWIR microscopy and a SWIR all-optical streak camera. It uses a 980-nm pulsed laser to excite rare-earth-doped nanoparticles and detect the SWIR emission.

Jinyang Liang, an INRS associate professor, said that the developed camera solution, called SWIR photoluminescence lifetime imaging microscopy using an all-optical streak camera (SWIR-PLIMASC), could be used by instrumentation companies for fast, efficient, and affordable lifetime mapping for general purpose material characterization. It could also be used for the analysis of a material's dynamic optical properties or structural changes, and the energy transfer process between two materials.

The anti-counterfeiting potential that the solution offers builds on that of traditional IR-based solutions. Traditionally, IR sensors have been used to detect the spectral range emissions of rare-earth-doped nanoparticles, which are easy to counterfeit. In contrast, the developed method focuses not only on the "invisible" emission but also on the signature extracted from the measurement of transient photoluminescence intensity decay.

## Illuminating the ultraviolet

Manufacturers in the semiconductor industry use UV spectroscopy for mapping devices and wafers to capture latent defects and optimize process control. This application is increasingly important with the proliferation of silicon carbide and gallium nitride devices. UV spectroscopy is used to study the layers of heterostructures for high-power devices in electric vehicles (EVs) and EV chargers as well as high-frequency devices for the 5G network, according to Rick Lytel, CEO of Klar Scientific in Pullman, Wash.

Klar has developed a spectroscopic mapping microscope that performs deep-UV (DUV) scanning to capture features in nearly every layer of a heterostructure. It is based on Klar's confocal mapping microscopy solution that was developed for visible and near-infrared (NIR) photoluminescence applications. Early adopters of the technology focused on ultrawide bandgap materials, such as the semiconductor material gallium oxide. Subsequent uses of the instrument have involved making photoluminescence scans of regions of interest, followed by making Raman scans of specific subregions to reveal interesting features and anomalies.

The scanning method is multimodal, and for its solution, Klar uses modular optical plug-and-play kits to enable a rapid switchover from photoluminescence to Raman, or to another photoluminescence wavelength. "One client combined the Klar maps with information gleaned from scanning electron microscopy to overlay the maps and identify the source of material damage," Lytel said.

Capturing mapping is still a challenge in using UV solutions for failure analysis. High-resolution UV mapping over portions of wafers is achievable with Klar's system, though high-resolution maps for entire wafers and deeper-UV excitations are more challenging to achieve, Lytel said.

A current trend involves UV light sources beyond the traditional UV LEDs enhancing microspectroscopy in the DUV and NIR ranges. CRAIC Technologies, of San Dimas, Calif., has introduced an advanced illumination system from 200 to 2500 nm for both reflectance and transmission microspectroscopy and imaging. According to company president Paul Martin, one interesting application for the company's microspectrometers is the characterization of nanostructures for which photon interactions are based on structural rather than chemical properties. One study involved metallic nanostructures with potential applications for color displays, data storage, and anti-counterfeiting technologies[1]. Another involved plasmonic metasurfaces with potential for use in digital displays and color printing[2].

### Terahertz in the quantum realm

In the high-throughput screening of quantum circuit components, terahertz microscopy is proving to be essential, as the method is operatational at very low cryogenic temperatures. In partnership with the U.S. Department of Energy's Superconducting Quantum Materials and Systems Center, scientists at Ames National Laboratory developed a terahertz scanning near-field optical microscope (SNOM) that measures frequency-dependent dielectric and conductivity responses. The microscope achieves sub-20-nm resolution and 100-fs time resolution at 0.1 to 3 THz frequency, operating at 1.8 K and under a magnetic field of 5 T. It can operate at sub-liquid helium temperatures and under a high magnetic field.

"There is no commercial SNOM instrument in the market operated at liquid helium temperature," said Jigang Wang, an Ames Lab scientist and professor of physics and astronomy at Iowa State University.

Quantum computers process information at speeds faster than conventional computers because qubits can simultaneously exist as 0 and 1 quantum states, whereas bits can only exist as one or the other. The ability of qubits to exist in their quantum state is enabled through the Josephson junction, which controls the supercurrent flow through the circuit. This flow must be at cryogenic temperatures and remain uniform and non-dissipative.

Using the cryogenic terahertz microscope, Ames researchers discovered a defective boundary in the Josephson junction that caused conductivity disruptions and impeded quantum computation-dependent long coherences times. "By taking advantage of single- [and] few-cycle terahertz pulses, terahertz SNOM provides a noninvasive and nearly contactless way to probe the low-frequency conductivity of materials at the nanoscale and with sub-picosecond temporal resolution simultaneously," Wang said.

"In comparison to IR microscopy, the low-frequency terahertz region is ideal for assessing the fundamental low-energy conductivity and resonance toward zero frequency associated with diverse collective modes in exotic topological states and superconductivity in condensed-matter systems."

jschlett180@gmail.com

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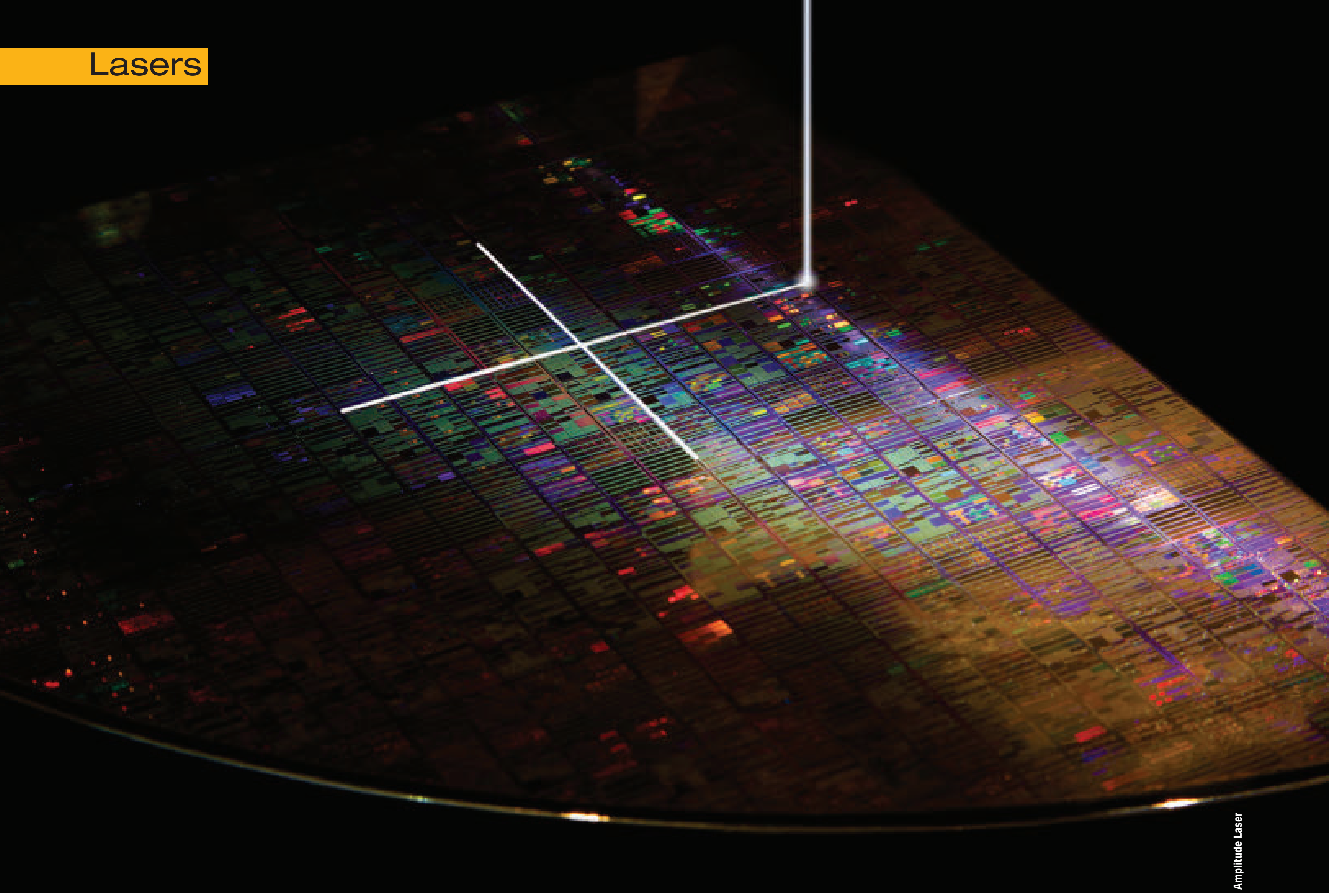



# Microprocessing
## Is Ready for More

The EPIC Technology Meeting on Laser Microprocessing demonstrated the maturity of technological building blocks for microprocessing with ultrashort-pulse lasers.

BY ANDREAS THOSS
CONTRIBUTING EDITOR

Laser microprocessing has been on the rise for decades. While technological roadblocks have influenced this progression, a close look at these roadblocks reveals that each has advanced to maturity. Productivity is key, and laser sources, scanners, and systems technology have made extensive progress; they are already used in large-scale applications, and much more growth is expected.

## Laser sources and scanners

In the 1990s, scientists found that laser pulses in the pico- and femtosecond regime could be used to cut and drill almost any material with significantly reduced heat-affected zones and smoother walls compared with nanosecond pulses. Evidently, these ultrashort pulses (USPs) were well suited for drilling submillimeter holes and/or micro-structuring surfaces.

During the following 20 years, application research refined this scientific result and defined a process window for USP laser processing (i.e., which pulse energies provided the highest ablation efficiency). The researchers found that for efficient processing, the pulse energy (in fact, it is the intensity) cannot be scaled to infinity. Simplified, the pulse duration should be below a picosecond, with pulse energies in the tens of microjoules range for small spots. Repetition rates can be set up to megahertz or even gigahertz, and pulse trains can improve the effectiveness of these pulses.

As some scientists would say, "The rest is just engineering." But it was not that easy. It took substantial inventions and countless feats of engineering to transform USP lasers from fragile lab instruments into rugged systems in OEM enclosures suitable for around-the-clock manufacturing processes.

These workhorses have been in the field for about a decade, running 24/7 without degradation in performance. At the European Photonics Industry Consortium (EPIC) Meeting on Laser Microprocessing in Vilnius, Lithuania, (read more on page 96), Martynas Barkauskas, CEO of Light Conversion, demonstrated how reliable today's sources have become when he shared performance data from some of the systems that Light Conversion has tracked in the field. These systems have essentially remained constant during 14 years of continuous operation. The company specifies more than 3 years' mean time between failures for its systems.

With uptime no longer posing a problem, source manufacturers explored several ways toward achieving increased productivity from their systems. One method is to look for higher repetition rates, improving systems toward megahertz or gigahertz rates. Scanners were not designed for such speeds and have become a bottleneck. These source manufacturers also have looked to short bursts to increase the throughput: In response, several have developed burst mode controls and looked for higher pulse energy. While physics limits the reasonable intensity to ~7× the ablation threshold, a higher pulse energy can be exploited for parallel processing with multibeam optics or processes with tailor-made beam shapes, such as Bessel beams.

All of these developments are ready for industrial production. For example, pulse triggering for bursts and varying pulse distances for curved shapes were already reported in 2023[1]. Improvements with

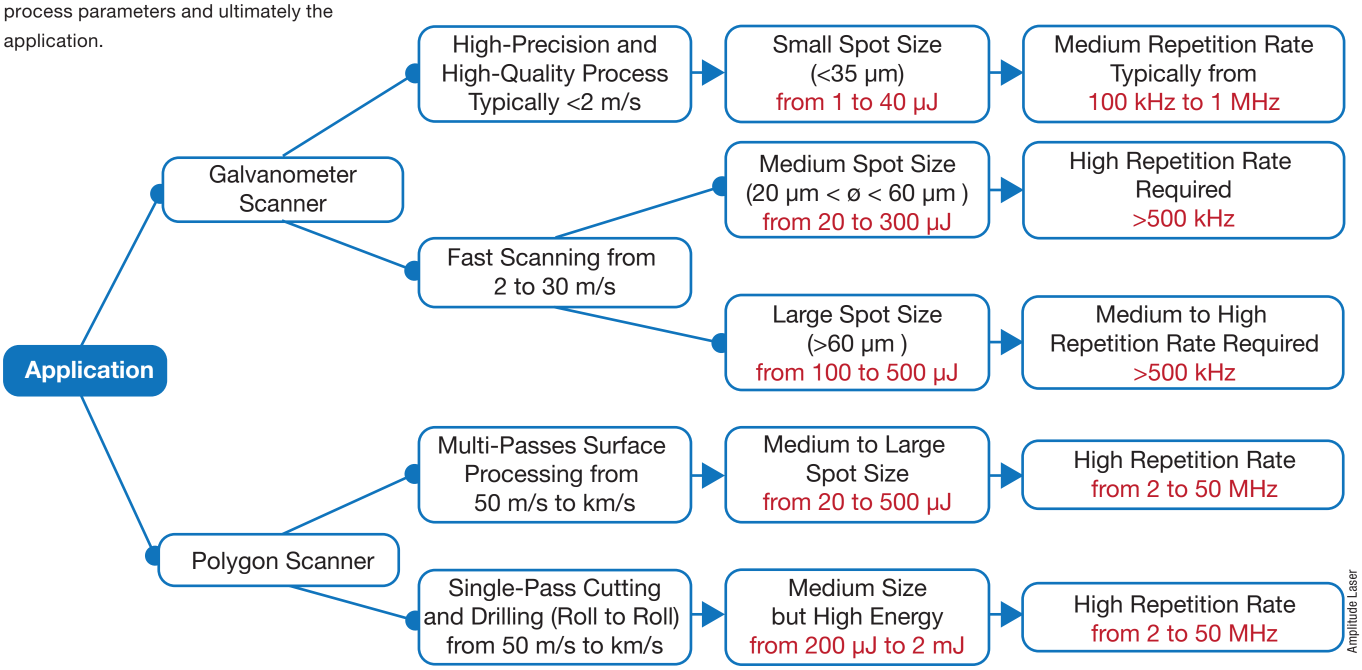



**Figure 1.** Combining advanced beam steering and an ultrafast laser. Choosing the right scanning technology depends on the process parameters and ultimately the application.

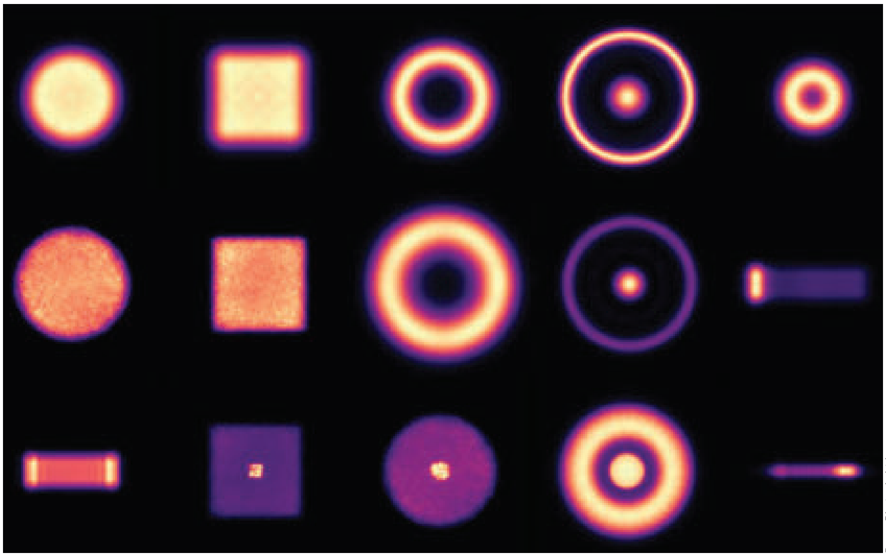



**Figure 2.** Modern optics can create almost every beam profile needed, in almost any shape and configuration.

scanners and multibeam optics are also underway.

## Numbers for context

Now, how do these developments contribute to throughput? Consider the values presented by Mantvydas Jasinskas, chief science officer of EKSPLA. In application tests on aluminum oxide ceramics, he demonstrated that EKSPLA ablated 6.4 $mm^3$/min with single pulses. With a single 92-pulse gigahertz burst, the scientists moved 10.4 $mm^3$/min. And with a megahertz sequence of single pulses, they still achieved 5.2 $mm^3$/min and 52.1 $mm^3$/min with a gigahertz burst in megahertz sequences.

This rate further increases with back-side ablation, in which the laser shines through glass and its focus moves upward. For this bottom-up milling approach, Jasinskas showed ablation rates of 619.5 $mm^3$/min (using a 2-MHz laser with 24-GHz bursts) in a soda-lime glass.

What about more power? Vincent Rouffiange, vice president, strategic business development director at Amplitude Laser, showed the evolution of the company's lasers to 1 kW and beyond. With each more powerful source, he said, people thought no one would ever need such lasers. But the experience that Amplitude found in the market is different. As a result, the company has increased the source power during the last several years. Time and cost arguments are behind this decision. Rouffiange estimated that processing time (T) relates to the source power P by $T \sim 1/P^2$.

All of this is to say that, apparently, source power does matter. Rouffiange expects that a 1-kW USP laser will arrive below €1000 per Watt. Considering the participants of the EPIC workshop and market research, it seems that regular USP laser sources with output powers between 10 and 300 W are standard off-the-shelf products. A few companies offer sources with ~1-kW output power, but these are either marketed as prototypes or sell in low numbers.

Aside from higher power, laser source providers are expanding to other wavelengths, such as UV (343 nm) or deep-UV (257 nm). These systems are available with reasonable lifetimes. Light Conversion, for example, specifies a 50-W UV source with a lifetime of 10,000 h or one year. Scanner solutions for these wavelengths were discussed at the EPIC workshop. It does not seem trivial today to change a complete scanner solution to accommodate UV optics.

## Scanners keep pace

Ablation with USP lasers is still measured in cubic millimeters per minute. For obvious reasons, it is paramount to increase the productivity of USP laser-based microprocessing. As the optimization of laser sources has been a prime area of focus, scanning technology is the logical subsequent roadblock to obtaining more throughput. Scanners must move faster for lasers with higher repetition rates. Otherwise, pulses will overlap, which would not necessarily increase throughput.

Amplitude's Rouffiange said that galvanometer scanners are now available with scanning speeds of up to 30 m/s, whereas a polygon scan head can reach up to 1000 m/s. In combination, both systems can serve in an industrial roll-to-roll solution with up to several meters per second throughput.

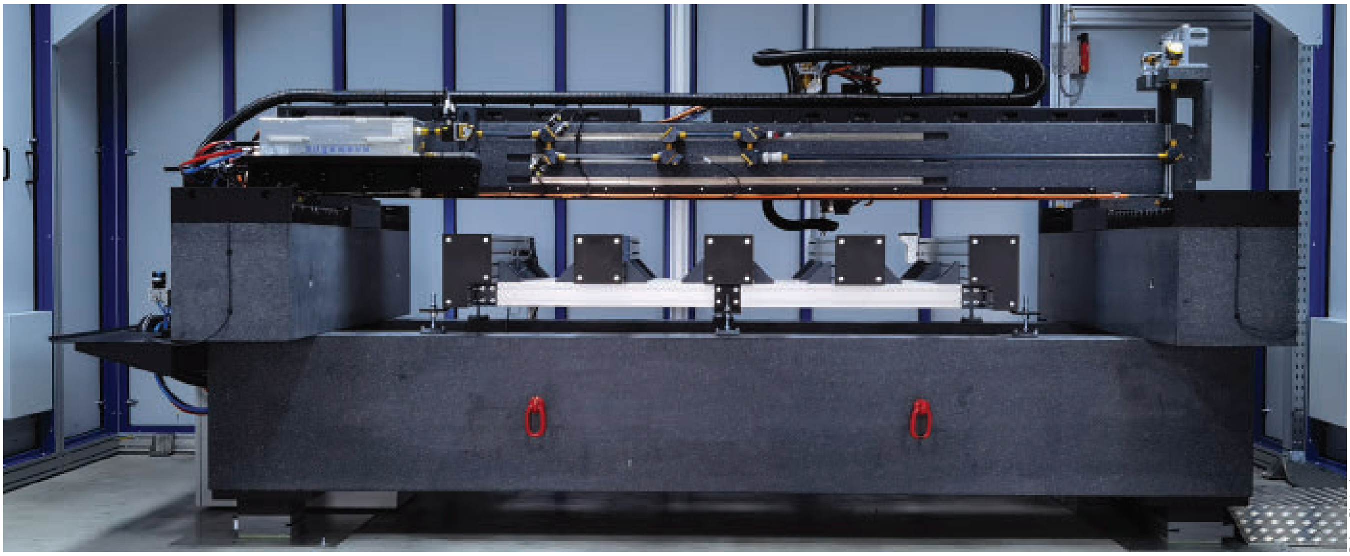
Selecting the appropriate scanner technology heavily depends on the applied process parameters — namely, repetition rate, pulse energy, and spot size. Each of these parameters depends on the application, Rouffiange said (Figure 1).

On the other hand, scanners can be adapted to new wavelengths, as required for the respective beam sources. This adaptation can be far from trivial, according to Holger Schlüter, head of business development at SCANLAB GmbH. First, USP lasers require the use of fused silica as an optical material. Fused silica experiences a strong change of index ($dn/d\lambda$) in the UV, which makes color correction of the f-theta lens for wide-bandwidth pulses difficult. SCANLAB, for example, succeeded with an optimized lens design and a high-performance UV coating for this purpose.

## Special optics make special beams

In the early days of materials processing, technology pioneers took laser sources with a defined beam profile and determined the tasks that they could accomplish. Today, this has changed completely: The application requirements define how the laser beam should look to realize the highest throughput. This is as true for laser macroprocessing as it is for microprocessing. And it is especially true for the shape of the beam profile. Fortunately, laser beams can be transformed into almost every shape (as Persephone Poulton, product development engineer from PowerPhotonic, showed (Figure 2)).

Behind such nice beam profiles is the consideration that a laser beam is a spatially distributed electromagnetic wave. Careful manipulation of the spatial and temporal phase of the laser beam leads to



Pulsar Photonics

**Figure 3.** Pulsar Photonics combined multibeam technology with a multi-gantry system and offers industrial machines that are capable of processing large volumes >10,000 cubic mm **(above)**.


Robert Bosch Manufacturing Solutions GmbH

**Figure 4.** Bosch Manufacturing Solutions (BMG) develops machines, including for multistage hybrid laser microprocessing of microelectromechanical systems (MEMS) **(right)**. The company's activities focus on laser welding, structuring, drilling, cleaning, marking, and fine cutting.

such profiles and to many more effects. A lens functions as a simple beam shaper, and more sophisticated beam shapers may use a micro-optical lens array to, for example, turn a Gaussian beam profile into a thin horizontal line expanding over 1 m.

Even more advanced systems, such as the one presented in Vilnius by Gwenn Pallier, product line manager at Cailabs, use reflective optics to create a Bessel beam, a very specific 3D beam profile with an extended focal length. While all of these optics are fixed, Lars Eng, CEO of Silicon Light Machines, presented a dynamic solution for phase manipulation. Silicon Light Machine's solution uses a microelectromechanical systems (MEMS) chip for spatial light modulation.

## Upscaling in process

Spatial phase modulation can be taken much further. It can turn one beam into a beam profile composed of many similar beams. This is a game-changing advancement because these beams can be used in parallel.

The multibeam optics concept was developed at the Fraunhofer Institute for Laser Technology ILT (Fraunhofer ILT) and commercialized by its spinoff Pulsar Photonics. The company applies the multibeam optics in conjunction with multi-scanner or multi-gantry systems (Figure 3). Pulsar Photonics was acquired by the materials and machinery expert Schunk Group in 2022, and now has more than 100 employees. Pulsar, a systems integrator, focuses on upscaling laser processes regarding processing time and area.

Multibeam optics can come in different shapes: Liquid crystal modulators or MEMS, for example, enable dynamic beam shaping, and diffractive optical elements (DOEs) achieve this in a static way. DOEs change the phase of the incoming beam by turning one beam into an array of hundreds, for example. In 2019, the Fraunhofer ILT researchers demonstrated a solution to drill 12,000 holes/s at micrometer precision using such beam-shaping optics.

Tim Kunze, CEO and cofounder of

Fusion Bionic, showed a method for upscaling that goes deeper into application: Fusion Bionic's machine uses interference fringes for texturing surfaces. This allows for pulse energies into the millijoule regime. Direct laser interference patterning is the company's core technology, and it is well suited for making periodic patterns on extended square meter surface areas for the creation of so-called functionalized surfaces. Kunze also showed the solution for surface cleaning, though there may be a cheaper solution for this use case.

Lidrotec is pioneering an exotic and promising process. The company's director of business development and sales, Christian Keil, introduced EPIC's Vilnius audience to the company's laser system that is designed to dice semiconductor wafers — a technology that brings the company into a huge and growing market. The solution performs the dicing through a thin layer of a nontoxic, transparent, low-viscosity liquid. Keil did not identify this fluid, but it is evident that such a solution could solve several problems currently associated with wafer dicing, including micro-cracks, debris, burrs, and more. Keil confirmed the company's use of USP lasers. A pilot is running on Lidrotec's premises, with a first machine delivery to a pilot customer planned for this year.

### Where is the beef?

The proof of the pudding is in the eating. And similarly, the proof of the innovative technology that is behind this upscaling is in the application. This is not obvious and simple for USP laser microprocessing. The supply chain in this field usually consists of various component providers, systems integrators, and some big players — all of which tend to walk their own way.

In Vilnius, laser makers such as Amplitude, Light Conversion, EKSPLA, and ams Technologies (distinguished from ams OSRAM) showed that they are ready to serve any application needs. These companies can provide plenty of application examples. They include aluminum sorting based on laser-induced breakdown spectroscopy (neoLASE/ams Technologies); through-glass-via drilling (Fluence); marking and welding of aluminum (PowerPhotonic); dielectric material milling and drilling (EKSLPA); stent cutting, polishing, and periodic surface structuring (Light Conversion); and surface texturing and electrical vehicle electrode cutting (Amplitude, Light Conversion, among others).

This list is an ad hoc collection of samples; it neither aspires to name all applications, nor can it mention all providers of the respective technology. Many of the companies participate in collaborative projects to strengthen the technology, which Rouffiange showed.

The systems integrators are a bit more specific in their application reports. Etienne Pelletier, laser applications engineer at Oxford Lasers Ltd., spoke about laser micro-welding of transparent and opaque materials, such as glass and metal. 3D-Micromac was certainly one of the larger systems integrators in the room in Vilnius, with more than 600 machine installations worldwide, and Pelletier listed a range of applications that it serves. Currently, 3D-Micromac, he said, has more than 50 systems deployed in the semiconductor industry: at least 30 systems in micro-diagnostics, more than 110 systems in photovoltaics, and more than 30 systems in roll-to-roll production.

3D-Micromac has an additional 150-plus systems in glass and display — and its department head for technology and innovation services, Thomas Gester, gave an introduction into laser glass processing. This can be performed on the top of the material, from the bottom, or in the bulk material. The examples referred to sophisticated microprocessing tasks rather than those for consumer products.

Martin Reininghaus, program manager at Pulsar Photonics, then reported on applications in tooling, embossing, and the semiconductor industry. Pulsar's latest machines process work pieces of 1 sq m with processing volumes beyond 10,000 cubic mm (Figure 3).

And then there was Andreas Russ from Bosch Manufacturing Solutions (BMG), a 100% subsidiary of the Bosch group. BMG is a turnkey special machinery provider for production equipment and automation. The company serves large industries such as automotive, energy, and consumer goods.

With a workforce of 1900 (including 42 laser experts) in nine locations, BMG has more than 4000 assembly and testing systems in the field. BMG's laser activities focus on welding, structuring, drilling, cleaning, marking, and fine cutting (Figure 4). Projects that have reached milestones with USP lasers have involved precision drilling in diesel and gasoline injection systems. For gasoline direct injection systems, the machines have tolerances of a few micrometers and produce more than 250 million holes per year. The machines are highly automated with high-quality requirements and 100% traceability. They offer fully automated laser monitoring as well as an automated calibration portfolio.

In addition to this well-known automotive application, Russ discussed projects from the semiconductor industry. Bosch Manufacturing tested a two-laser multi-step ablation system for silicon wafers. The effective ablation rate was >0.5 mm³/s, reaching a surface roughness of <0.5 µm.

## In summary

It is safe to say that most aspects of the technology for laser microprocessing are mature. Currently, interesting ideas are entering the market at a beneficial pace, and certain ideas offer scaling opportunities for higher throughputs and extended workpiece areas.

As for what is on the way, applications such as precision tool making and semiconductor or glass processing are coming. The rapid growth of several players gives rise to the assumption that this field is prospering and that there is more to expect.

th@thoss-media.de

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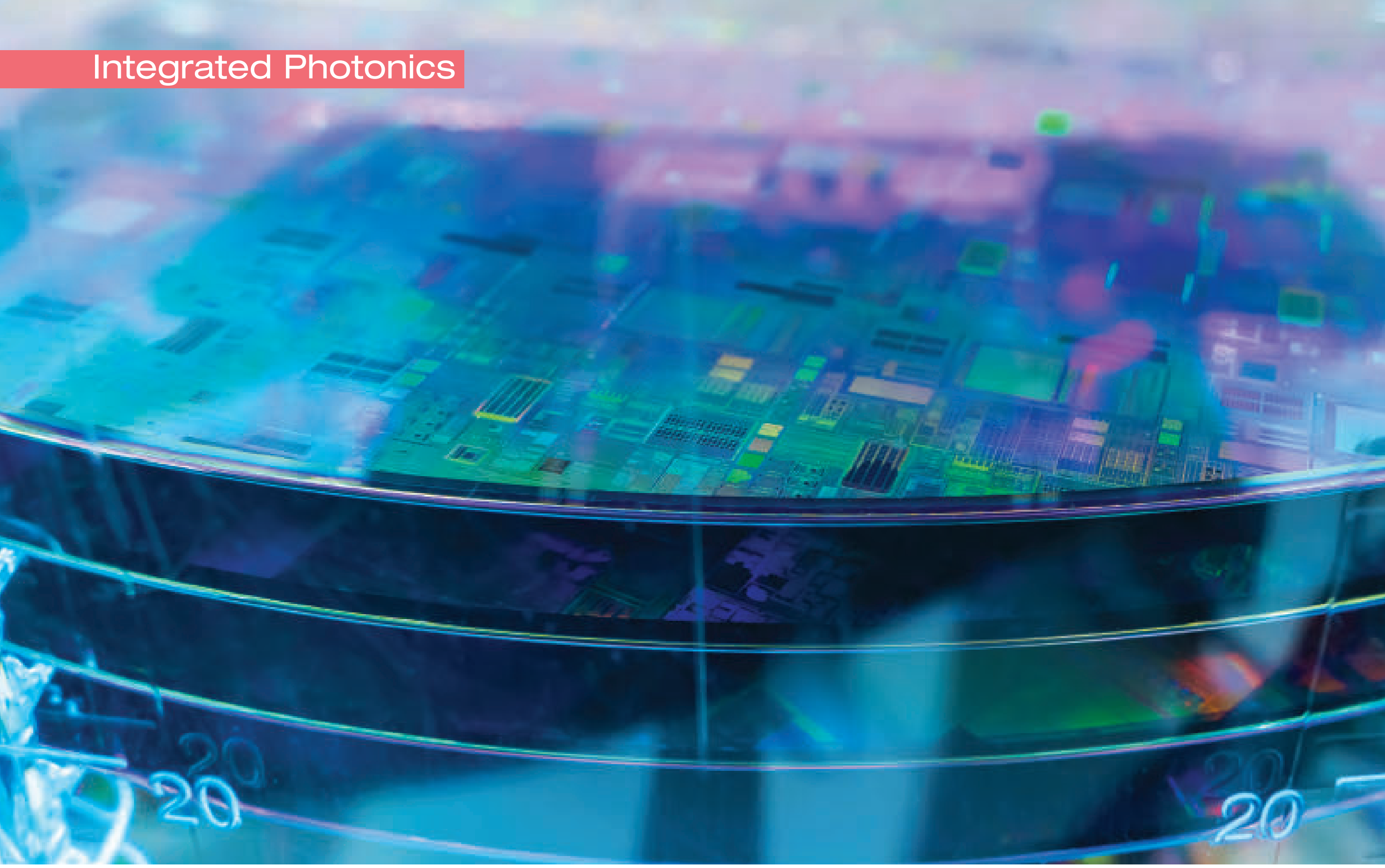

# Illuminating the Future:

## Navigating the Integrated Photonics Industry and Supply Chain

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## The growth trajectory of integrated photonics technologies necessitates a robust supply chain to support multiple materials platforms as well as design, manufacture, and test requirements.

BY ABDUL RAHIM, PHOTONDELTA, AND FAISAL KAMRAN SONY EUROPE BV

The integration of photonic devices at the wafer scale has emerged as a transformative force, offering a reliable and scalable pathway to implement complex photonic functions cost-effectively on a chip. While integrated photonics has long been synonymous with optical communications, today's landscape presents unprecedented challenges and opportunities — including those that fall outside the bounds of traditional optical telecommunications and data communications. As data volumes surge across growth sectors, the industry faces mounting pressure to deliver faster, more energy-efficient solutions and continuously improve the price-performance ratio.

The scale of this transformation is remarkable: Millions of transceivers now form the backbone of our digital infrastructure, providing high-speed optical connectivity across virtually every layer of the optical communications network. With data growth showing no signs of abating, the deployment of optical ports and integrated photonic transceivers continues to accelerate.

A recent European Conference on Optical Communication (ECOC, 2024) offered compelling insights into how the integrated photonics industry is adapting to meet the explosive traffic growth driven by AI and cloud services. The development of 100-GHz analog bandwidth electro-absorption modulated lasers, breakthroughs in thin-film lithium niobate (Mach-Zehnder) modulators, and the development of the first 200-GBd coherent driver modulator are among the latest solutions showcased by industry leaders. The availability of 800-Gbps transceivers and steady progress toward 1.6-Tbps capabilities further signal the industry's relentless push forward. These advancements, coupled with innovations in pluggable transceiver form factors and the scaling feasibility serializer/deserializer (SERDES) to 400 Gbps, demonstrate the field's upward trajectory. Similarly significant are the energy savings promised by co-packaged optics — though challenges persist in reliability, serviceability, and testability — as well as the potential energy efficiency gains enabled through linear-drive technology.

### Call it 'silicon's second revolution'

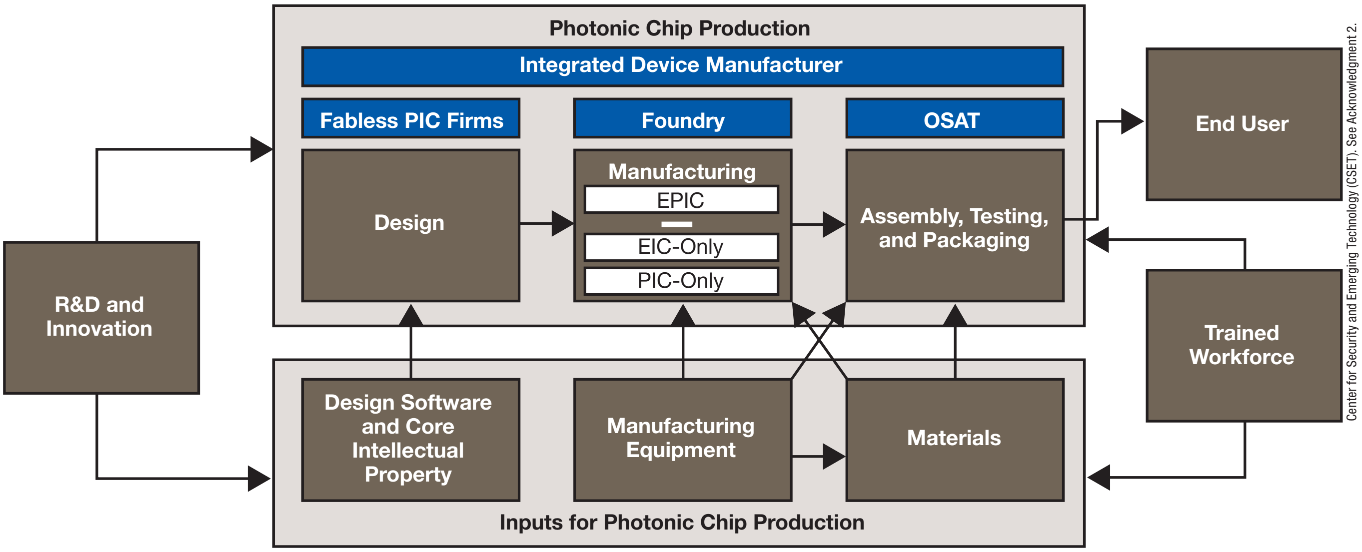
What sets the current moment apart from those that have come before is the renewed appeal of integrated photonics for chip-scale optical connectivity. For the microelectronics sector, integrated photonics — and particularly silicon photonics — represents more than just another technology. Rather, it is an extension of silicon's vast potential. This convergence enables the seamless integration of optoelectronic functionality with existing silicon capabilities, from logic to high-bandwidth memory and specialized features, to create powerful solutions for AI applications.

### Vision to reality: The foundational years

The journey of integrated photonics traces back to a pivotal moment in 1969 when Stewart Miller shared his visionary perspective in the *Bell System Technical Journal*. Coinciding with Enrique Marcatili's groundbreaking demonstration of an on-chip waveguide and directional coupler, Miller's work — and the early days of the technology — were marked by a methodical quest to identify ideal material systems for photonic integration. Researchers meticulously evaluated various materials against a comprehensive set of criteria: their transparency window, potential for electronics integration, fabrication feasibility, and capability to perform both active and passive photonic functions.

This wave of exploration prompted intensive investigation of several promising material systems. Compound semiconductors such as indium phosphide (InP) and gallium arsenide, ferroelectrics such as lithium niobate, and various dielectrics underwent rigorous testing as researchers worked to demonstrate fundamental building blocks that would pave the way for more sophisticated photonic functions on-chip. A significant milestone emerged in 1975 with one of the first demonstrations of monolithic electronic-photonic integration.

By the late 1980s, the landscape of what would become today's mainstream PIC platforms — InP and silicon photonics (both silicon-on-insulator (SOI) and silicon-nitride-on-insulator (SiN-on-insulator) — began to take shape. InP's advanced position on the technology




The photonic integrated circuits (PICs) production framework illustrates the interconnected ecosystem of design, manufacturing, assembly, and end user applications. Key stakeholders include fabless PIC firms, integrated device manufacturers (IDMs), foundries, and outsourced semiconductor assembly and test (OSAT) providers, supported by essential inputs including materials, equipment, and workforce. Original electronic integrated circuit (EIC) foundries are engaging with silicon photonics to increase wafer throughput. Some have developed capabilities to integrate both into electronic-photonic integrated circuits (EPICs). See Acknowledgment 2.

maturity curve culminated in a breakthrough: the first photonic integrated circuit (PIC) combining a laser and modulator in 1987. Another crucial development, the demonstration of a low-loss SiN waveguide, occurred in the same year and expanded the material possibilities for integrated photonics.

### The rise of commercial platforms

The integrated photonics narrative took an interesting turn in 1985, when Richard Soref proposed the use of silicon as a material for integrated photonics through demonstrations of waveguides and switches on highly doped silicon substrates. Soref's proposal was a major disruption: Compound semiconductors' relatively mature position enabled rapid advancement in integrated functionalities, despite the fact that silicon was a newcomer to the realm of photonic integration.

In the dot-com era, photonic integration positioned itself as a cornerstone technology for telecommunications applications. InP PICs led the commercial charge, enabling the integration of tens of photonic components on a single chip. Meanwhile, SOI- and SiN-on-insulator-based silicon photonics, though still primarily in research phases, were making steady progress toward industry implications. This period culminated in the late 1990s with the emergence of early-iteration SOI PICs and Bookham Technology's pioneering launch of the first silicon photonics product, in 1998.

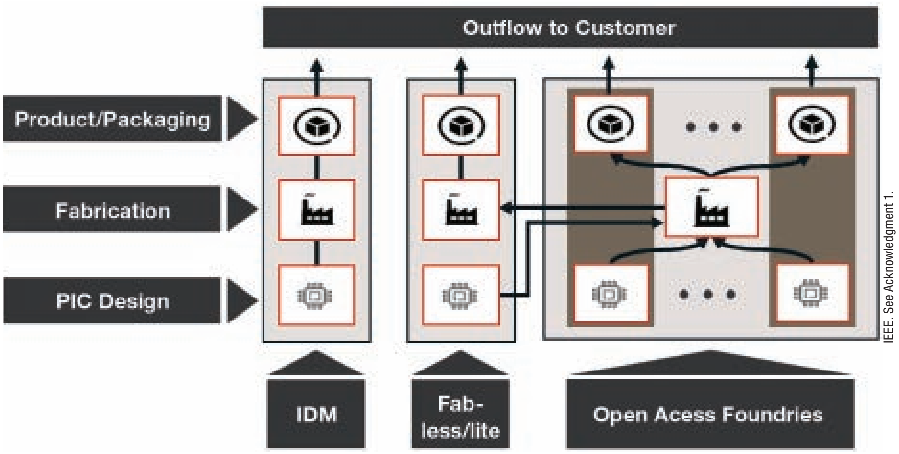
A fascinating divergence in development paths would characterize the post-dot-com era. InP PICs continued their steady march forward, enhancing both building block performance and scaling densities. Vertically integrated InP PIC companies strengthened their market position, delivering increasingly sophisticated solutions tailored to telecommunications and data communications demands.

At the same time, silicon photonics underwent its own transformation, marked by the pivot from thick SOI (with silicon guiding layers of a few micrometers) to thin SOI, featuring submicron silicon guiding layers. This shift enabled the development of silicon photonics building blocks on larger 200-mm substrates using established CMOS process tool sets. This transition to thin SOI enabled integrated device manufacturers (IDMs), fabless companies, research centers, and academic institutes to begin development of fundamental building blocks using a range of approaches. While thick SOI technologies maintain their relevance for R&D and certain commercial applications, this transition catalyzed widespread innovation in the technology space.

### Democratization of photonic integration

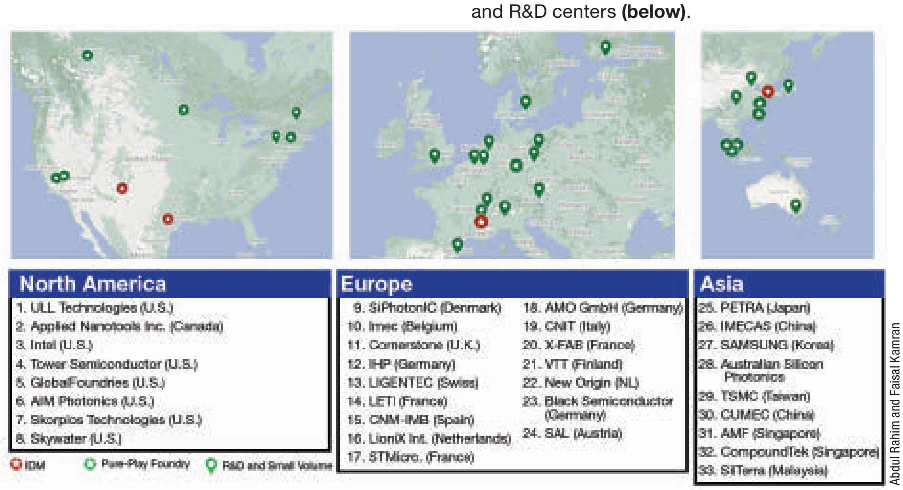
Spurred by the advent of thin SOI, the efforts of engineers and manufacturers yielded impressive results, including low-loss passive devices, high-speed modulators, and advanced detectors. These developments laid the groundwork for significant commercial milestones, with Luxtera (since acquired by Cisco) launching commercial thin SOI silicon photonics products around 2007. Breakthrough products from Acacia Communications (Cisco) and Intel followed, and SiN PICs continued to evolve, though primarily within university laboratories.

Critically throughout this period, each material platform continued to strengthen its unique attributes and chart its own course. InP PICs distinguished themselves through fully monolithic integration of high-performance photonic functions spanning light generation and processing to detection. Silicon photonics on SOI substrates leveraged existing CMOS infrastructure and process tool sets, combining compact form factors with dense integration capabilities. The




Access models for photonic integrated circuit (PIC) manufacturing depict the transition from vertically integrated device manufacturers (IDMs) to more collaborative models such as fabless/fab-lite and open-access foundries **(left)**. Fabless/fab-lite models either completely outsource manufacturing or keep application-specific in-house manufacturing while outsourcing the rest. Open-access foundries leverage economies of scale, standardization, and ecosystem-wide innovations.

The silicon photonics foundry landscape. Established and emerging silicon-on-insulator (SOI) and silicon nitride (SiN) processes are currently available with commercial foundries and R&D centers **(below)**.




SiN variant carved its own niche by offering superior passive device performance and enabling applications beyond traditional telecommunications and data communications wavelength windows.

## The open access revolution

The earliest commercially available PIC technologies were the exclusive domain of IDMs or a select few fabless companies engaged in joint development programs with IDMs (or with research foundries). Academic institutions played a crucial role in this landscape, with university and research center cleanrooms serving as incubators for groundbreaking demonstrations. These so-called hero demonstrations set benchmarks across the board. Among the most innovative are Bell Labs' sophisticated 15 × 15 arrayed waveguide multiplexer on InP (1992); The National Centre for Scientific Research (CNRS)-University of Paris' SOI-based ring modulator (1997); MIT's ring resonator implementation (1999); Twente University's SiN biosensor (1999); Zhejiang University's silicon-based arrayed waveguide grating demonstration (2000); and Ghent University's use of deep-UV lithography for SOI waveguides in collaboration with imec (2002).

In 2005, integrated photonics adopted the first of what would become many concepts from the established microelectronics industry — specifically the decoupling of design and technology offerings. The adoption of open-access multi-project wafer runs democratized access to PIC technologies developed by research institutes, making them available to any third-party designer at an affordable price. This democratization unfolded through several key initiatives: ePIXnet in 2004 (which later split into ePIXfab and JePPIX), followed by Opsis in 2012, and programs through the Agency for Science, Technology and Research (A*STAR's) Institute of Microelectronics (IME), and Photonics Electronics Technology Research Association (PETRA). As the design community expanded, technology platforms began to standardize and mature, albeit in their own regional and technological silos. The initial development of passive and active building blocks has evolved into a sophisticated ecosystem.

## The ecosystem emerges

Today's integrated photonics landscape reflects this rich history of technological evolution and democratization. With a growing number of companies offering PICs-based solutions, a supply chain has begun to take shape. The convergence between integrated photonics and CMOS electronics supply chains has created opportunities and synergies, particularly as more materials, design, equipment, and packaging vendors from the CMOS microelectronics industry venture into integrated photonics technologies.

The evolution of integrated photonics from its conceptual beginnings in the Bell Labs era to this sophisticated ecosystem also tells a compelling story of technological persistence and innovation. The unprecedented demands of AI computation and the explosive growth in data center traffic have positioned integrated photonics as an enabler of communications as well as a fundamental solution to computing's most pressing challenges. The semiconductor industry's embrace of integrated photonics technologies, particularly as it moves toward a trillion-dollar milestone by 2030, marks a significant shift in the technology landscape.

Still, standardization must continue to provide access to mature routes, while democratization of integrated photonics technologies promises to accelerate innovation across multiple fronts. The industry's delivery of higher speeds, lower power consumption, and improved cost structures will be crucial to address the computational bottleneck that stands between us and the next wave of AI advancement.

### Elements of a supply chain

As integrated photonics matured from research-driven innovation into commercial adoption, its supply chain began to broadly mirror that of the microelectronics industry, especially in its blend of specialization with collaboration. The ecosystem now encompasses design/intellectual property (IP) houses, material suppliers, foundries, equipment vendors, and packaging providers. Each contributes to a cohesive pipeline that ensures the development of sophisticated PICs.

As it relates to PIC design, a modular dynamic, enveloping collaboration between photonic and electronic design houses, presented a great promise in aiding the optimization of circuit functionality. In the initial stages, PIC design relied on in-house tools tailored for specific projects. Today, advancements in electronic design automation (EDA) have ushered in sophisticated software solutions, enabling seamless PIC design. Major EDA vendors now integrate photonic design capabilities, facilitating the co-development of electronic and photonic circuits. Unified Electronic-Photonic Design Automation (EPDA) flows are emerging, too, enabling the optimization of electronic-photonic codesign and the optimization of building blocks through advanced physical-level simulation techniques. These include finite difference time domain, finite element method, and mode solving. As a result of photonic and electronic design houses collaborating in this way, comprehensive design stacks, incorporating pre-developed photonic IP blocks, continue to spread. This modular approach has broadly kickstarted innovation by enabling fabless companies and foundries to streamline development cycles.

In manufacturing, vertically integrated IDMs initially enjoyed dominance. This was particularly evident with InP technology. While IDMs remain key players, the ecosystem has evolved with the emergence of open-access foundries. European research institutes pioneered this shift, offering access to InP, SOI, and SiN platforms. Similar initiatives followed in the U.S. and Asia.

By 2014, commercial pure-play foundries had started to incorporate silicon photonics into their portfolios. And today, major microelectronics foundries offer open-access silicon photonics platforms. In SiN technology, the rise of boutique foundries for low-volume production, alongside larger players providing scalable 8-in. substrate processes, have spiked the prominence of this material platform. High-quality SiN processes often incorporate external partnerships to integrate active functions, enhancing performance and adaptability.

InP manufacturing predominantly relies on 2- to 4-in. wafers, but the growing demand for larger and more integrated

Abdul Rahim and Faisal Kamran

The present III-V PICs foundry landscape shows a limited number of pure-play fabs to balance a strong presence of integrated device manufacturers (IDMs).

PICs is driving a transition to 6-in. substrates. Meanwhile, silicon photonics benefits from mature 8-in. and 12-in. wafer platforms. Twelve-inch technologies offer superior uniformity and performance due to advanced process tool sets.

Design and simulation are not the only facets of the PICs ecosystem to borrow from the microelectronics industry. Integrated photonics heavily depends on the equipment and expertise of the microelectronics industry. Equipment vendors are tailoring existing tools to accommodate the unique requirements of PIC manufacturing, including the precise layering, etching, and lithography processes. As photonics continues to scale, these tailored solutions are ensuring the consistency and quality needed for high-volume production.

Packaging photonic chips presents a dynamic challenge; it requires solutions that address high-speed electronic interconnects, thermal management, and mechanical stability. The packaging landscape is diverse and fragmented, driven by the pressing need for cost-effective solutions. Recent innovations include the introduction of glass interposers, wafer-mounted interposers with detachable connectors, and advanced fiber attach techniques for specialized fiber arrays. Traditional gold box packaging has been a costly standard, and plastic packaging methods are now emerging, offering cost-effective alternatives without compromising functionality.

Electronic-photonic co-packaging is also gaining traction; large outsourced semiconductor assembly and test (OSAT) providers are investing in capabilities that bridge the two domains. Moonshot R&D projects aim to refine processes, such as wafer reconstruction and detachable optical connectors, while commercial entities are introducing assembly design kits (ADKs) to standardize packaging workflows. These ADKs enable designers to ensure compatibility between foundries and packaging houses, streamlining the production pipeline.

For its part, testing remains an integral — though underdeveloped — element of the integrated photonics supply chain. Unlike microelectronics, the industry lacks independent test houses, relying instead on in-house testing by fabs and packaging providers. Fortunately, wafer-level test tools now support the characterization of passive devices and low-to-high-speed active components. These tools are critical for maintaining quality control and ensuring that manufactured wafers meet stringent performance standards. The absence of independent test facilities highlights a potential area for growth as demand for PICs continues to rise.

### Demand drivers and future needs

The supply chain for integrated photonics reflects the industry's rapid evolution, mirroring the collaborative and innovation-driven nature of its microelectronics counterpart. From custom-built design tools to open-access foundries and modular packaging solutions, the ecosystem continues to mature, driven by advancements in materials, processes, and equipment.

As demand surges across telecommunications, health care, and AI-driven applications, the supply chain must overcome fragmentation and scale its capabilities. The convergence of photonics and electronics ecosystems signals a promising future in which integration and standardization will unlock the full potential of PICs to meet the challenges of a data-centric world.

The integrated photonics supply chain is increasingly shaped by surging demand for high-performance transceivers, particularly in data centers. These devices form the backbone of global digital infrastructure and enable high-speed, low-latency data transfer essential for AI workloads, cloud services, and modern telecommunications. PICs play a critical role, delivering unprecedented energy efficiency and scalability. With projections of 3.2-Tbps transceivers by 2026 and the ongoing adoption of co-packaged optics, the reliance on integrated photonics for next-generation data center operations continues to expand.

Beyond data centers, integrated photonics is pivotal in automotive/autonomous vehicles (lidar), health care (biosensors and optical imaging), and quantum computing, where precision and miniaturization are paramount. These applications not only drive innovation in photonic manufacturing but also underscore the need for a robust, scalable supply chain.

The supply chain must adapt to new challenges and opportunities as applications diversify. Standardizing interfaces for the heterogeneous integration of materials is a pressing need. The integration of mainstream PIC technologies, such as silicon photonics and InP, into cohesive systems will be essential for optimizing performance and reducing costs. Ubiquitous access to unified electronic-photonic design flows is of equal importance. Enabling unified workflows would streamline the codesign of photonic and electronic components, fostering greater collaboration across the ecosystem and accelerating time-to-market for new solutions.

The growing demand for integrated photonics reinforces the need for a seamless connection between design, manufacturing, and packaging innovations. By addressing these future needs, the industry can meet the evolving requirements of high-speed computing, sensing, and communications.

## Meet the authors

Abdul Rahim, Ph.D., serves as ecosystem manager at PhotonDelta, where he is developing an innovative integrated photonics ecosystem. He is dedicated to fostering collaboration among Dutch, European, and global stakeholders to drive advancements in the field; email: abdul.rahim@photondelta.com.

Faisal Kamran, Ph.D., serves as principal technology analyst at Sony. He is a leading photonics and business expert with extensive experience in technology evaluation, global collaboration, market analysis, sustainable business strategies, and mentoring startups; email: faisal.kamran@sony.com.

## Acknowledgments

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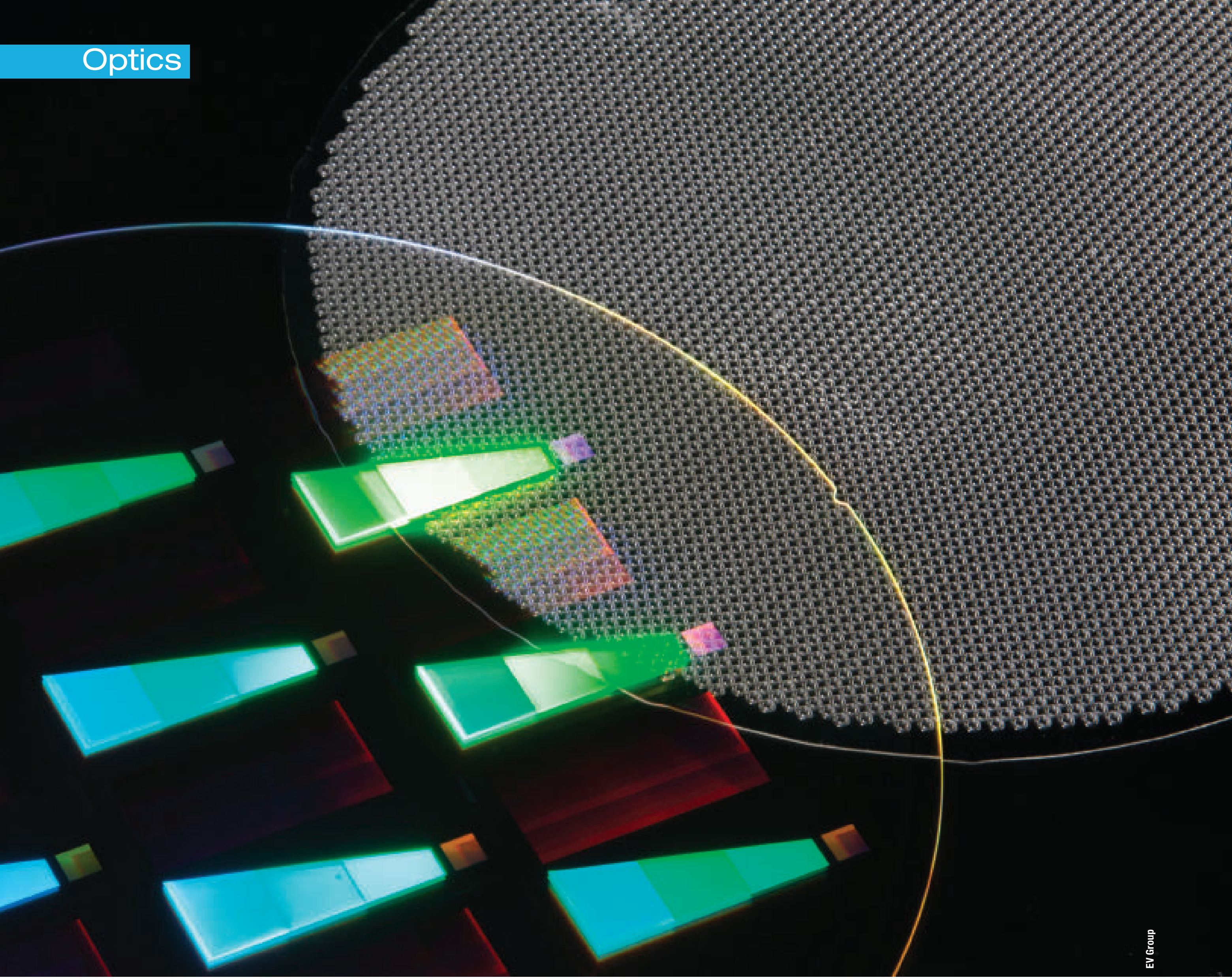



# Shrinking Optics

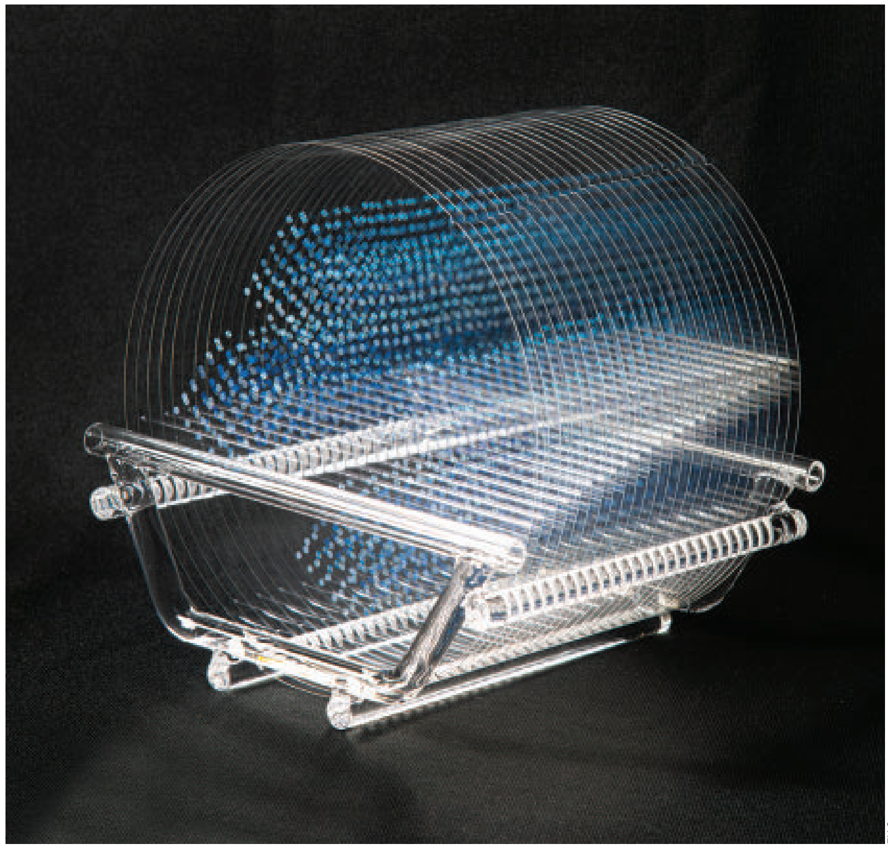
## Heighten a Focus on Manufacturing and Metrology

Examining three facets of the micro-optics value chain — metrology, manufacturing, and application — sheds light on a field that is pushing boundaries in multiple sectors.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

The transition of micro-optics from an emerging field into a cornerstone of modern optical systems offers considerable evidence in support of the commercial potential of light manipulated at microscopic scales. And, as the micro-optics technology space burgeons, an evolution is underway in the protocols spanning metrology, manufacturing, and applications. Today, biomedical devices, lidar, augmented and virtual reality (AR/VR), and telecommunications are among the sectors that are benefiting from breakthroughs in resolution, miniaturization, and functionality.

As it relates to broadening the commercial prospects for micro-optics, continued success depends heavily on sustaining the evolution of these protocols. Each of these areas — metrology, manufacturing, and application — presents distinct challenges and opportunities, ultimately shaping the future of optical technology from R&D all the way to the end user.



EV Group

An increased demand for meta-optical elements (MOEs) has brought manufacturing methods, such as nanoimprint lithography (NIL), as well as materials, into focus.

## AR/VR, electronic devices, and imaging

Fundamentally, micro-optics surpass the performance capabilities of classical optics. For example, meta-elements and microlens arrays precisely manipulate the propagation of light at subwavelength scales. These optics can replace conventional bulky optics for compact, lightweight devices and enable new, and often novel, applications.

These applications are flourishing in segments such as AR/VR and consumer devices. According to market research firm Yole Group, the progress of micro-optics can be tracked by investment amounts into emerging segments, including AR. One recent report revealed that micro-optics-focused startups that are expected to be part of the AR supply chain have received more than $300 million in investment since 2017.

Other consumer devices tell a similar story, though on a commercially accelerated scale.

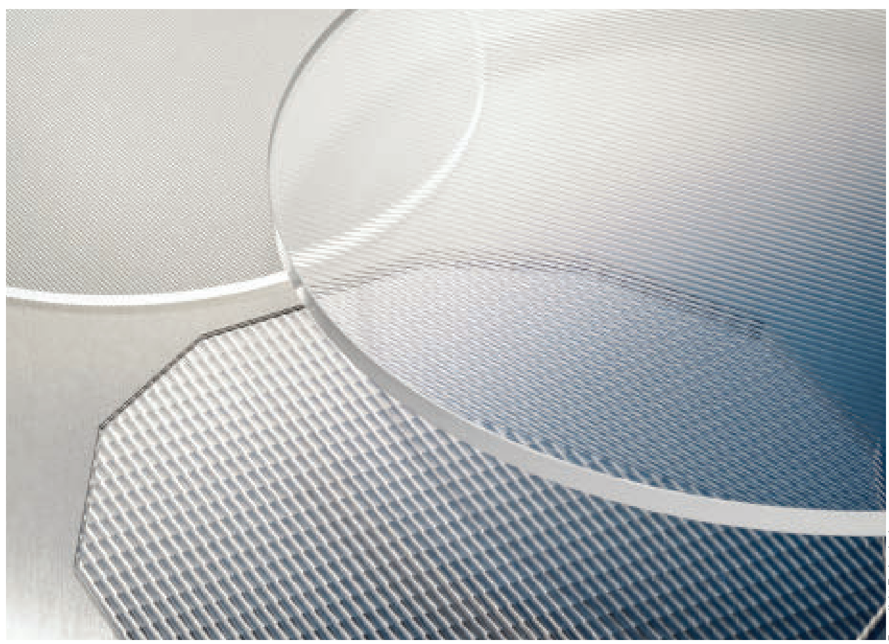
"In smartphones and tablets, silicon-based metasurfaces will start to be integrated into 3D sensing modules for performance improvement or cost optimization," said Yole Group technology and market analyst Raphaël Mermet-Lyaudoz. "With Apple making this choice recently, we can expect the company to integrate them into its entire product line, resulting in more than 100 million units per year," said Axel Clouet, also a technology and market analyst with the firm.

AR/VR systems depend on micro-optics for immersive visuals. Microlens arrays and diffractive waveguides direct light from displays to the user's eyes, minimizing distortion and maximizing field of view. Waveguides, in particular, project images onto transparent surfaces, blending digital content with reality. As AR/VR devices become increasingly sophisticated and user-friendly, the need for more advanced micro-optics is

Focuslight Technologies

A fiber coupler array (the final product) compared to a wafer **(left)**. Both are made from a glass with a high refractive index.

Offering a wide range of element sizes is crucial to meeting the needs of various micro-optics applications **(below)**.



Focuslight Technologies

driving progress in design and manufacturing.

Still, there are obstacles to manufacturing at scale. Today's metasurfaces for certain imaging applications can be produced using standard semiconductor processes, with few bottlenecks in place to prevent demand from being met. However, producers of nano-imprinted AR components have yet to standardize a manufacturing process that balances optical quality, throughput, and cost. But for now, the pace of market growth is allowing the current capabilities to meet demand.

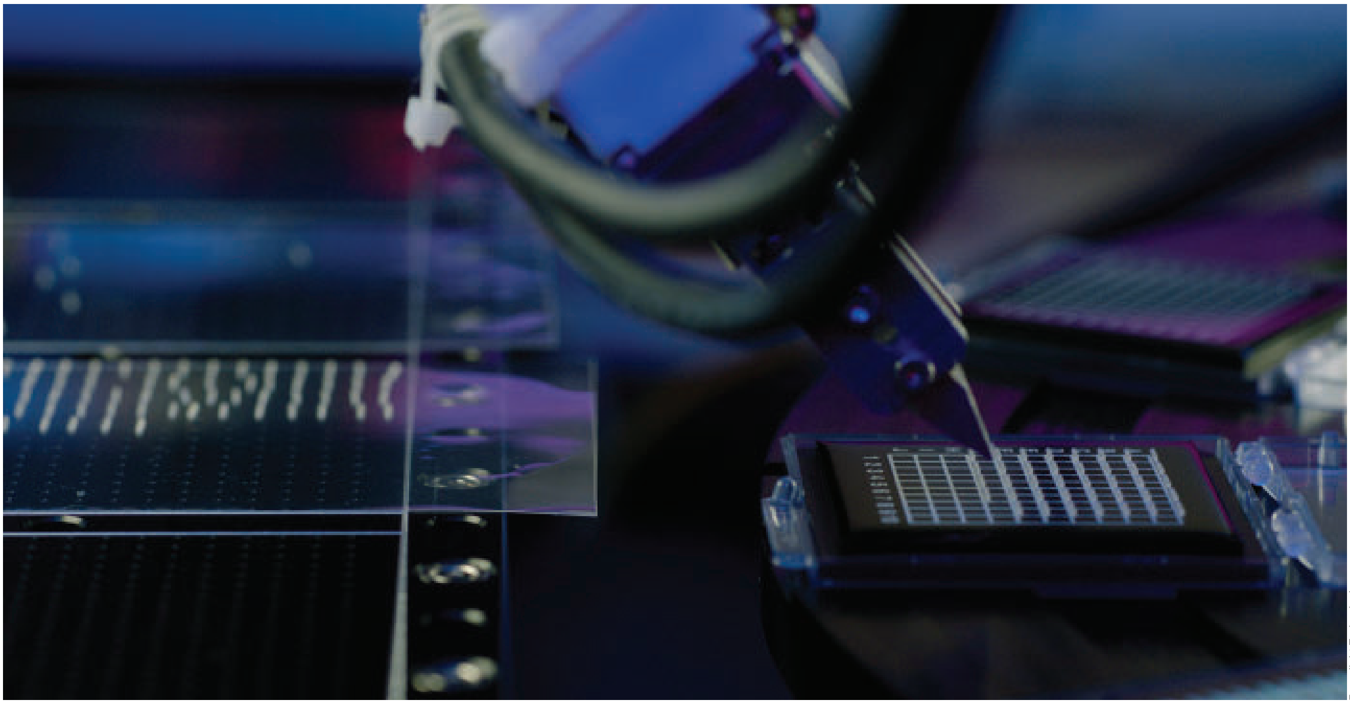
Beyond imaging, metasurfaces find use for advanced marking solutions, such as for authentication. Switzerland-based Morphotonix, for example, uses precise photonic crystal manufacturing to limit counterfeiting on metal surfaces. The company's solution is based on nano-engraving metallic articles with a precision of 130,000 dpi. Morphotonix also molds chocolate surfaces with microstructures to generate eye-catching rainbow-colored holograms.

## Diverse application potential

In the field of biomedical imaging, diagnostic devices including endoscopes incorporate microlenses and fiber optic components. These optics enable high-resolution imaging with minimal invasiveness, helping physicians diagnose conditions more accurately and with less risk to the patient. Further, the use of gradient-index lenses, which vary in refractive index across the optic, allows for focusing light in extremely tight spaces. This enhances the imaging capabilities of these tools.

In optical sensing, lidar systems, which feature in autonomous vehicles as well mapping systems, rely on micro-optics for necessary beam shaping, focusing, and directing. Micro-optics in lidars facilitate the function of the laser pulses to measure distance(s). By improving the precision and efficiency of these optical components, manufacturers enhance the resolution and range of lidar systems to make them more effective for real-time object detection and 3D mapping.

Micro-optics are also integral to advancements in telecommunications and photonics, particularly in fiber optics and PICs. Microlenses and beam-shaping optics are used to couple light efficiently between fibers and photonic chips, minimizing losses and improving signal



Focuslight Technologies

A fully automatic pick-and-place machine can streamline crucial steps for high-volume production.

quality. And in data centers, where speed and efficiency are paramount, micro-optics help to optimize light transmission through densely packed optical networks to ensure a faster and more reliable transfer of data.

## Metrology tools and technologies

As micro-optics become more complex and their applications more demanding, the challenges in metrology will mount. The questions and objectives for experts will surpass those pertaining to measuring form or surface roughness. Rather, they will focus on solving complex problems that arise from different material properties, surface geometries, and wavelength-specific performance criteria.

Specialized tools and techniques are needed to perform accurate characterizations for each of these considerations. White light interferometry is a preferred technique for noncontact measurement, whereas confocal microscopy systems are particularly useful to evaluate steep surface angles and intricate geometries.

"For classical optics, which typically range from 0.5 to 4 in. in diameter, conventional test procedures are sufficient," said Dirk Hauschild, senior strategic marketing expert at Focuslight Technologies. "However, micro-optical elements, particularly when produced in large arrays, require specialized parallel testing not commonly used [for] classical optics."

Wavefront sensors are used to assess optical performance, measure light propagation, and reveal aberrations, focal quality, and diffraction effects. In this metrological setting, wavefront sensing ensures that the optics perform as designed, particularly for laser-based applications and optical communication systems in which wavefront integrity is critical. In partnership with a measurement tool provider, Focuslight Technologies enhanced its systems to measure the thickness of 300-mm wafers, enabling precise calculation of optical path differences in high-numerical aperture diffraction-limited microlenses. This allowed for the generation of simulations and performance maps, helping customers verify the repeatability and reproducibility of its components.

But in these cases, even the selection of surface file data formats can lead to errors in production, as well as in quality control — which is an element of manufacturing in which metrological considerations are highly prioritized. A challenge lies in minimizing systematic surface errors with the use of precise metrology. Injection molding, for example, is a common method for manufacturing micro-optics components that requires precision metrology at every stage of production. Equipment providers, such as New Hampshire-based Precitech Inc., use both in situ and post-fabrication metrology to ensure that lens molds meet the necessary tolerances for the target manufacturing steps.

## Material-driven metrology challenges

Much like how the requirements of an optical element vary depending on application, different materials introduce unique metrology requirements. For example, the use of glass — widely favored for its optical clarity and broad wavelength transmission — requires metrology solutions to measure its surface roughness and form within nanometer tolerances. Yet since the transparency and high refractive index of glass makes surface measurement challenging with conventional profiling tools, interferometry with phase-shifting techniques is commonly used to measure surface form and wavefront error.

Polymers are popular in micro-optics fabrication for their cost-effectiveness and ease of manufacturing, especially for high-volume production. However, polymers pose challenges in terms of thermal stability and deformation. This means that metrology systems must assess initial quality and account for material creep or dimensional changes. Coherence scanning interferometry is often used in such cases to evaluate surface texture, step height, and material consistency across different batches.

Crystalline materials, such as silicon and gallium arsenide, are used in PICs, and their utility extends to infrared applications. These materials pose distinct challenges in birefringence and anisotropic etching behaviors. In one example, Sony Digital Audio Disc Corporation uses white light interferometry as well as atomic force microscopy to meet the required tolerance levels for light transmission and reflection.

### AI in metrology

The integration of automated systems into production lines is underway throughout manufacturing. Real-time monitoring during fabrication enables quick adjustments, enhancing production efficiency and ensuring that each component meets the necessary and often rigorous specifications.

To maintain the quality and performance of micro-optical components, wafers, and stacks of thin substrates, solutions such as Äpre Instruments' phase-shifting and spectrally controlled interferometers must provide real-time feedback to allow manufacturers to make immediate adjustments.

"Eliminating back surface reflections with [spectrally controlled interferometry] greatly shortens the feedback loop, as required in automated metrology," said Robert Smythe, president of Äpre Instruments Corporation.

The incorporation of artificial intelligence (AI) also serves as a direct link between increasingly advanced metrology systems and practices, and sophisticated micro-optics.

"By integrating advanced automation and AI-driven metrology into the production line, manufacturers can ensure lenses meet quality standards while reducing costs and waste," said Peter de Groot, scientist emeritus at Zygo Corporation. "Focusing on modular and adaptable systems allows companies to future-proof their investments and remain agile in the face of new challenges."

### Beyond standard wafer-level

Wafer-level fabrication techniques such as nanoimprint lithography (NIL) and photolithography, are well established in the manufacturing of micro-optics. However, innovations in the broader field of manufacturing technology are developing past standard processes, particularly as demand increases for more complex geometries, higher throughput, and multifunctional optical elements.

In response, new-to-develop approaches to manufacturing place a premium on increasing flexibility, improving scalability, and incorporating more materials into the fabrication process. Silicon-based metalenses, for example, are typically produced using traditional semiconductor processes such as ultraviolet (UV) lithog-

raphy and etching. Diffractive optical elements use nanoimprint techniques, which enable high-volume manufacturing and are compatible with polymer-based resists.

In contrast, laser-based structuring, which uses ultrafast laser pulses to directly write optical structures onto materials, provides the flexibility to create custom patterns without the need for masks or molds. Laser-based structuring is especially suitable for prototyping or low-volume production of specialized optics as a result.

Other techniques support individual aspects, or process steps of the micro-optics manufacturing operation. The integration of multiple materials within a single optic, creating hybrid systems that combine the benefits of different substrates, is one trend that requires advanced bonding techniques and precision alignment processes. For example, glass microlenses can be combined with polymer-based diffractive elements to produce optics that can handle broadband light and offer superior diffractive properties. In this case, the bonding and alignment are vital to ensure that optical performance is maintained without introducing unwanted stresses or distortions. When fabricated to meet target specifications, such hybrid optics open possibilities for complex light manipulation in compact systems.

"There is a continuous push toward higher levels of integration," said Thomas Achleitner, business development manager at EV Group (EVG). "At EVG, we are imprinting photonic structures on photonic integrated circuits, CMOS sensors, and next-generation displays. Accurate pattern fidelity and [having] full control of residual layers and the optical elements are prerequisites to address the demanding markets."

Achleitner also emphasizes the importance of NIL for alignment accuracy, where sub-300-nm precision is often required for high-integration projects. In general, smaller elements are made using manufacturing technologies that have either been developed for, or are now found in, semiconductor manufacturing environments.

In current nanoimprinting tools, the alignment of multiple imprints, such as front-to-back surface(s), is typically within 1 µm. This alignment accuracy is determined by the aperture size, which is several microns or larger, rather than the smallest feature size, which can be as small as 50 nm.

According to Achleitner, another trend in recent years has been a significant push toward meta-optical elements. These elements feature a structured high refractive index surface, and the millions of meta-atoms that compose the surface of each have critical dimensions of only a few tens of nanometers with very high aspect ratios. Manufacturing such components, Achleitner said, requires sophisticated manufacturing technology that is typically only found in semiconductor manufacturing.

Ultimately, the intended application is the critical factor for determining key parameters. For imaging applications, the modulation transfer function is paramount. For meta-optical elements, lens efficiency takes precedence.

## Up to scale

In terms of scalability, techniques such as glass reflow molding, as well as laser-based structuring, are helping to advance wafer-level optics manufacturing. Glass reflow involves heating glass to a specific temperature, at which it softens and conforms to a prefabricated mold. This enables the mass production of highly precise microlenses and optical components directly on a wafer.

Sony Digital Audio Disc uses high-volume injection molding and NIL to produce micro-optical components, such as diffractive optical elements, microlenses, and gratings with complex geometries that are fabricated on full polymer wafer substrates. Although the company is currently focused on development projects, it is aiming to become a provider of polymer micro-optic fabrication solutions, with mass production to follow.

"After 37 successful years in the entertainment industry, we are now establishing our partly unique production technologies and processes in the field of refractive and diffractive micro-optics and photonics," said Rudolf Ablinger, manager of product and service development at Sony Digital Audio Disc. In addition to the manufacturing processes, Ablinger said the company is producing and using various coating processes for the planned undertaking.

## Reducing barriers to entry

The success of micro-optics in core application areas such as biomedical, automotive (optical sensing), and AR/VR has increased the installed base for micro-optics production equipment. This in turn has allowed the ecosystem to develop predominantly with existing production capacity. Consequently, the entry barriers for production capabilities, such as NIL and UV molding, are decreasing.

As these barriers decrease, manufacturers are deploying high-precision robotic systems to align and assemble micro-optical systems with micron-level accuracy. These systems often incorporate real-time metrology feedback loops, enabling the manufacturers to adjust parameters such as pressure, temperature, and alignment based on immediate measurement data. This level of control minimizes human error and significantly improves yield, especially in high-complexity optics where even small deviations can lead to performance losses. Automation has also moved forward into post-fabrication processes, such as coating and packaging, where robotic systems ensure consistent quality across large production volumes. For micro-optics used in sensitive environments, such as medical devices or space applications, hermetic sealing and precision coating is critical.

"We are just at the beginning of how to make engineering of products and processes using the benefits of photons," Focuslight Technologies' Hauschild said.

"LED and laser in combination with micro-optics [have] already changed our lives and will be a solution for many challenges that we will face in the future. And it will be maybe one of the tools needed to bring and keep this planet in a good shape for coming generations."

mariefreebody@physics.org


# Ready for Takeoff: Drone-Based Sensing Takes Flight

Uncrewed aircraft can effectively bring sensor systems into challenging environments. Implementing these advanced systems can require a large investment and considerable planning.

BY MICHAEL EISENSTEIN
CONTRIBUTING EDITOR

Mines are inherently challenging places to work, but even within such an environment, certain tasks are considered particularly risky. In the aftermath of a blasting operation, for example, miners must assess the resulting opening in the rock and determine whether valuable ore can be recovered or whether additional excavation is needed.

The traditional method that miners have used to perform these critical functions puts them in a precarious position. "They were actually sticking a laser scanner on a pole into these cavities," said Brandon Duick, CTO at Exyn Technologies. "It's not the safest thing to have engineers or surveyors have to get that close to the space where there could potentially still be falling rock."

Exyn offers an alternative: uncrewed aerial vehicles (UAVs), commonly known as drones, that use high-precision lidar sensors to autonomously navigate newly blasted openings, and generate detailed 3D maps that allow miners to plan their next steps from a safe distance.

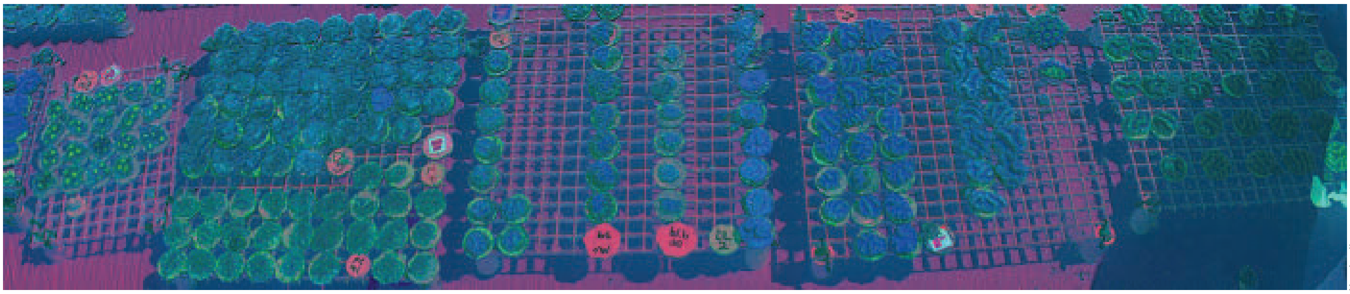
Exyn is not the only company marketing such a solution, and a growing number of industries are finding opportunities to deploy sensor-laden drones in a similar fashion to acquire detailed environmental data that would otherwise be dangerous for human workers to obtain, or that pose logistical challenges.

"A lot of what we do is reducing risk for people," said Adam Bilmes, cofounder and senior director of business development at Inspired Flight Technologies, citing the example of using drones to assess the condition of high-voltage power transmission lines. Some companies in this area, such as Quantum Systems, are providing drone-based sensing to assist soldiers on active battlefields. Others, such as AgEagle and Sentera, are developing airborne mapping solutions to evaluate crop health and identify sites of weed or pest infestation.

But tapping into these capabilities has its own difficulties. Even as more companies specializing in drone-based sensing enter the field, this technology remains expensive and requires a certain level of expertise that is still lacking in many industries. "We are not anywhere close to really broad adoption," said David Blair, vice president and general manager of remote sensing at Headwall Photonics.

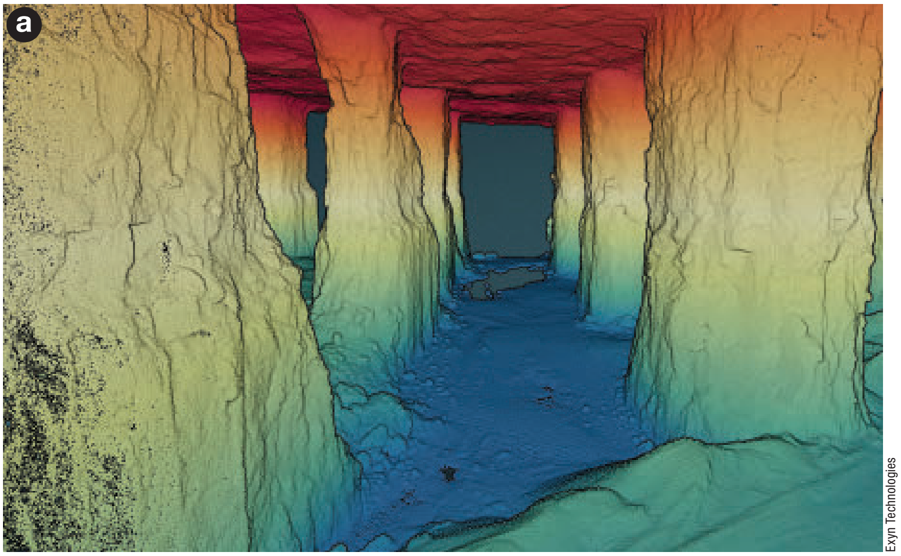

Headwall

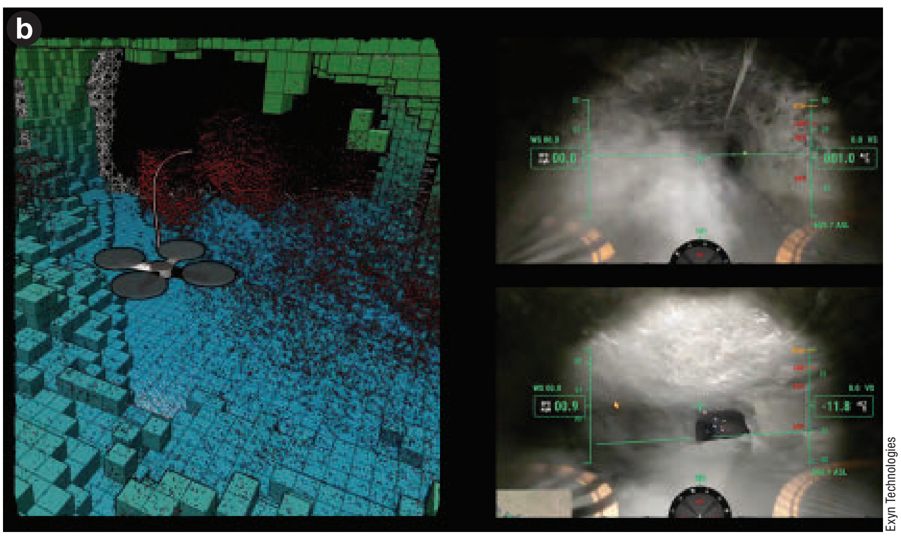
Optical sensors have been shrunk to easily mount onto uncrewed aerial vehicles (UAVs) **(right)**. Hyperspectral imaging sensors can now weigh <5 kg, offering users more options for deployment.



Headwall

Scanning coral tanks onshore with uncrewed aerial vehicle (UAV)-mounted sensors allows scientists to gather valuable data in their mission to conserve and restore oceanic species along the Florida coast **(below)**.




Lidar scanning can provide detailed 3D images in low-light environments — a powerful asset for navigating dark and dust-filled underground spaces, such as mines **(a)**.

Miners can assess the structural integrity of underground areas using drones while keeping workers at a safe distance **(b)**.

“There’s still quite a gap that has to be closed.”

## No mere toy

Drones have been popular playthings for hobbyists for some time. Their capabilities are evident in eye-catching aerial photographs, and their usage among nonindustrial consumers has shaped the narrative around the growth of the technology.

Over the past several years, drones have matured into useful tools for research, industrial, and other applications. On the one hand, regulators have established and implemented formal guidelines around how users can deploy UAVs. In 2016, the U.S. Federal Aviation Administration issued the set of rules known as Part 107 — Small Unarmed Aircraft Systems, which delineates how and where drones can be deployed and establishes certification requirements for commercial users. The European Union issued its own drone regulations and certification guidelines, which came into effect in 2020.

Drones themselves have simultaneously evolved, and in a considerable way. “A lot of folks building drones in their garage is really where this industry started,” said Bilmes — who added that Inspired Flight Technologies was founded in a similar fashion in 2017. But when the goal is to deliver reliable sensing capabilities to leading players in sectors such as agriculture, mining, oil and gas, or even defense, this approach simply will not fly. Today’s commercial UAVs are far more sophisticated and are precision-engineered systems. “We’re building aircraft that have to go through extraordinarily rigorous quality systems, and safety and reliability is everything,” Bilmes said.

In parallel, sensor developers have been turning their sophisticated instruments into compact, travel-ready packages that can operate stably in rigorous real-world conditions. Companies such as Headwall, founded in 2003, specialized initially in laboratory-scale instruments for hyperspectral imaging — developing tools for spectroscopic analyses of material and chemical properties of samples by scanning large swaths of the visible and infrared spectrum. “Around 10 years ago, we really started to recognize this inflection point where you have large spectrometers, computers, and data-processing systems all starting to miniaturize,” Blair said. Today, the company has downscaled commercial hyperspectral imaging sensors to a power-efficient 4-kg package roughly the size of a toaster.

Scaling down is only half the battle. These airborne sensors must also withstand a broad range of temperature and humidity levels, rapid movements, and vibrations in flight while still delivering quality results. Duick pointed out that even though miniaturized lidar sensors are already a common feature on cars to enable driver assistance and autonomy, UAVs are exposed to more challenging operating conditions.

“We try to fly as smoothly as possible, but sometimes you’ll have decent-size accelerations and angular rotations,” Duick said. “If we’re talking about millimeter accuracy, we have to impose very strict deformation requirements on all the parts.”

## Many points of view

Despite these engineering challenges, would-be drone users can now choose from a wide range of integrated sensing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Sensor-mounted drones enable users to gather critical data in dangerous or challenging environments.

modalities, depending on the requirements of their application. Optical photography and lidar sensors are among the most mature approaches, and both can be used to generate data-rich 3D maps of complex environments in settings ranging from construction and civil engineering projects to environmental sustainability efforts.

Photogrammetry is a more affordable option than lidar but may not generate the same level of fine detail. Also, photogrammetry is typically best suited for brightly lit or outdoor environments. For example, UAV manufacturer Quantum Systems recently collaborated with conservationists to deploy drones equipped with high-resolution cameras to find and classify endangered animal species, such as black rhinos in Namibia's Kuzikus Wildlife Reserve. Lidar-based scanning may be a better solution in situations in which more resolution is needed — Exyn's scanners can achieve 1-cm resolution — and is also generally considered the best solution for indoor or other low-light environments. "In a mining space with no light and lots of dust, the only way to really get the geometric information that those customers are after is from lidar," Duick said. Exyn's lidar systems have also found use in outdoor settings such as forest canopies, with the goal of assessing tree growth and health.

Spectral analysis sensors are also now gaining momentum for more specialized analytical applications. These include hyperspectral sensors, which can perform spectroscopic analyses across a broad gamut of wavelengths from the visible into the mid-infrared. As a lower-cost alternative to hyperspectral analysis, users may opt for multispectral sensors. These sensors can be configured to selectively analyze a more limited number of defined wavelengths, typically on the order of four to six, within the visible to near-infrared range.

Spectral analysis systems are powerful for use cases in which the goal is to extract deeper insights about chemical conditions in a given environment. For example, Bilmes said that Inspired Flight customers have used drone-based multispectral analysis to detect leaks in oil and gas pipelines. Hyperspectral sensing is more expensive to deploy, but it adds value in terms of its versatility, according to Blair, which can give it a potential edge in settings such as agricultural research or geological exploration. "A single multispectral few-band sensor can't adapt if the environment changes," he said. "Elements that show up and decline and transform are areas where we would rather focus." These can include processes such as crop disease onset, changes in ecosystem(s) that are occurring over time, and water quality assessment.

Additional specialized instruments that are carving out a niche in the drone-based sensing market include UAV-borne infrared-sensitive thermal cameras. These devices are proving to be popular in military and public safety contexts as well as wildlife monitoring efforts. In these cases, the goal is to unobtrusively collect information about people or animals on the ground. The use of aerial magnetometric analysis is also expanding for geological surveys, including exploration for mineral wealth and the discovery and profiling of archaeological sites.

### Some turbulence ahead

Many other considerations go into launching a UAV-based surveying or sensing program. Among them is deciding which of the two major categories of drones — fixed-wing and multi-rotor — should be used. Each has distinct advantages and limitations.

Fixed-wing drones, which resemble airplanes or gliders, can generally cover greater distances and offer superior stability to multi-rotor drones. But this class of drones also tends to be more expensive. Multi-rotor drones are more maneuverable and can hover in place for extended analysis of a site of interest, but they also travel more slowly and capture less data per outing. Some drone systems blur these lines; for example, Wingtra's WingtraOne UAV uses rotors to achieve vertical takeoff and landing, making it easier to launch and recover while also achieving a balance of maneuverability and range.

Drone-makers are also pushing toward higher levels of autonomy. Most UAVs are compatible with waypoint-based navigation, where the user predesignates a course on an already-mapped area and then allows the drone to go about its work. Exyn's recently launched Nexys system offers a solution that uses sensor data to independently navigate its way through uncharted territory with minimal user intervention. "In general, if the lidar can see it, then our system and our algorithms will safely avoid it or scan around it as best as possible," Duick said. These capabilities are particularly valuable in the context of unexpected events, such as a mining tunnel collapse, which can dramatically alter the site landscape relative to existing maps, he said.

On the sensor side, many sensor manufacturers strive to deliver solutions that are relatively agnostic in terms of drone compatibility, which gives users the flexibility to obtain a sensor-UAV pairing that best aligns with their needs as determined by application. “We actually don’t interface with the drone at all other than a mechanical interface and power line,” Blair said. “That way we can easily port from system to system.”

Nevertheless, quality concerns do come into play. Blair said that Headwall prefers to partner with established companies with robust customer support processes, for example. There are also geopolitical considerations. “Over the past few decades, we’ve really relinquished a lot of our capabilities overseas to China,” Bilmes said. Chinese company DJI, he said, manufactures today’s most popular consumer and commercial drone models. The U.S. Department of Defense has added DJI to a list of companies affiliated with the Chinese military, rendering it ineligible for many government contracts. But this has also triggered broader concerns around the commercial use of DJI technology as well as a lawsuit in response from the drone-maker regarding this designation and the resulting loss of business.

But Bilmes also pointed out that it has proved to be harder for American-made drones to compete in price. And indeed, the cost of entry can be high. For example, Inspired Flight’s commercial drones cost between $20,000 and $30,000 even before incorporating the sensor component, where sophisticated instruments also carry price tags of tens of thousands of dollars. This has limited the reach of drone-based sensing in some areas, most notably agriculture, in which most farmers lack the deep pockets of those in the mining or fossil fuel industries.

Not included in the cost is the need for operator experience. Bilmes stresses the importance of having a specialist within the organization who “owns” any drone-based surveying program and is well-versed in the safety, technical, and regulatory considerations associated with UAV use. “Somebody with good operations experience or a military background tends to be a very nice dovetail into this, or somebody that comes from an aviation background of any sort,” he said.

## Automatic for the people

Obstacles such as these, when it comes to drone usage, are not insurmountable. According to Bilmes, it is realistic to obtain Part 107 certification for commercial UAV operation with just a few weeks of training, and certain organizations already offer drone-based sensing as a service.

Blair believes that costs will decrease as the sector expands and more early movers demonstrate the utility of drone-based sensing. He said that it is not always essential to pay top dollar to get good value from a surveying effort. “Especially when you start in a research market, there’s always this drive toward the best — the best specs, the best performance, the best image, the best everything,” he said. “The question is: Does it work for the purpose you need?”

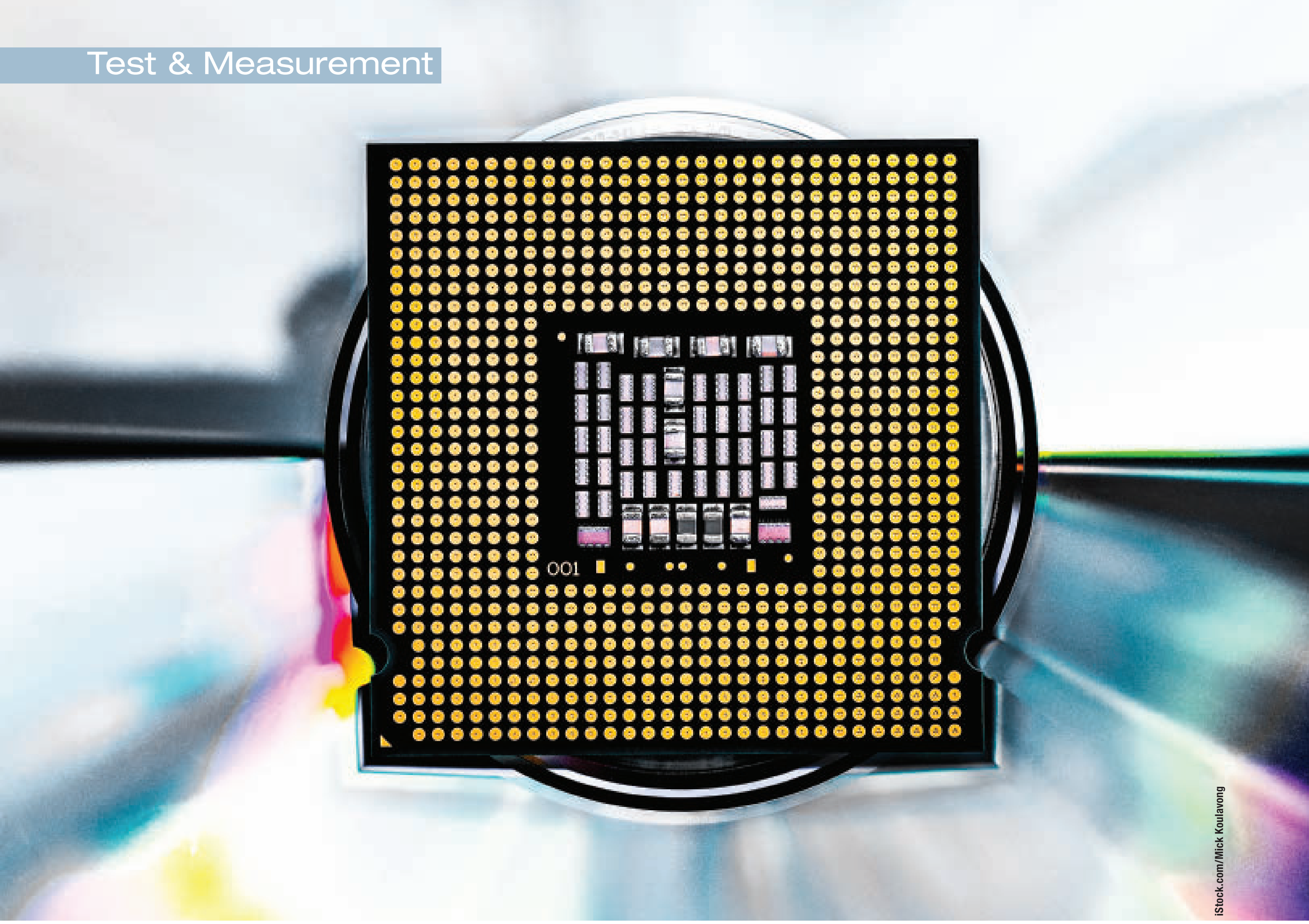
A growing number of consumer-tailored systems are also entering the market. In 2023, Sentera launched its Aerial WeedScout platform, in which drones generate detailed maps of weeds down to quarter-inch resolution within a given field. These maps can then be used to guide the precise application of herbicides. The company reported that this turnkey solution can reduce the use of such chemicals by up to 70%, without negatively affecting the overall field productivity.

These systems will deliver an even greater value as they become smarter and more autonomous, with the capacity to perform more onboard data processing and decision-making. This will generally simplify aerial sensing projects while also making each run more efficient and productive.

Blair believes this to be an evolutionary leap that will be essential to the field’s growth.

“Until we really build robust workflows that a technician in the field can really operate robustly, routinely, and essentially unsupervised, it will still be in the early stages of adoption,” he said.

michael@eisensteinium.com

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# Positioning Technology Proves to Be Pivotal in High-Precision Manufacturing

The drive for miniaturization continues. Nanopositioning technology is advancing to meet the needs of component and device fabricators worldwide.

BY KNUT HAUKE AND
MARC SCHENKELBERGER
MKS NEWPORT

As it relates to semiconductor and electronics manufacturing, miniaturization seems to have no limits. A simple examination of the components and even many of the finished devices fabricated in today's manufacturing environments makes it easy to perceive this trend.

Yet despite the ubiquity of miniaturization in modern manufacturing, the processes and technologies necessary to fabricate nanostructures present dynamic challenges. Manufacturers supporting the semiconductor and consumer electronics industries have overcome many constraints on the road to sustainable miniaturization, or scaling, as it is known in the semiconductor industry.

One area of notable advancement is in positioning technology and equipment: For structures in the nanometer-size range, it is critical to optimize positioning technology to meet the requirements of a given production process. As the physical capabilities of this technology have progressed, the emergence of intelligent solutions in nanopositioning technology have further established opportunities to achieve extremely high levels of precision.

As a result, advancements in positioning technology — paired with several key drivers from within industry — are enabling the creation of smaller, more powerful, and energy-efficient semiconductor devices.

## Individual requirements

Industrial positioning systems for the semiconductor and electronics industry are typically configured individually to meet the distinctive requirements of an individual production task. Though different production processes may appear similar, or achieve similar outcomes, the need for individual configuration stems precisely from the stringent nature of these requirements.

Industrial positioning systems are characterized and evaluated based on several factors, ranging from accuracy and repeatability to physical, in-process requirements. For example, travel distances, or the required process area, is a crucial parameter and is used to indicate which distances the positioning system can cover in the axial directions. Similarly, step size, which refers to the smallest step or minimum incremental motion (MIM) that a device can reliably execute continuously, is a parameter that may be difficult to obtain. MIM values are commonly mistaken for resolution (R) values and may not be specified by all equipment manufacturers. In fact, step size, and MIM itself, does not correspond to the resolution of the encoder. This parameter may also be determined using methods that are not consistent from manufacturer to manufacturer.

Additional factors that a user may conflate are repeatability and accuracy. Repeatability describes the ability of a system to reliably approach the same position several times in response to the same command. Within this parameter, there is a distinction between unidirectional and bidirectional repeatability. With bidirectional repeatability, approaching the position from both directions is considered, so that the reversal error when changing positions is also considered.

On the other hand, absolute accuracy quantifies the deviation between the actual and target positions. Accuracy can be specified in terms of total travel, or per-unit length.

Optimizing step-and-settle time, or the time that it takes to move from one measuring or processing point to the next, and to settle stably on it within a definable position window, is another crucial factor affecting performance and process results. The guidance deviation of an ideal linear motion, as indicated by straightness and flatness, presents yet another variable that a user must monitor. If a movement is carried out exclusively in the x direction, flatness refers to any deviation in the z direction. Straightness, meanwhile, pertains to any deviation in the y direction.

To maintain high accuracy and repeatability for positioning systems, manufacturers offer calibration services to determine the error topography of a mechanical platform.

MKS Newport

**Material Properties of Air Bearing Stage Materials**

| | Granite | Steel | Aluminum | Newport SiC Standard | Newport SiC Advanced |
|---|---|---|---|---|---|
| Density: d | 2.7 | 7.8 | 2.7 | 2.7 | 3 |
| Young's modulus: E, (GPa) | 70 | 210 | 70 | 240 | 350 |
| Stiffness (E/d) | 25 | 25 | 25 | 90 | 120 |
| Thermal conductivity: TC (W/m·K) | 2 | 50 | 150 | 30 | 140 |
| Thermal expansion: TE ($10^{-6}$/K) | 5 | 11 | 22 | 3.5 | 3.5 |

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d: density measurement; E: Young's modulus (stress/strain measurement of an elastic material, measured in gigapascals (GPa)).

Depending on the application, mechanical and air-bearing positioning systems, also called air-bearing stages, may also be used. In classic positioning systems, the carriage slides over mechanical-ball or crossed-roller bearings. In air-bearing positioning systems, the carriage moves on a thin layer of clean compressed air or gas.

Finally, if only one of the axes requires very high precision, a hybrid system is a good option. These solutions use air bearings to position in only the one axis (the scanning axis), while positioning along the second is carried out mechanically (the stepping axis).

## Positioning systems in-vacuum

The optimal positioning system for a given application depends on the required specifications as well as the available budget. However, the use of air-bearing systems has a fundamental limiting factor: They cannot be operated inside vacuum chambers. Because lithography processes used in/for semiconductor manufacturing that operate with extreme-ultraviolet light require an ultrahigh vacuum, mechanical bearings are the suitable component.

To achieve necessarily high accuracy and repeatability for this application, manufacturers such as MKS additionally offer the calibration of the mechanical positioning systems to determine the error topography of a mechanical platform. For a classic 300- × 300-mm wafer, for example, the grid is scanned in 10-mm steps, and an interferometer can be used to determine the exact position. This value is compared against the encoder value to determine the offset. The correction data set this comparison generates is stored in the motion controller and is used to improve the accuracy of the motion system.

If the requirements in both absolute accuracy and the travel speed values of a positioning system are high, positioning systems with a sliding carriage made of silicon carbide (SiC) offer significant benefits.

This approach yields significantly higher absolute accuracy: For example, in tests to map an xy unit from two standard Newport XML350-S axes, the absolute accuracy improved by at least by a factor of 10. Since the axes are not perfectly orthogonal to each other in this instance, the combined error turns out to be much larger than just the sum of the two individual accuracies — it would certainly be significantly >10 µm in the 300- × 300-mm plane. But after mapping, the system achieved an absolute accuracy of <0.5 µm in the xy plane.

## Air bearings: Frictionless precision

When inspecting wafers or masks for lithography applications that require maximum levels of precision, air-bearing positioning systems offer significant advantages. The load can be moved either linearly or rotationally, depending on the design of the system. And unlike traditional ball or crossed-roller bearings, there is no mechanical contact when moving an air-bearing stage.

Since there is neither play between the interacting mechanical parts of the drive system nor friction in the bearings, these elements can create several distinct advantages. First, it fundamentally eliminates the typical sources of error in mechanical bearings. And due to the planar structure with only one sliding carriage in the xy plane, the design is also significantly flatter than those with fully mechanical systems. This leads to considerably lower angular error(s) and better flatness and straightness value(s). At the same time, due to the lack of friction, air-bearing systems generate less heat, and positional stability is greater than in fully mechanical systems. Furthermore, the system can be moved at a consistent speed. The speed stability of air-bearing positioning systems is >0.1% — with step sizes down to just a few nanometers.

If the requirements in both absolute accuracy and travel speed values of a positioning system are high, positioning systems with a sliding carriage made of silicon carbide (SiC) offer significant benefits. This ceramic composite combines the positive properties of several individual materials, as shown in the table. It is as stiff as steel, as light as aluminum, and exhibits a thermal expansion coefficient similar to that of granite.

Due to the high rigidity of the slide and its low weight, such air-bearing systems work more dynamically, and therefore achieve a higher throughput than conventional systems. Plus, a SiC sliding carriage can offer additional flexibility in design. The overall high degree of integration with just a few individual components makes the positioning system more robust and increases its service life.

## Intelligent solutions

Additional adjustments can influence the overall performance of a system to meet the unique requirements of an application. For example, the use of a SiC wafer chuck is recommended to achieve a high throughput rate in wafer production. Compared with a metal structure, this chuck is lighter and flatter and has the same thermal properties as the sliding carriage. This means that the components are optimally coordinated with each other. In addition, the wafer chuck can be integrated directly into the xy sliding carriage, if necessary, which ensures the low overall height of the setup. This enhances both the precision and the dynamics of the complete system.

For applications that require extreme levels of xy accuracy, interferometer-based solutions can be used in addition to classic displacement measurement systems, such as linear encoders. A mapping concept, such as the one described earlier, is integrated into the positioning system such that the position is read directly at the measuring point, eliminating, for example, encoder interpolation or Abbe error(s). Suppliers including MKS can integrate ceramic interferometer mirror solutions, which have excellent surface quality and dynamic properties, into positioning systems. As in the case of the wafer chuck, these ceramic mirrors can be built directly into the xy slide, so that they are an integral part of the positioning system and fit into the overall concept of the positioning platform in terms of their thermal properties.

Still other processes in lithography and/or wafer inspection may require active alignment of the wafer on the z-axis, in "tip and tilt," or in the theta range. For this purpose, repeatable and stable positioning, without compromising the dynamic performance of the xy stage, is necessary.

## Miniaturization: Underlying factors

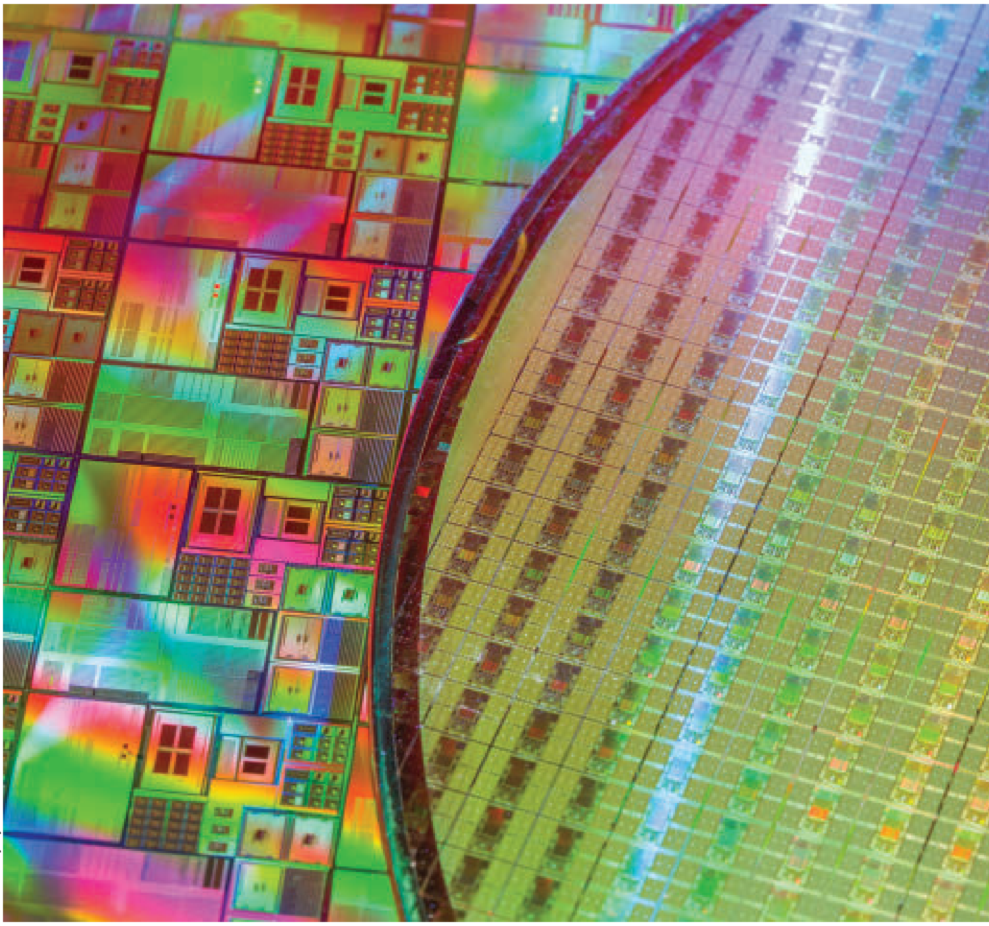
Numerous drivers are combining to collectively push the semiconductor industry to continue developing smaller, more efficient, and more powerful technologies. These drivers exist despite the growing challenges associated with further scaling. In some cases, these drivers themselves have already spurred innovations in manufacturing processes and/or components and systems.

Certain advancements, such as those in lithography (particularly extreme-ultraviolet lithography) have allowed for more precise patterning at smaller scales, enabling the production of smaller features on chips. Moore's law itself requires lithographic advancements; the number of transistors on a chip would double approximately every two years, leading to increased performance and reduced cost per transistor. This has led to continuous advancements in miniaturization to keep up with industry's expectations, and the subsequent development of smaller, more densely packed transistors.

Material innovations in the form of new materials and processes have meanwhile enabled manufacturers to overcome the physical limitations of traditional silicon-based transistors. High-k/metal gate (HKMG) stacks, fin field-effect transistors (FinFETs), and gate-all-around (GAA) transistors all serve to meet this need. These materials allow for smaller and more efficient transistors, helping to maintain scaling even as traditional silicon-based approaches face physical limitations.

And since smaller transistors require less power and generate less heat, which is critical for the reliability and longevity of electronic devices, heat dissipation and power efficiency have emerged as core drivers to manufacturing at scale. This, paired with a growing need to integrate more functionality onto a single chip, has pushed miniaturization further into manufacturers' focus. Miniaturization allows for more complex systems on-chip,

Semiconductor production requires positioning systems that are finely tuned and tailored to meet distinct and precise requirements.



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which can integrate diverse functionalities into smaller form factors.

External factors are also causing a shift toward sustained miniaturization. Reductions in the cost per transistor are necessary for industry players to remain competitive, which has in turn created a need for smaller, more efficient manufacturing processes. Miniaturization allows for more transistors per wafer, reducing costs and improving yields, which is crucial for economic viability in producing advanced semiconductors. Also, consumer electronics, especially mobile devices, demand increasingly smaller, faster, and more energy-efficient components. The consumer market's push for thinner, lighter, and more powerful devices is a major contributor to ongoing miniaturization in semiconductors.

## Looking forward

Positioning systems used in semiconductor and consumer electronics production are finely tuned systems that are individually adapted to the respective requirements. Their configuration requires expertise and experience, and their manufacture is complex and subject to stringent specifications. For this reason, air-bearing stages, in particular, are only offered by several manufacturers worldwide. Close collaboration between the chip tool maker, or system integrator, and the positioning systems manufacturer in the design process is essential to ensure desired performance. Choosing the proper technologies and adapting them individually, though in combination with intelligent concepts, is necessary to guarantee the overall success of a project.

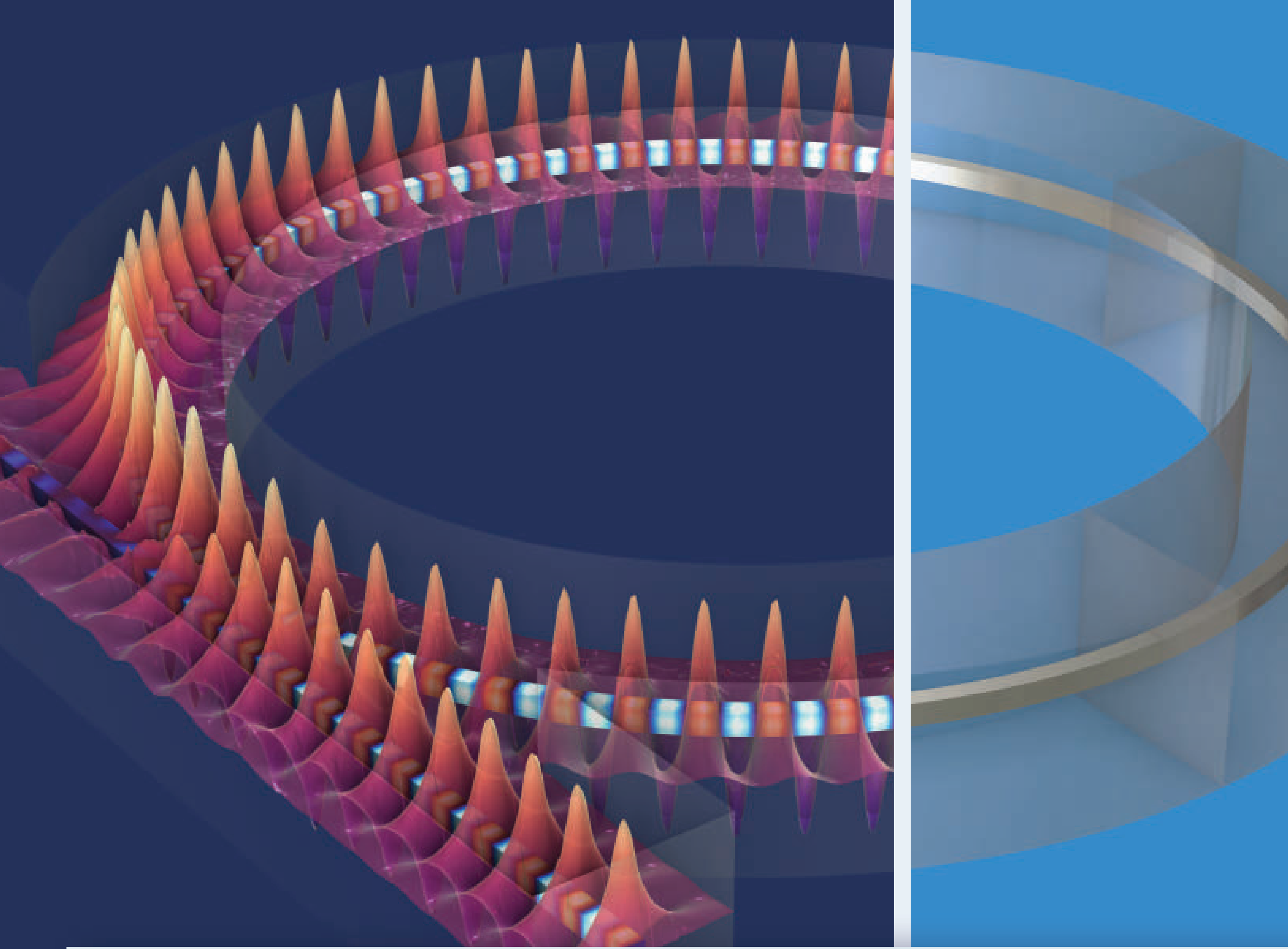
This is especially important to consider in the context of the anticipated manufacturing road map for the semiconductor and consumer electronics sectors. Tiny structure sizes of just a few nanometers have already been planned for the next generation of chips. And already the number of transistors on a given chip is constantly setting records. This level of integration can only be achieved if manufacturing technology keeps pace. Whether in the lithography itself, the inspection of wafers and masks, or in the bonding of different components, countless processing operations require positioning technology that is highly precise and reliable. Logically, the positioning accuracy must be even more fine-grained than the structures themselves.

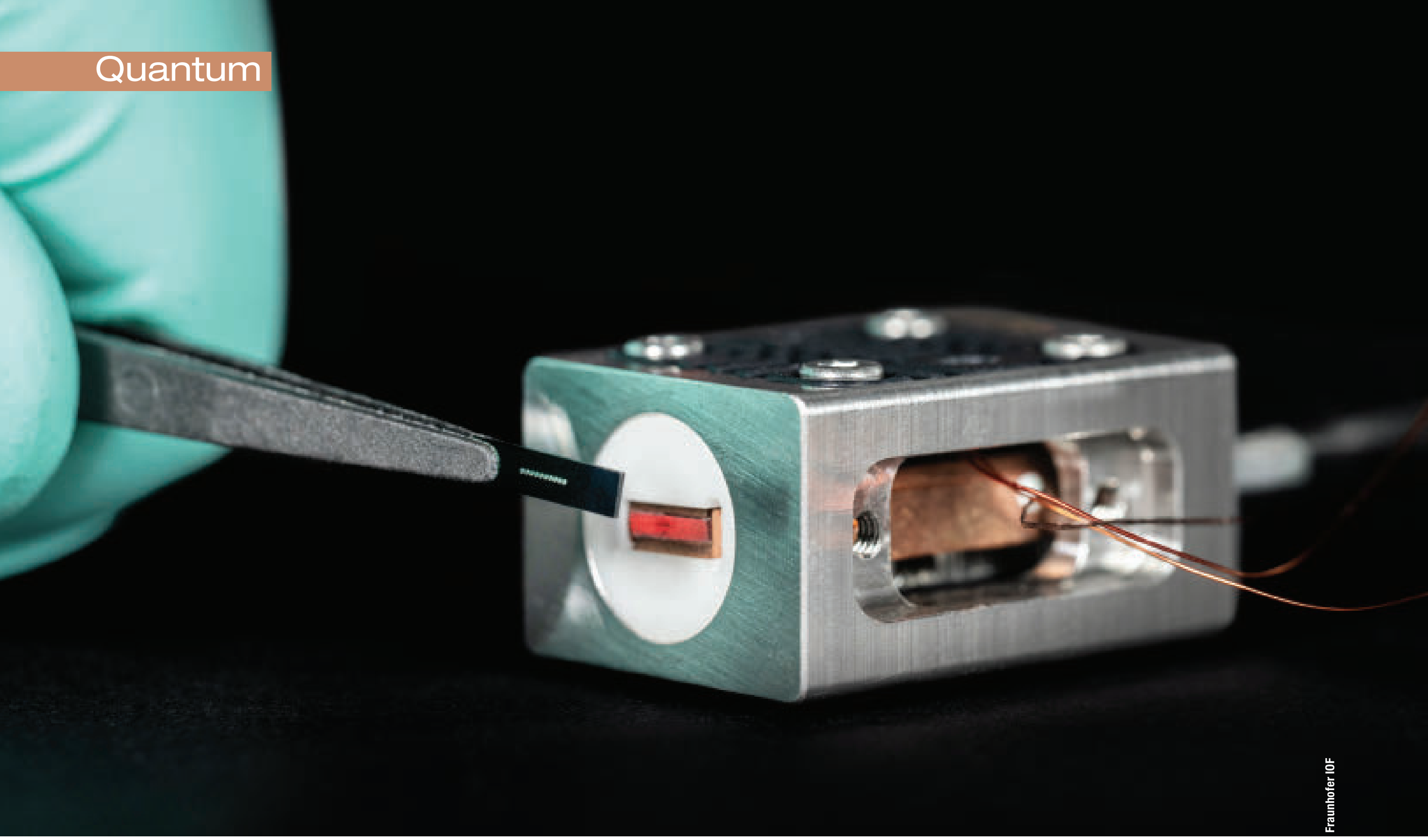
Of course, these are not the only challenges. Reconciling the required precision and manufacturing quality of necessary process steps with the target throughput represents a dynamic on which all manufacturers must place a premium. Logistic decisions are also paramount. Automated systems, which are increasingly prevalent in wafer production and inspection, usually operate 24/7. Therefore, they place high demands on system availability.

## Meet the authors

Knut Hauke is Newport senior sales territory manager at Newport Spectra-Physics GmbH, based in Darmstadt, Germany; email: Knut.Hauke@mks.com.

Marc Schenkelberger, Ph.D., is Newport sales manager for Newport Spectra-Physics GmbH; email: Marc.Schenkelberger@mks.com.






# A Small Photon Source Promises to Enhance Quantum Communication

A compact photon source for space-based quantum key generation underscores the promise and technological readiness of quantum communication solutions for secure cryptography.

BY ERIK BECKERT AND CHRISTOPHER SPIESS, FRAUNHOFER IOF, AND ANDREAS THOSS, CONTRIBUTING EDITOR

In recent years, quantum computers have made headlines, while quantum communication solutions have made it to markets. Simple solutions, such as quantum random number generators, have been transferred into smartphones. Similar quantum encryption modules for terrestrial telecom router systems are available off-the-shelf.

But this is just the beginning, and more sophisticated solutions are in the development pipeline. “[Quantum communication] adoption is expected to accelerate over the coming decade as quantum computing cybersecurity risks increase,” according to McKinsey & Company’s third annual Quantum Technology Monitor, in April 2024.

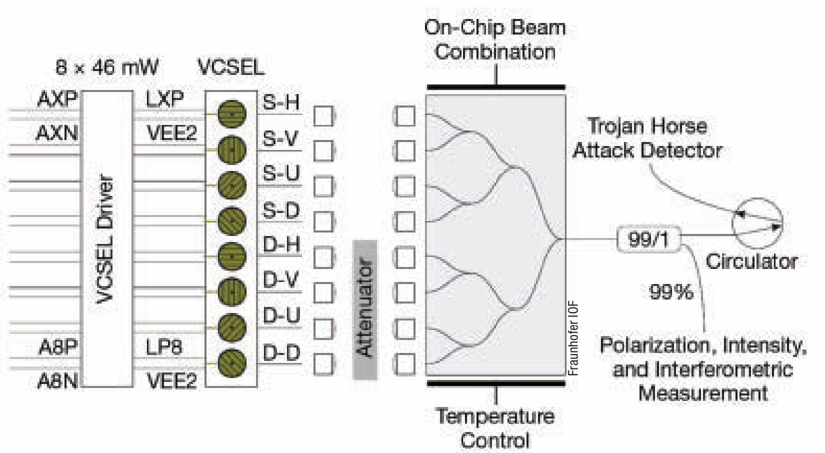
## Quantum cryptography basics

Quantum communication essentially refers to quantum encryption. And essentially, for quantum encryption, two quantum effects are exploited.

The simpler of the two is based on the statistical nature of quantum effects. If, for example, the radiation of a laser is attenuated until there are one or zero photons per time unit left remaining, then this light signal can be exploited as a random generator. This can be assumed to be physically safe, since such light emission is unpredictable by its quantum nature. A sequence of photons (or signals with several photons) and voids can easily be converted into random numbers. Other quantum effects can also complete this function.

Entanglement is a more sophisticated effect. To understand entanglement, it is critical to know that some quantum effects produce two photons that have a defined relation, such as perpendicular polarization states. The peculiar aspect of this quantum effect is that the exact states of both photons remain undefined until the state of one of the two photons is measured. If one state is measured, the other gets fixed instantaneously. The 2022 Nobel Prize in physics was awarded to three scientists who proved this behavior experimentally.

**Figure 1.** A schematic of the eight-channel VCSEL source for polarization encrypted photons. See Reference 4.



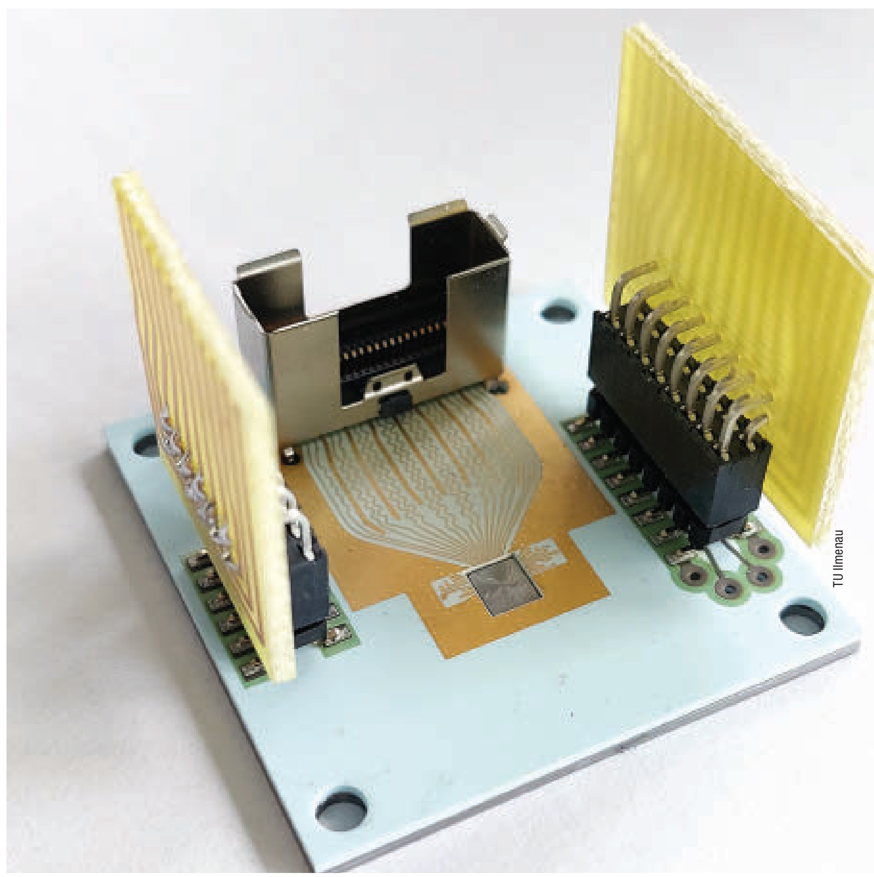




**Figure 2.** A ceramic printed circuit board (PCB) is bonded to a molybdenum heatsink of a similar size. The PCB carries the VCSEL and driver chip **(center)**. The wings are plugs for thermal management components. The plug in the back will connect to the gigahertz driver signal. See Reference 4.

As for cryptography, the benefit appears simple: An entangled photon can be measured only once. Effectively, eavesdropping by a third, malicious party to observe this effect becomes impossible, because it destroys the entanglement. It is also important to note that other quantum systems, with different physics, and sometimes more states, show a similar behavior.

The problem with entangled photons (or any other entangled quantum entity) is its elusive nature. Measuring single photons has been performed in microscopy long ago, for example, but noise remains a challenge in this case. The generation of single photons is even more difficult, particularly as it relates to heralding: As a pair of entangled photons is destroyed by any measurement, a separate heralding signal is helpful for use as a trigger of subsequent processes.

Often, a unification of the two quantum communication ideas can solve this heralding problem. When entangled photons are generated, one may serve as a herald, or trigger signal, while the other serves as part of a random sequence that becomes the actual quantum key.

It is also important that single photons can neither be amplified nor replicated; one remains one. Replicating a single photon into a similar "fresh" photon does not change anything. Fractional attenuation is impossible and thus, the photon is either there or it is lost.

Therefore, the distance over which a quantum signal can be transmitted (i.e., single photons) depends on the attenuation of that line. In conventional fibers, this value is up to ~80 km, and in free space, it might extend to thousands of kilometers if there is no air in between. Repeaters that reproduce entanglement are a subject of considerable research efforts, as are entanglement and/or quantum storage devices.

Quantum key generation is vital in quantum communication, since, in most applications, it is seen as sufficiently secure if a quantum key is exchanged and if larger data volumes can be exchanged afterward, using the key in conventional encryption algorithms. In other words, the transmission of secret data could be secure if entangled photons were used. However, these entangled photons are difficult to generate, suffer from high transmission losses, and are subject to detection noise. As a result, the rate of successful transmission of entangled signals is low, often on the order of a few bits per second.

No matter if the signal is an entangled photon or a quantum random signal, the secure quantum signal is usually used only for the transmission of the quantum key. After a successful quantum key transmission, the real data is encrypted and transmitted on a conventional connection.

### Quantum key distribution

The method of preparing random quantum states and sending them — for example, from Alice to Bob — is referred to as prepare and measure. Sophisticated protocols have been developed to ensure that the quantum key sequence is transmitted and processed safely and efficiently. The most common protocol is known as BB84, as it was proposed by Charles Bennett and Gilles Brassard in 1984. This protocol uses the polarization of photons as the quantum effect for a safe quantum key transmission (or transmissions). Alice sends a sequence of polarized photons to Bob, where the base can switch between horizontal/vertical (H/V) and diagonal/antidiagonal (D/A). To exclude eavesdroppers, the actual base is fixed after the transmission and half of the transmitted data is discarded. Part of the data is compared between Alice and Bob and the rest remains a safely transmitted quantum key.

Rather than relying on entangled photons, this protocol relies only on a sequence of randomly generated quantum states, from a trusted source, which serve as a cryptographic key. These states may consist of several photons. While this makes the generation and detection of polarization states easier, it also allows an eavesdropper to strip off single photons from the signal. These are called photon-number-splitting attacks.

The practice of using decoy states can widely suppress this class of attacks. Decoy states are additional photon pulses with varying intensities inserted alongside the actual signal pulses used to encode key information. Decoy states are used to capture photon statistics. Since eavesdroppers cannot distinguish between signal and decoy pulses, any attempt to

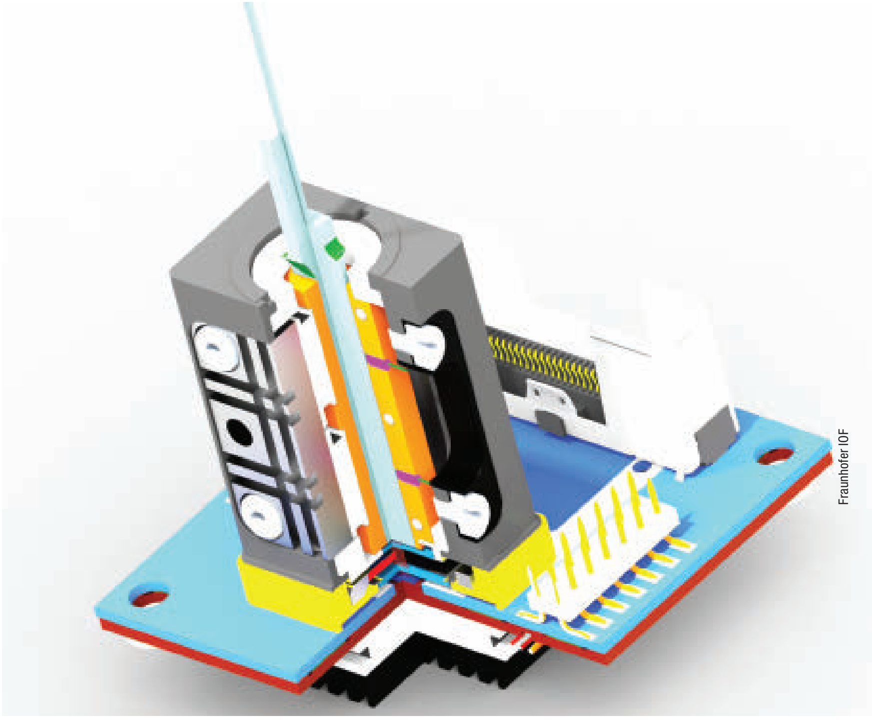



**Figure 3.** The printed circuit board (PCB) in Figure 2 is shown with the KOVAR frame housing the optics that are fixed on top of the VCSEL chip. The tiny glass tip on top of the housing is the waveguide combiner, where the polarization signal comes to exit.

interfere with the communication will be detectable through the discrepancies introduced in the decoy statistics. Alice and Bob can compare these statistics to determine whether photons were stripped off. In such a case, they would repeat the measurement until the statistics are equal.

### A photon source for quantum states

When Bennett and Brassard presented their protocol for safe quantum communication in 1984, they assumed a weak, or faint, photon source[1,2]. For commercial purposes, this is still the most popular way to generate signals for quantum communication. The primary challenges are in creating a photon source that can produce indistinguishable and randomly polarized photons at a high rate while maintaining compactness and energy efficiency.

In 2014, Gwenaelle Vest and Harald Weinfurter proposed the use of VCSELs for this purpose[3]. This solution enabled high pulse rates in the gigahertz range, and it made the technology both compact and field-deployable.

Now, a team at Fraunhofer Institute for Applied Optics and Precision Engineering IOF (Fraunhofer IOF) in Jena, Germany, has developed a new source based on the VCSEL concept. The Fraunhofer IOF researchers' hybrid faint pulse source uses a linear array of eight VCSELs, promising higher spectral and temporal indistinguishability, enhanced polarization quality, and robust scalability for real-world applications (Figure 1). The system was in fact developed for a potential communication link from a low-Earth-orbit satellite to an optical ground station.

### Backbone of the photon source

The developed system uses a common gallium arsenide (GaAs) substrate for eight VCSELs with lithographically structured polarizers developed at the University of Stuttgart to enable the precise generation of polarization-encoded photons. This allows the source to efficiently support the four polarization states required by the BB84 protocol (H/V/D/A), while maintaining its ultra-compact form factor.

One of the main features of the developed system is its spectral indistinguishability, which it achieves through temperature leveling of the substrate to maintain a variation of significantly less than 0.5 K across the array. Centered at 850 nm, the wavelength differences are therefore approximately <40 pm, with >90% overlap at full width at half maximum.

Further, the integrated polarization gratings are electron beam written and can be aligned very precisely to the required direction. Preliminary data showed that on-chip polarizers can achieve at least 12-dB extinction ratio in diagonal, and at least 20 dB in a horizontal or vertical direction[4].

### System architecture and optical design

Four of the eight VCSEL channels are designated to supply decoy states by using an attenuator that reduces the amplitude of these pulses by ~4 dB. This approach enhances the overall security of the quantum communication link, as it allows the system to produce both signal and decoy pulses at the same spectral and temporal conditions. An integrated digital-to-analog conversion further enables the lasers to be driven with up to 5 GHz (Figure 2). It is expected that this signal is to come from an additional quantum random number generator.

The optical system of the source is housed in a KOVAR box with a low expansion coefficient (Figure 3). It houses the fixtures for a first collimation microlens array, the attenuator for the decoy states, and another microlens array for refocusing the eight beams onto the waveguide where they are merged into one output channel (Figure 3). The overall coupling efficiency is 99% without Fresnel losses. The 1% loss is due to the residual elliptical mode mismatch when the VCSEL modes are coupled into the waveguide, which is surrounded by a heatsink, which itself warrants a closed-loop temperature control to avoid any additional birefringence. The polarization-independent waveguide combiner is provided by the Institute of Photonics and Nanotechnology at Politecnico di Milano in Italy.

### Next steps

The eight-channel VCSEL source for BB84-based quantum key distribution with decoy states is miniaturized with integrated components using a space <40 × 40 × 43 mm. The signals from the eight separate channels are distinguishable with a spectral resolution of <50 pm and at a phase delay of <1 ps.

These specifications make the solution a strong candidate for a cubesat-size space mission, and all technologies have been selected to be ready for space qualification in the future. The prototype will be presented at Photonics West 2025.

### Meet the authors

Erik Beckert earned his diploma in precision engineering and a doctorate in optoelectronics system integration from Technical University of Ilmenau, Germany. He heads the Opto-Mechatronical Components and Systems department at Fraunhofer IOF in Jena, Germany; email: erik.beckert@iof.fraunhofer.de.

Christopher Spiess is a research associate and photonics innovator at Fraunhofer IOF. As a senior system engineer and project team leader, he specializes in advanced quantum communication systems and their technological implementations. Spiess earned a Ph.D. from Friedrich-Schiller University Jena; email: christopher.spiess@iof.fraunhofer.de.

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

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# About Lasers and a Dinosaur

BY ANDREAS THOSS
CONTRIBUTING EDITOR

If you look at the photonics landscape, you will see some well-known hotspots: There is of course Jena (my hometown) in Germany; Rochester, N.Y., and Tucson, Ariz., in the U.S.; and Eindhoven in the Netherlands. Vilnius, the capital of the Baltic state Lithuania, might not be the first place that you think of, but it's definitely up there, too.

Lithuania is a small country, roughly twice the size of the state of Maryland, with a population of 2.9 million. Its status as a photonics hotbed, especially in ultrashort-pulse laser technology, owes to the academics and the many reputable brands that headquarter in Vilnius. Light Conversion, Standa, EKSMA Optics, and EKSPLA are among the firms that have been established in Vilnius during the last 40 years. Today, 60 companies and more than 2000 people working in lasers and photonics call the country home, said Gediminas Račiukaitis, who serves as head of the laser department of the Center for Physical Sciences and Technology (FTMC) and president of the Lithuania Laser Association in Vilnius.

On the industry side, Light Conversion is Lithuania's largest laser maker. The company develops and manufactures ultrashort-pulse lasers, employs 600 people, and has procured more than €100 million in annual sales revenues. Today, more than 7500 of its laser systems are active in the field.

In September, Light Conversion hosted the European Photonics Industry Consortium (EPIC) Technology Meeting on Laser Microprocessing — the first such meeting in Lithuania since 2015. Company CEO Martynas Barkauskas personally led participants on a tour of the company's state-of-the-art facility. The company moved into a new building in 2021, and the space is nearly full after years of double-digit growth.

### A dinosaur serves the laser community

Lithuania's foundation in laser research is a long-term success story. The first laser built there was completed in 1966, and in the decades that followed, innovations emerged in the field of ultrashort-pulse lasers. The method of optical parametric chirped pulse amplification was invented by a research group at Vilnius University and represented a major advancement in improving the amplification of ultrashort pulses. Needless to say, Lithuania, and Vilnius in particular, has always been a home to many physics and laser students.

Yet this does not completely explain their long-term engagement and their commercial success. Germany is only an hour from Vilnius, and the U.S. is tempting. So why do students stay and continue to build a robust local laser industry?

I posed this question to Račiukaitis, who smiled and told me the story of FiDi and the dinosaur. FiDi, which stands for the "Day of Physics" in Lithuanian, has been celebrated in Vilnius since 1969. During the Brezhnev (head of the Soviet Union, of which Lithuania was a part of at that time) era, a group of physicists fought for a day of physics — and got it. FiDi has been celebrated ever since; the area surrounding the university is transformed into PhysLand, with many attractions, such as potato cannons, and laser experiments are open to the public.

"In 1978, some physics students had the idea to build a dinosaur — a large one, with a car inside," Račiukaitis said. "On the Day of Physics, in April, they moved it within a great procession of several kilometers through the whole city of Vilnius to the philological department of the university. And they have done this every year since then!"

Such an activity gets noticed in a small country. In 2014, even the Lithuanian president, Dalia Grybauskaitė, took part in FiDi46. It was at the high time of her campaign for the next term, and apparently the pictures of her and the dinosaur did not hurt, as she would soon win another term. The whole story of FiDi (and Dinas Zaurus) can be seen on YouTube (www.youtube.com/watch?v=O_I3pXlSe4M).

Believe it or not, FiDi and the dinosaur have helped to shape a positive image of physics in Lithuania as well as generations of physics students in Vilnius. During the months of preparation, participants not only learn team skills but also make friends for life. This is where the Lithuanian laser elite forms as a team. Consider local photonics students, for example, and ponder how such an annual project would drive their spirit.

And these teams extend beyond academia. When Lithuanian graduates visit Vilnius for an interview, they may find a buddy from a previous FiDi parade sitting across the table from them. At the very least, the CEO they are talking to is likely to be a Lithuanian who has followed the same career path and who knows exactly what to expect. As the most prominent example, Barkauskas himself studied in Vilnius and started as a postdoc at Light Conversion before moving into the service department, learning about customer needs and technical problems. Today as CEO, he enjoys close connections to local professors, competitors, and new entrepreneurs. And of course, he has helped build a dinosaur.

EPIC

Nail Garejev

Vilnius hosts the Day of Physics (FiDi) and its annual parade **(above)**. The famed dinosaur leads the pack.


Andreas Thoss

Gediminas Račiukaitis, head of the laser department of the Center for Physical Sciences and Technology (FTMC) and president of the Lithuania Laser Association in Vilnius, Lithuania, leads a session at the EPIC Technology Meeting on Laser Microprocessing **(left)**.

Four company visits and 20 presentations highlighted the proceedings of the 2024 EPIC Technology Meeting on Laser Microprocessing **(upper left)**. The meeting was held in Vilnius, Lithuania, Sept. 25 to 26.

## What's hot and cooking?

EPIC is an industry consortium, and so its Technology Meeting presentations are unrelated to academic achievements and instead focused on technological progress in industry. Industrial applications of ultrashort pulses were the main theme of the EPIC Technology Meeting on Laser Microprocessing. Texturing large surfaces became a hot topic. Lasers — including those with gigahertz bursts — as well as scanners, software, beam-shaping mechanisms, and ultraviolet (UV) pulses each took the spotlight. Drilling glass with a bottom-up approach, in which the beam from the top starts drilling from the bottom and moves upward, was mentioned repeatedly. Multibeam systems and fringe-based processing was also the focus of many discussions. One guest asked about the potential for an application to emerge that requires the development of a deep-UV scanner (another hen-and-egg discussion).

New ideas were also presented — such as laser dicing of semiconductors — through a liquid. Germany-based startup Lidrotec offers machines that perform this function. A layer of a flowing liquid on the surface allows clean and dust-free dicing of materials, such as silicon carbide, said Christian Keil, Lidrotec's developer of business development and sales. The liquid is (obviously) transparent and nonpoisonous, and it has a low viscosity.

Andreas Russ came from the other end of the scale. At Robert Bosch Manufacturing Solutions, Russ is group leader for laser technology for special machines. His team provides the automotive industry with complete solutions for various laser processes. This includes systems engineering, machine construction, and process development.

I found the work of this unit to be a surprising answer to the old "make or buy" question: I supposed that a large company, such as Bosch, would benefit from purchasing from one of the numerous system integrators. But, as I was told later, the company did not want to share all of its process know-how. In this context, making is of course better than buying.

The machines that Russ' unit delivers must be fully networked and optimized for 24/7 operation with minimum downtime. This equates to, for example, monitoring both the laser and the process, as well as storing all data for traceability. Russ shared application examples that ranged from diesel injection nozzles to surface polishing of silicon wafers. The challenges — managing machines around the world in different climates and with different levels of operator expertise — are considerable. Russ' presentation journeyed into the world of big industry, and the audience followed with great excitement.

To view more from the Day of Physics,
visit www.youtube.com/watch?v=O_I3pXISe4M.

### Going out to companies

EPIC Technology Meetings have a strong bias toward networking. “People come here to synchronize,” said Tim Kunze, CEO and cofounder of Fusion Bionic, a solution provider for laser-based surface functionalization. “They promote their offers or find a partner whose services they need.”

Often, this happens during one of the frequent coffee breaks, or over dinner. But the company visits are also excellent for this purpose. Even the bus trips can develop into a one-to-one pitch, if you know how to make it. Of course, the company visits themselves serve a similar purpose.

EPIC facilitated four company visits in Vilnius. Following the tour of Light Conversion, a visit to EKSMA Optics gave an answer to another major question: What is the difference between the two local brands EKSMA and EKSPLA? EKSMA, it turns out, stands for “experimental scientific equipment” while EKSPLA stands for “experimental lasers.” Also on the itinerary was Workshop of Photonics (WOP). A site visit to this company provided insights into its Bessel-beam-based technology for in-glass processing of microfluidic structures.

Also, Remigijus Šliupas, CEO and cofounder of Optoman, offered interesting details about the company’s market reach. Of the 300,000 optical coatings that Optoman sells each year, 19% go to the local industry, 37% are sold in Germany, and only 5% are sold in America. Like most companies, Optoman runs its machines 24/7. Labor shortages are an issue, which Šliupas takes as motivation to push automation.

### What to take home

EPIC meetings are intense networking events. Two days feel like five, and Vilnius was no different, with two dinners, 20 presentations, four company visits, and many hours of networking. Several of the presentations can now be downloaded from the EPIC event page.

There were a few key takeaways from the event. First, the laser industry is thriving in Lithuania and driving international expansion. A crucial part of the supply chain is in Vilnius, and with the tight connection to the main university, local industry has a steady source of qualified staff. They can and will grow with a focus on exports.

Second, laser micromachining is on the verge of finding more mass applications. Companies, such as Bosch, are driving applications in the automotive industry. The largest system sales are actually in semiconductor processing and consumer electronics manufacturing. It remains to be seen whether systems for structuring metal surfaces will catch up to semiconductor sales figures. The technology has reached a level of efficiency and scalability that is now competitive with that of established technologies.

So, another EPIC meeting concluded, providing the participants with valuable insights and contacts. And it seems reasonable not to wait another nine years for the next such event in Vilnius.

th@thoss-media.com

# Improving Laser Damage Resistance of Calcium Fluoride in Microchip Fabrication

BY JUE WANG AND INDRAJIT DUTTA
CORNING INCORPORATED

The rapid growth of advanced and intelligent technologies that power our daily lives — including hyperscale data centers, artificial intelligence, and smarter consumer electronic devices — is fueling the demand for more computing power and requiring even more powerful semiconductor chips. Driven by the need to support the rate at which this exponential technological growth is occurring, industry is adopting new photolithography tools that can print chips faster and with smaller features.

Amid semiconductor manufacturers aiming to realize higher throughputs and extend the lifetime of deep-ultraviolet (DUV) lithography systems, the use of an optimal material, as determined by the application, can in turn be a key determinant of performance, cost, and durability (Figure 1). Printing chip circuits at this scale demands an extremely precise laser as well as durable supportive optics. To meet these requirements, the selection of material is a critical consideration.

Historically, industry has favored argon fluoride (ArF) excimer lasers in and for lithography systems for the semiconductor industry. Recent improvements to these DUV sources have increased power levels from 60 to 90 W, and up to 120 W. The nanosecond-pulsed lasers operate at a wavelength of 193.4 nm, which corresponds to a photon energy of 6.42 eV[1].

Owing to high fluency, excellent lifetime stability, and high damage threshold in the DUV, crystalline materials — for example, calcium fluoride ($CaF_2$) — have been widely considered the materials of choice for ArF laser-based microchip fabrication.

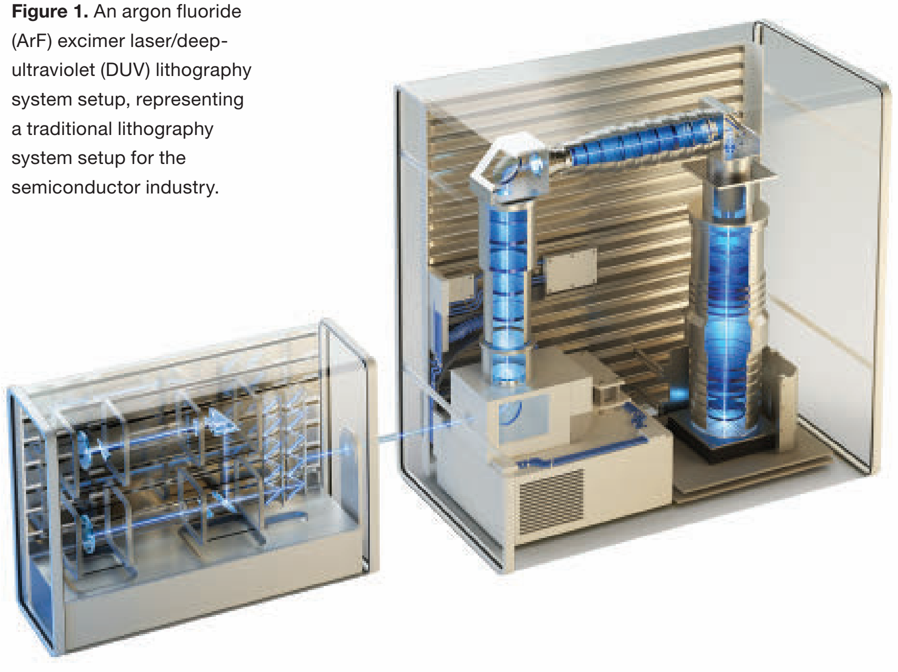


**Figure 1.** An argon fluoride (ArF) excimer laser/deep-ultraviolet (DUV) lithography system setup, representing a traditional lithography system setup for the semiconductor industry.

## Low-loss and laser-durable $CaF_2$

In recent years, semiconductor industry partners increasingly demanded higher-UV photon energies, longer pulse lengths, improved speckle performance, and higher pulse power densities to print more chips. $CaF_2$ laser windows and other optical materials were unable to meet necessary performance requirements, because these materials were becoming damaged after short exposure times.

In this context, an optimized material supporting low-loss and laser-durable $CaF_2$ laser windows was needed to support the next generation of high-powered lasers[2]. Corning Incorporated, with a history of growing $CaF_2$ ingots, developed a $CaF_2$ material for microlithography and laser optics applications that offers advantages compared with the previous materials. Additional research was subsequently dedicated to improving surface finishing, preparation, and coatings, which play a critical role in both the lifetime and optical performance of $CaF_2$ laser windows. Subsurface damage-free surface finishing and protective coatings extend the lifetime of $CaF_2$ laser windows by several orders of magnitude.

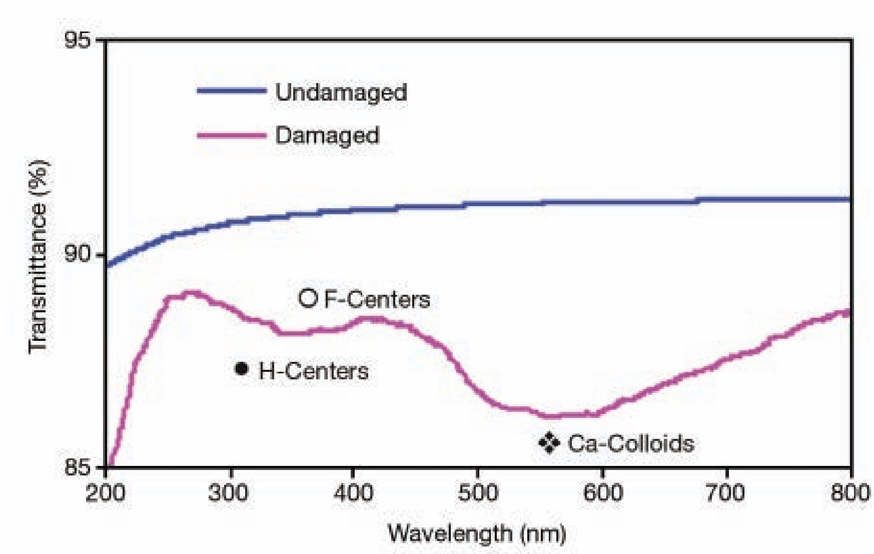
 All images courtesy of Corning Incorporated. 

## Laser and plasma coloration

Obtaining a fundamental understanding of the interaction of high-energy photons with $CaF_2$ optics is critical for improving the durability of these laser optics. ArF laser-induced damage of $CaF_2$ is associated with metallic calcium (Ca)-colloid formation. This is shown in Figure 2, in which the bulk surface Ca-colloid absorption leads to a purple appearance. The laser coloration is the result of a combination of the laser interaction with $CaF_2$ surface and bulk and a broadband absorption between 520 and 580 nm[1].

Plasma coloration, on the other hand, is a surface phenomenon and has a sharp absorption peak at 580 nm. The purple coloration in this instance is due to point-defect formation and agglomeration under ArF laser irradiation or plasma bombardment. Agglomeration of F-centers forms metallic Ca-colloids, causing a purple appearance. This purple appearance can also be observed on enhanced plasma-cleaned $CaF_2$ (Figure 3). A $CaF_2$ surface that is free from subsurface damage is obtained by uniting mechanical polishing and chemical etching, which increases laser damage resistance.

The Corning laser durable grade $CaF_2$ crystal shows superior laser damage resistance in comparison to ArF laser-grade $CaF_2$. Several generations of protective coatings for $CaF_2$ (for example, PCCF and PCCFxi) further extend the lifetime of $CaF_2$ laser optics.



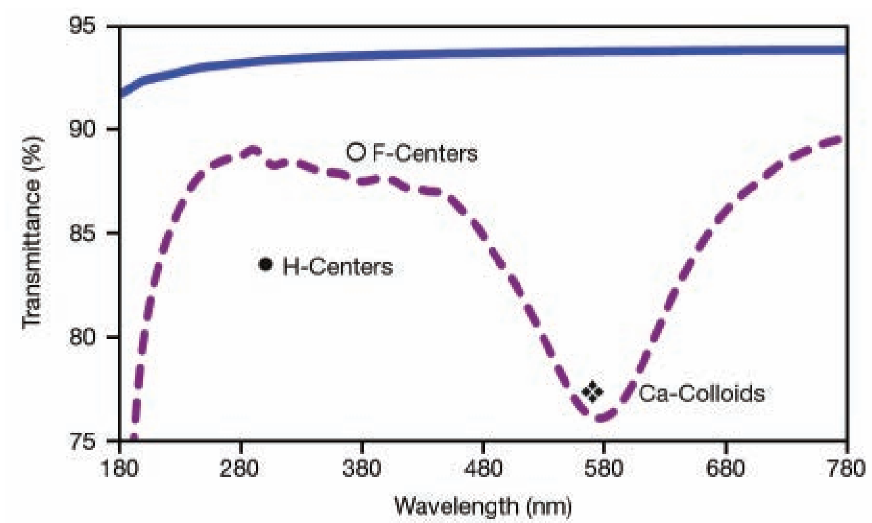




**Figure 2.** Spectral transmittance of argon fluoride (ArF) laser-damaged calcium fluoride ($CaF_2$), indicating absorptions associated with calcium (Ca)-colloids, F-centers, and H-centers. Spectral transmittance of an undamaged $CaF_2$ is included for comparison **(top)**.

**Figure 3.** Spectral transmittance of enhanced plasma-cleaned calcium fluoride ($CaF_2$), indicating absorptions associated with calcium (Ca)-colloids, F-centers, and H-centers **(bottom)**.

## High-energy x-ray coloration

High-energy x-ray exposure provides an effective means to simulate point defect formation in bulk and mobilization in comparison to the ArF laser-based accelerated lifetime damage test[3]. As a result, a high-energy x-ray coloration test was performed to compare the damage resistance between the earlier-generation material and the developed $CaF_2$ material following laser plasma coloration.

X-rays are generated when accelerated electrons blast a metal target or anode. A heated tungsten filament produces electrons, which are accelerated in-vacuum by a high electric field in the range of 20 to 60 kV toward the metal anode. The corresponding electric current is in the range of 5 to 100 mA. The total intensity of the x-ray is proportional to the square of the accelerating voltage, the filament current, and the atomic number of the anode[4].

The rhodium-anode x-ray tube, with an x-ray emission of 20 KeV, was used for

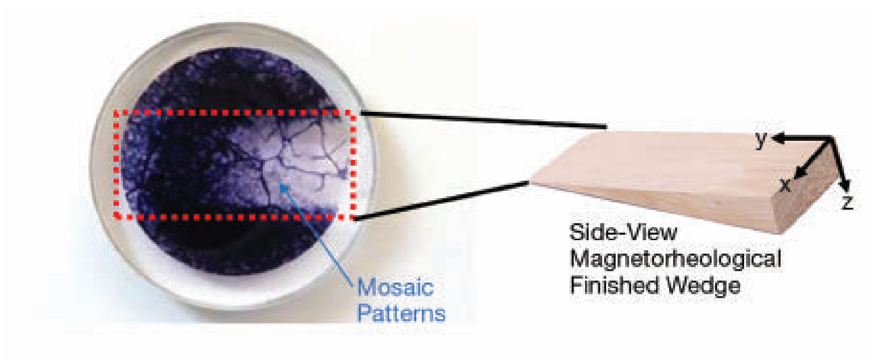



**Figure 4.** X-ray coloration of ϕ1″ calcium fluoride ($CaF_2$) after 12-h exposure followed by a magnetorheological finished (MRFed) wedge **(left)**.

**Figure 5.** Three surface-polished ϕ1″ calcium fluoride ($CaF_2$) after 1.5-h x-ray test exposure **(middle)**.

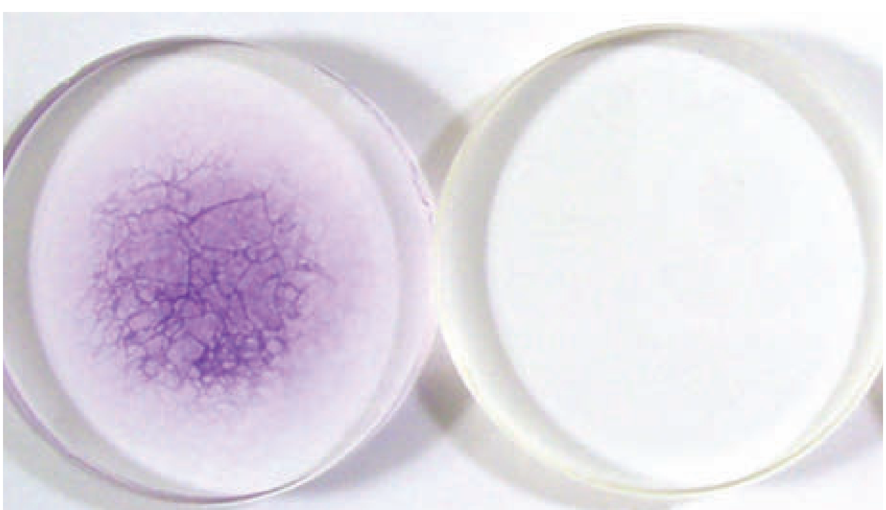


**Figure 6.** Deluxe polished ϕ2″ earlier-generation material **(bottom left)** and laser durable grade calcium fluoride ($CaF_2$) after 3-h x-ray exposure.

the x-ray exposure experiment. The high-energy x-ray coloration may reveal buried sub-grain boundaries. Further, the purple coloration has a textured pattern that is clearly revealed over the magnetorheological finished wedge (Figure 4). In this case, this pattern may represent a collection of sub-grain boundaries interacting with the high-energy x-rays. Since $CaF_2$ single crystals have sub-grains that have small angular misalignment, high dislocation density is expected to surround the sub-grains, forming sub-grain boundaries. The high dislocation density promotes purple coloration when exposed to high-energy x-rays.

Also, in $CaF_2$, dislocations are surrounding the sub-grain boundaries; these imperfections reduce the $CaF_2$ bonding energy. The energetic radiation of the high-energy x-ray leads to the separation of fluorine atoms from the bonded $CaF_2$ structure and the formation of fluorine vacancies. The aggregation of the fluorine vacancies forms high-density nanosized metallic Ca-colloids around the sub-grain boundaries. The Ca-colloids have a strong absorption of ~580 nm, leading to a purple appearance.

For surface quality assessment, three pieces of ϕ1″ $CaF_2$ samples with different surface polish qualities were exposed to the high-energy x-ray for a period of 1.5 h (Figure 5). The intensity of the purple coloration is proportional to the subsurface damage on the $CaF_2$ surfaces. In other words, the technique enables the visualization of the hidden subsurface damage layers.

For bulk crystal quality assessment, a pair of subsurface damage-free ϕ2″ earlier-generation material and laser durable grade $CaF_2$ were exposed to the high-energy x-ray. The x-ray exposure time was doubled to 3 h for the bulk quality assessment.

## Results

As shown in Figure 6, purple coloration does not appear on the subsurface damage-free laser durable grade $CaF_2$. This result suggests that this material is more damage-resistant to the high-energy x-ray in comparison with the earlier-generation material.

Further, in acquiring the Raman spectra at ambient conditions, the pristine $CaF_2$ (nonirradiated) showed a fundamental mode peaked at 320 $cm^{-1}$ (Figure 7). The x-ray-irradiated sample, (or colored $CaF_2$) has several additional broad peaks at 140 $cm^{-1}$, 220 $cm^{-1}$, 280 $cm^{-1}$, and 430 $cm^{-1}$. These peaks correspond to Ca-colloids[5].

The high-energy x-ray coloration additionally appears to indicate that the developed material has superior crystal quality compared with the earlier-generation material, which is depicted in Figure 6.

The high-energy x-ray coloration suggests that the developed laser durable grade $CaF_2$ material has improved crystal structure in comparison with the earlier-generation material. This results in greater damage resistance to high-energy photons and indicates that it will be able to meet the demanding material specifications for laser optics.

wangj3@corning.com
duttai@corning.com

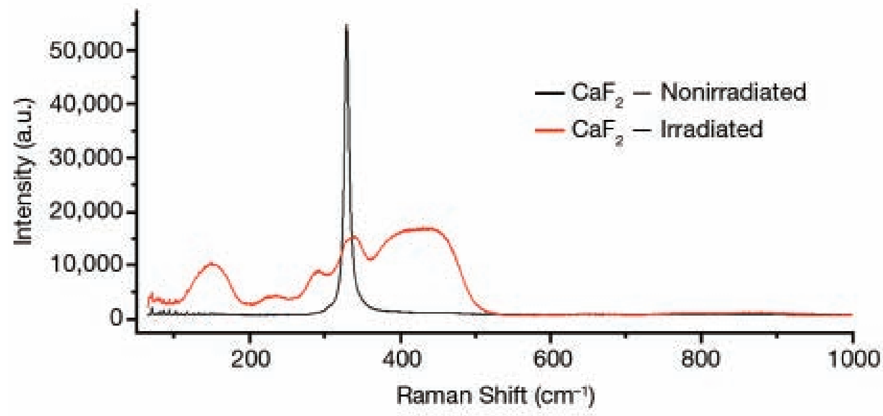


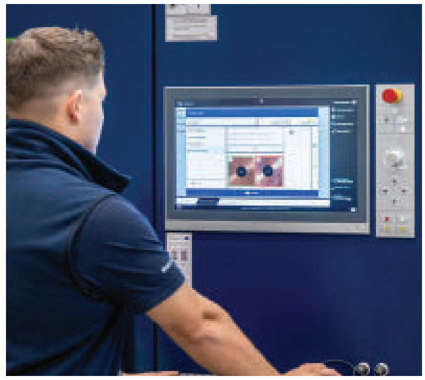

**Figure 7.** Raman spectra were acquired following x-ray testing at ambient conditions. A 100-mW laser at 532 nm was used to expose the samples for 30 s. These spectra were collected with five accumulations using a quasi-backscattering geometry and micro configuration with 100× magnification. The pristine calcium fluoride ($CaF_2$) (nonirradiated) shows a fundamental mode peaked at 320 $cm^{-1}$.

## References

1. J. Wang and G.P. Cox (November 2020). ArF laser-induced damage of calcium fluoride windows with protected anti-reflection coatings. *Proc SPIE*, Vol. 60, Article No. 3, Fairport, New York.
2. J. Wang et al. (March 2023). Surface and bulk damage resistance of calcium fluoride optics assessed by x-ray induced color centers. *Proc SPIE*, Vol. 12402, Article No. 8, San Francisco, California.
3. M. Babaeian et al. (December 2022). Hot-spot monitoring of ArF laser at HDC and high energy mode using low reflective beam splitter. *Proc SPIE*, Vol. 12300, Article No. 6, Rochester, New York.
4. P. Brouwer (2018), *Theory of XRF, getting acquainted with the principles* [booklet]. Almelo, Netherlands: Malvern Panalytical BV.
5. I. Alencar et al. (2016). Irradiation effects in $CaF_2$ probed by Raman scattering. *J Raman Spectrosc*, Vol. 47, No. 8, pp. 978-983.


## LED Testers

The BTS256-LED-UV (shown) and BTS256-LED-IR from **Gigahertz-Optik** are LED testers for single UV and IR LEDs, respectively. The testers include a built-in integrating sphere with a cone-shaped measurement port enabling hand-held or fixtured testing of PCB-mounted LEDs for radiant power, spectral power distribution, and peak intensity, among other benchmarks. The BTS256-LED-UV is calibrated for wavelengths between 200 and 550 nm with a bandwidth of 5 nm and radiant power levels from 10 μW to 2 W, while the BTS256-LED-IR is calibrated for wavelengths between 750 and 1100 nm with a bandwidth of 5 nm and radiant power levels from 0.3 μW to 5 W.
**info-us@gigahertz-optik.com**



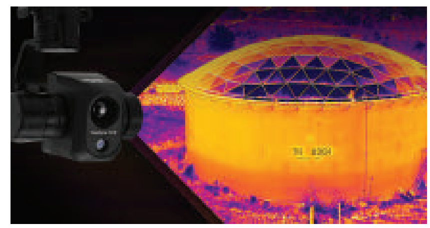
## Laser Cutting Machine

The TruLaser Series 1000 Lean Edition from **TRUMPF** is a laser cutting machine for industrial applications that require a lower production volume. The TruLaser Series 1000 Lean Edition features an online monitoring function, reversible collision protection, nanojoint technology, and a cutting guide function.
**info@de.trumpf.com**

## Femtosecond Fiber Laser

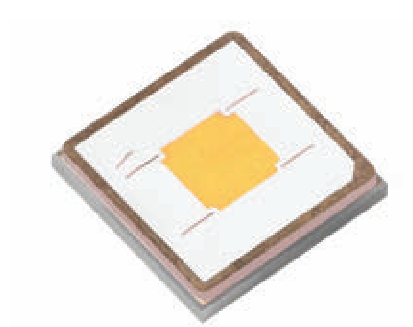
The VINCI-1064 from **TeraXion** is a femtosecond fiber laser for applications including


terahertz generation, multiphoton microscopy, and two-photon polymerization. The VINCI-1064 features a high peak power, short pulse durations of 50 fs, and a robust architecture.
**info@teraxion.com**



## Dual-Sensor Drone Payload

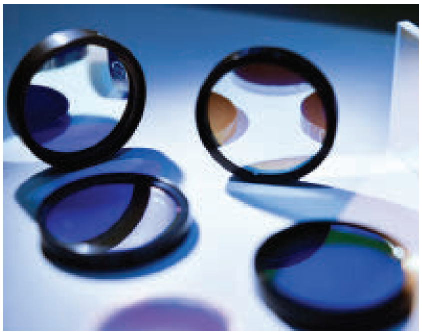
The Vue TV128+ series from **Teledyne FLIR** is a thermal-and-visible camera payload module for use in industrial inspection applications on uncrewed aerial systems. The ITAR (International Traffic in Arms Regulations)-free camera module pairs a 128×-zoom, 16-MP visible camera with the company's 640 × 512 resolution LWIR Boson+ thermal camera within a quick-connect gimbal. The Vue TV128+ series features the company's MSX Multi-Spectral Dynamic Imaging software, thermal sensitivity ≤20 mK, and an IP54 rating.
**flir@flir.com**



## Warm White LEDs

The SFT-40 series from **Luminus Devices** are high-power warm white LEDs that use vertical chip technology for high lumen density and small emitting angles, and phosphor-on-chip technology for uniform color distribution across radiation angles. The SFT-40 series also feature a color rendering index (CRI) of >95, warm white color temperatures between 2700 and 3000 K, a maximum power of 900+ lm at 4 A and 13 W,

and a flux of 400 lm at 1.5 A, 90 CRI, 50 R9, and Tj = 85 °C.
**sales@luminus.com**



## Optical Filter Sets

The Newport ODiate Fluorescent Filter Sets from **MKS Instruments** are single-band optical filter sets designed for wavelength ranges of common fluorophores used in fluorescent imaging. The filters use the company's thin-film coating technology designed to produce bright, high-contrast images and to maximize signal-to-noise ratios. The Newport ODiate Fluorescent Filter Sets are targeted at common fluorophores including DAPI, TRITC, GFP, FITC, Texas Red, and Cyanine (CY3.5) and feature excitation, emission, and dichroic filter options.
**sales@newport.com**


## Eight-Channel Spectrophotometer

The DS-8X from **DeNovix** is an eight-channel spectrophotometer designed for full-spectrum 1-μL UV-visible measurements from 190 to 840 nm for DNA, RNA, and protein quantification. The stand-alone device fits into GxP compliance environments with optional 21 CFR Part 11-ready software and installation qualification-operational qualification packages. The DS-8X can measure eight samples in ~10 s and features the company's EasyApps software containing configured applications for commonly measured biomolecule types.
**info@denovix.com**

## Portable 800GE Benchtop System

The Interconnect and Network Performance Tester 800GE Benchtop from **Keysight Technologies** is a multiport, multiuser, and multispeed portable design and validation platform that tests AI, high-performance computing, data center interconnects, and network infrastructure. The platform supports high-power consumption optical receivers up to 30 W while addressing test requirements of manufacturers of network equipment, silicon chips, optics, and cables as well as cloud service providers and

data center operators. The Interconnect and Network Performance Tester 800GE Benchtop features the company's software for network traffic simulation and is available in both a two-port and a four-port model.
**usa_orders@keysight.com**

## 2D PSDs and Analog Modules

The APX-VNG0031PSD series (shown) and E-VNG0031PSD series from **Advanced Photonix** are 2D position-sensitive detectors (PSDs) and companion analog modules, respectively. The APX-VNG0031PSD series are 2-mm 2D tetra-lateral extended visible indium gallium arsenide PSDs with a spectral range of 400 to 1700 nm, 2kΩ interelectrode resistance, and 20-µm position detection error. The E-VNG0031PSD series products feature APX-VNG0031PSD detectors integrated with transimpedance amplifiers with a spectral range of 400 to 1700 nm, a cutoff frequency of 5 MHz, SMA connectors, and UNC threading for cage and optical mount compatibility.
**info@advancedphotonix.com**

## Blue Laser Scanner

The Revopoint MetroX 3D Scanner from **Revopoint 3D** is a 3D blue laser scanner for capturing small and medium objects without the need for scanning spray on glossy or black items. The scanner's 14 blue laser cross lines can capture larger surface areas, while its seven blue laser parallel lines are for capturing fine details, edges, and complex surfaces. The Revopoint MetroX 3D Scanner also features a full-field mode using 62 lines of blue structured light to create point clouds of up to 7 million points per second with metrology-grade accuracy of up to 0.03 mm and precision of up to 0.01 mm.
**sales@revopoint3d.com**

## Optical Phantoms

**Edmund Optics**' OCT phantoms and diffuse reflectance phantoms provide off-the-shelf, standardized, ready-to-use tools for the calibration and optimization of imaging systems in research and clinical applications. The OCT phantoms offer a controlled sample for testing and calibrating OCT systems featuring optical properties such as refractive index, scattering coefficient, and absorption coefficient. The diffuse reflectance phantoms are available in sizes of 25 × 25 mm and 50 × 50 mm for muscle, brain, and adipose tissue imaging.
**sales@edmundoptics.com**

## $CO_2$ Laser Lenses

**Laser Research Optics**' line of $CO_2$ lenses are designed to match the lasers used by sign and plaque makers. The lenses are optimized for 10.6 µm and feature focal lengths in 1.5 to 7.5 in., in 0.5-in. increments. The lenses are antireflection-coated and available with dual-band coatings to aid in system alignment.
**sales@laserresearch.net**

## Stereo Vision Camera

The Gemini 335Lg from **Orbbec** is a stereo vision 3D camera for use with autonomous mobile robots in fulfillment centers, warehouses, and factories, as well as for robotic arms in bin picking and palletizing/de-palletizing tasks. The camera operates in both passive and active laser-illuminated modes for high-quality depth and RGB output in indoor and outdoor lighting

conditions. The Gemini 335Lg features support for transmissions of up to 6 Gbps and long-distance connection up to 15 m, built-in depth processing via the company's ASIC MX6800 depth engine, support for simultaneous connection between 16 cameras, and USB support.
**info@orbbec3D.com**

## Gas Imaging Camera

The OGI Camera from **LightPath Technologies** is an optical gas imaging platform that detects fugitive gas emissions for oil and gas applications. The camera uses IR imaging to detect and visualize emissions and leverages a non-germanium lens for higher sensitivity. The OGI camera can detect methane, volatile organic compounds, hydrocarbons, and other industrial gases that can be harmful to the environment or human health.
**sales@lightpath.com**

## Integrated Optical Amplifier

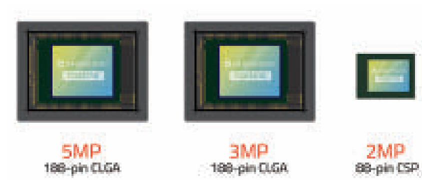
The DarkStar Utility Amplifier from **XKL** amplifies the optical signals carried in fiber optic cables for transmission over long distances and is designed for internet service providers, carriers, and other connectivity providers. The amplifier supports up to four fiber links, managing a range of optical components, including erbium-doped fiber amplifiers, Raman amplifiers, tilt and equalization filters, and an optical time-domain reflectometer.
**customersolutions@xkl.com**

## Miniature Microscope

The SUPERNOVA-600 from **Transcend Vivoscope** is a miniature microscope for real-time microscopic in vivo imaging of neuronal and cellular activities in the brain. The SUPERNOVA-600 incorporates the company's TLens tunable optics for fast autofocus capabilities for applications such as two-photon microscopy and free-moving animal imaging.
**info@tvscope.cn**

## Bioimaging Platform

The HT-X1 Plus from **Tomocube** is a bioimaging platform for capturing 3D images of cells and organoids for biomedical research applications. The platform is equipped with a CoaXPress camera and AI-powered image reconstruction algorithms, reducing scan times and allowing for 3D imaging of full 96-well plates in <30 min. The HT-X1 Plus also features a large field of view, flexible light source options, as well as color bright-field imaging and advanced correlative fluorescence imaging capabilities.
**info@tomocube.com**




## Back-Side Illuminated Sensors

The BSI GS sensors from **OMNIVISION** are back-side illuminated global shutter sensors for machine vision applications, including industrial automation, robotics, logistics, barcode scanners, and intelligent transportation systems. The sensors use a stacked-die architecture to enable thinner modules with better light absorption as well as the company's Nyxel NIR technology to boost quantum efficiency between 700 and 1050 nm. The BSI GS sensors feature small 3.45-µm pixels that achieve a shutter efficiency at 106 dB, 20 Ke- full-well capacity, on-chip dual conversion gain high dynamic range, and resolution options of 2 MP, 3 MP, and 5 MP.
**sales@ovt.com**

## 3D Lidar/Indirect TOF Sensor

The Q-Vision F540 from **Quanergy** is an indirect time-of-flight lidar sensor for applications in lo-


gistics, warehouse management, construction, and agriculture. The sensor supports a range of industry-standard programming languages and tools, including C, C++, Python, MATLAB, ROS1/2, OpenCV, and PCL for integration into existing development environments and automation systems. The Q-Vision F540 features on-sensor image signal processing capabilities, an integrated 2-MP RGB camera, and high dynamic range adaptation.
**sales@quanergy.com**

## SWIR Camera Series

Cheetah SWIR cameras from **Imperx** are industrial SWIR cameras designed for foreign object detection, wafer inspection, temperature monitoring, and ground and air-based vehicles. The cameras are based on Sony's SenSWIR image sensors, using indium gallium arsenide photodiodes in conjunction with CMOS readout circuitry to extend the spectral sensitivity into the SWIR. The Cheetah SWIR cameras are offered in imaging resolutions of 0.33 MP, 1.31

MP, 3.21 MP, and 5.32 MP with Camera Link and gigabit Ethernet Vision output options and an operating temperature range of −30 °C to 75 °C.
**sales@imperx.com**

## 50G PON OLT-ONU Devices

The BCM68660 and BCM55050 from **Broadcom Inc.** are 50G PON optical line terminal-optical network unit (OLT-ONU) devices for the acceleration of AI and machine learning at the edge and 50G fiber broadband network applications. The devices feature embedded AI/machine learning packet processing and traffic management cores, symmetric 50G ITU (International Telecommunication Union) PON/XGS-PON/GPON support, and 40× greater speed and lower latency than traditional devices.
**support.spectrometer@broadcom.com**

## Confocal Raman Microscope

The Apollo M from **CRAIC Technologies** is a confocal Raman microscope for applications including materials research, nanotechnology, pharmaceuticals, biomaterials, and semiconductor analysis. The microscope's confocal imaging system enables acquisition of high-resolution, 3D images of materials with enhanced spatial resolution and depth

profiling capabilities. The Apollo M also offers, multimodal imaging and automated analysis workflow capabilities.
**sales@microspectra.com**


### Thickness Measurement System

The 3DS Series from **Bold Laser Automation** is a confocal thickness measurement system for the measurement of electronics, medical devices, and filtration products. Integrated with Keyence CL Series laser sensors, the system uses continuous in-line and discrete off-line inspection as well as real-time data plotting and archiving. The 3DS Series is capable of handling materials up to 1 m × 500 mm and features a measurement accuracy of ±1 µm and bidirectional repeatability within <±0.02 mm.
**info@boldlaserautomation.com**

### Sub-Micron Positioning Stages

The Z110 Series from **Optimal Engineering Systems (OES)** are sub-micron z-axis positioning stages for mounting fixtures, optics, cameras, lasers, and wafer handling. The black anodized aluminum alloy stages have a resolution of 0.5 µm when driven with a 10-steps-per-step micro-stepping driver and up to 0.039 µm may be achieved with higher resolution micro-stepper motor drivers. The Z110 Series is available in travel strokes of 15, 30, 50, and 75 mm and features preloaded crossed roller bearings and 1-mm-per-motor-turn lead screws.
**sales@oesincorp.com**

### Laser Module

The FLEXPOINT MVpulseHP from **LASER COMPONENTS** is a pulsed laser module that can be used for open-air inspection tasks, such as the inspection of roads and rails. The module's maximum pulse length and duty cycle are preset at the factory so that the laser diode cannot overheat and are controlled during use by an integrated microcontroller. The FLEXPOINT MVpulseHP is available in the wavelengths of 445 nm at a power maximum of 1000 mW and

520 nm, 660 nm, and 808 nm at a power maximum of 500 mW with pulse lengths between 20 μs and 20 ms.
**info@laser-components.com**


## Fiber Optic Visual Fault Locator

The CableMaster VFL from **Softing Inc.** is a fiber optic visual fault locator, continuity tester, and polarity detector. The locator provides continuity testing and fault location for optical fibers in both single- and multimode by emitting a pulsed or continuous Class 2 visible laser. The CableMaster VFL emits light at 635 nm, transmits <1 mW of power, and can test fiber optic cables up to 5 km.
**sales@softing.us**

## Fiber Optic Feedthrough

The KTRAV-ST-M10 from **SEDI-ATI Fibres Optiques** is a fiber optic hermetic feedthrough designed for single- and multimode fibers up to 1000-μm heart. The feedthrough is compatible with applications in vacuum/ultrahigh vacuum and pressure environments of up to 600 bars. The KTRAV-ST-M10 features insertion losses of 0.3 dB typical at 1310 nm on SMF28 fiber.
**contact@sedi-ati.com**

## Edge Computer

The POC-700-FT series from **Neousys Technology** is a compact, fanless computer for edge computing applications. Built on Intel Alder Lake Core i3-N or Atom x7425E processors, the computer has a flat-top heatsink design that reduces its overall dimensions. The POC-700-FT series supports an M.2 2280 M key for SATA (Serial Advanced Technology Attachment) solid-state drives (SSDs) and a mini-PCIe socket for WiFi, LTE/5G, or controller area network bus devices and additionally features an expansion module design for COM, USB 3.1 Gen 1, ignition power control, or SATA ports for 2.5-in. HDD/SSD.
**sales@neousys-tech.com**

## Voice Coil Servo Motor

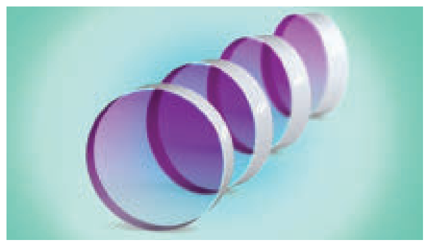
The GVCM-032-025-02M from **Moticont** is a compact linear voice coil servo motor for applications including medical devices, laser machining and drilling, scanners, laser beam steering and filtering, optical focusing, dynamic vibration absorption, testing, sorting, and assembly. The motor has a built-in 31.8-mm-diameter shaft and

bearing with a 25.4-mm-long housing and total length of 34.95 mm. The GVCM-032-025-02M features a continuous high-force-to-size ratio of 9.3 N, 29.3 N of peak force at a 10% duty cycle, and a shaft with a M2.2X0.45 × 5.1-mm-deep thread.
**moticont@moticont.com**

## Optical Water Analyzers

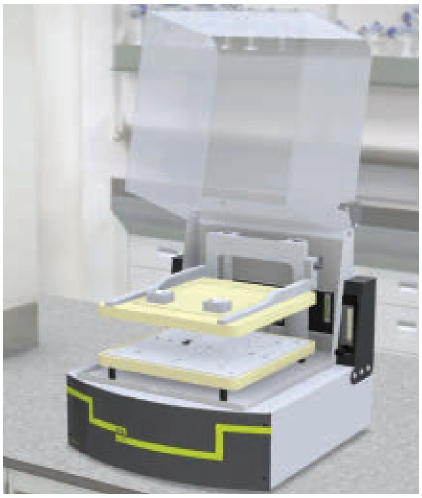
The UviTec analyzer product family from **ABB** comprises optical analyzers for the inspection of water sources and for the wastewater industry. Including optical sensors, controllers, a suite of add-on accessories and a data analytics and software solution, the family uses spectrophotometric and fluorescence measuring techniques to deliver lab-quality water analysis results in the process environment. The UviTec analyzer product family features UV and visible technology

that enables the rapid detection of a wide range of water quality parameters and compounds in real time.
**ftir@ca.abb.com**



## UV Optics

**OPTOMAN**'s UV laser optics can withstand >10,000 h of laser irradiation, preventing downtime of the laser system, and feature an ion beam sputtering coating for consistent spectral performances and high laser-induced damage thresholds without experiencing a color-changing effect.
**info@optoman.com**



## Isothermal Calorimeter

The iso-BTC e from **H.E.L Group** is a benchtop isothermal calorimeter for the measurement of heat dissipation in semiconductors, either individually or in situ on a printed circuit board. The iso-BTC e's direct measurement of heat power supports the design of chips and printed circuit boards by identifying thermal bottlenecks, power dissipation, and providing thermal validation to prevent overheating.
**contact@helgroup.com**

## Optical Polishing Pitch

The Gugolz Optical Polishing Pitch line from **Meller Optics** is a line of optical polishing pitch that is petroleum-free and comes in five hardness grades ranging from soft to hard. Melting points range from 52 °C to 87 °C. Made from wood resin, the Gugolz Optical Polishing Pitch line can be used for the blocking, lapping, and polishing of precision optics. The pitch can additionally be sliced and melted, and poured onto a lap.
**sales@melleroptics.com**

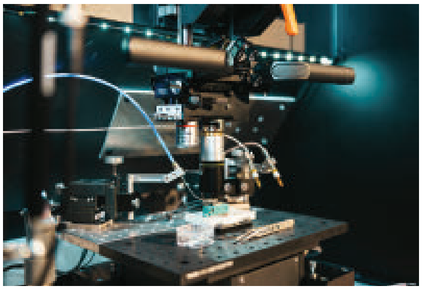
## Metal Surface Cleanliness Instrument

The CleanoSpector from **Dyne Testing** is a hand-held instrument for the testing of metal cleanliness in industrial settings. The instrument provides noncontact and nondestructive inspection of metal surfaces detecting contamination on the metal's surface by emitting focused UV light onto the surface and measuring the fluorescence from any organic compounds, such as oil, grease, coolants, release agents, and cleaning fluid. The CleanoSpector works on both metals and ceramics and uses various spacers that can provide measurements of different part shapes to ensure the correct focal length.
**sales@dynetesting.com**

## Staining Reagent Kit

The CellO-IF from **AMS Biotechnology** is an immunofluorescent staining reagent kit

designed to accelerate the labeling of organoids and spheroids directly in hydrogels or extracellular matrices, while preserving structures and cellular integrity. The CellO-IF allows for the elimination of harvesting, clearing, transferring, and centrifuging and is available in formats for labeling either 3D or 2D samples.
**info@amsbio.com**



### Semiconductor Failure Analysis Tool

The QD m.0 from **QuantumDiamonds GmbH** is a quantum-based device designed for semiconductor chip failure analysis. The system uses diamond-based quantum microscopy to detect and localize faults in integrated circuits. The QD m.0 can extract electrical current information across multiple layers of 2.5D/3D packages and chiplet-based architectures.
**info@quantumdiamonds.de**


# Product News


### USB3 Camera

The USB 3.1 Gen 2 10 Gbps from **Alkeria** is a USB3 camera for applications that require higher frame rates and smoother real-time image processing. The camera eliminates the need for frame grabbers and dedicated boards, and features a cable with a maximum length of up to 20 m, allowing for flexibility in system design.
**sales@alkeria.com**

### Photochemistry Reactors

**Asynt**'s range of photochemistry reactors can be used in both batch and flow equipment. The reactors scale reactions from milligrams to potentially multiple kilograms, with smaller batch photochemical reactors for the smaller quantities, to continuous-flow photochemistry reactors equipped with high-power sources for increased throughputs. Asynt's range of photochemistry reactors require the use of LEDs for controlled reactions at repeatable strengths and are designed to provide narrow emission bands and limit power degradation between the source and reagent via efficient light transfer methods.
**enquiries@asynt.com**


### Fiber Laser Platform

The EDGE FL series from **Coherent Corp.** is a fiber laser series designed for cutting applications in the machine tool industry. Available with power levels from 1.5 to 20 kW, the series' supplied fiber is 25-m long with a core diameter between 50 and 100 µm.
**info@coherent.com**

### IR LED Chip

The IR:6 technology from **ams OSRAM** is a thin-film infrared LED chip technology for use in medical equipment and IR LED emitters used in manufacturing applications. The technology can emit light at a 920-nm dominant wavelength along with wavelengths of 850 and 940 nm. The

IR:6 technology also features a central bond pad for better current spreading and a lower forward voltage, a roughened chip surface for higher decoupling efficiency and higher brightness, and an increase in brightness by up to 35% and efficiency by up to 42% compared with the existing chip technology used in ams OSRAM's IR LED emitters.
**sensors@ams.com**

## Piezo Stage Family

The P-545 PInano family from **PI** (**Physik Instrumente**) is a piezo stage family for applications including biological imaging, semiconductor inspection, photonics testing, particle tracking, 3D imaging, and superresolution microscopy. The stages integrate space-tested piezoelectric drive technology along with position feedback sensors for nanometer-precise measurements. The P-545 PInano family features closed-loop control, sub-nanometer resolution, multi-axis flexibility, and a digital servo piezo controller and driver with USB.
**info@pi-usa.us**

## Compact DPSS Lasers

**Frankfurt Laser Company**'s line of compact diode-pumped solid-state (DPSS) lasers are designed to provide solutions for a wide range of industrial, medical, scientific, and optical applications. The lasers have a laser diode-pumped design for high durability and expected lifetimes of up to 10,000 h. The compact DPSS lasers are available at central wavelengths of 561, 577, and 589 nm at output powers of 800 and 1000 mW and feature a power stability of <5% rms over 4 h, a power consumption of <20 W, and function under pressures of 0.02 kPa.
**sales@frlaserco.com**

## RGB-IR USB Camera

The See3CAM_CU83 from **e-con Systems** is a 4K RGB-IR USB camera for applications including biometric access control, in-cabin monitoring, crop health monitoring, image-guided surgeries, and smart patient monitoring. The camera incorporates the company's RGB-IR separation algorithm to separately process RGB and IR frames from the sensor and does not include mechanical switch filters. The See3CAM_CU83 features onsemi's AR0830 sensor.
**sales@e-consystems.com**

# Industry Events

## JANUARY

**A3 Business Forum**
**(Jan. 20-22)** Orlando, Fla.
Contact A3, +1 734-994-6088; www.automate.org/events/business-forum-2025.

**SPIE BiOS 2025**
**(Jan. 25-26)** San Francisco.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/photonics-west/exhibitions/bios-expo.

**SPIE Photonics West 2025**
**(Jan. 25-30)** San Francisco.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/photonics-west.

## FEBRUARY

**Biophysical Society Annual Meetings**
**(Feb. 15-19)** Los Angeles.
Contact the Biophysical Society, +1 240-290-5600, **society@biophysics.org**; www.biophysics.org/2025meeting.

**SPIE Medical Imaging**
**(Feb. 16-20)** San Diego.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/medical-imaging.

**SEMICON Korea 2025**
**(Feb. 19-21)** Seoul, South Korea.
Contact SEMI, +82 2-531-7800, **semiconkorea@semi.org**; www.semiconkorea.org/en.

## MARCH

**Pittcon**
**(March 1-5)** Boston.
Contact The Pittsburgh Conference, +1 412-825-3220, **info@pittcon.org**; www.pittcon.org/pittcon-2025.

**International Laser Safety Conference**
**(March 3-6)** Orlando, Fla.
Contact The Laser Institute, +1 407-380-1553; www.ilsc.ngo.

**LASER World of PHOTONICS China**
**(March 11-13)** Shanghai.
Contact Messe München GmbH, +49-89-949-11468, **info@world-of-photonics.com**; www.world-of-photonics.com/en/china.

## PAPERS

**11th International Conference on Machine Vision and Machine Learning**
**(Aug. 17-19)** Paris.
**Deadline:** Abstracts, Jan. 23
Contact International ASET Inc., +1-613-834-9999, **info@mvml.org**; www.mvml.org.

**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.

**SPIE Smart Structures + Nondestructive Evaluation**
**(March 17-20)** Vancouver, British Columbia.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/smart-structures-nde.

**Image Sensors Europe**
**(March 18-19)** London.
Contact Image Sensors Europe, +1 330-762-7441; www.image-sensors.com/image-sensors-europe.

**W3 + Fair WETZLAR**
**(March 19-20)** Wetzlar, Germany.
Contact FLEET Events GmbH, **w3plus@fleet-events.de**; www.w3-fair.com/en/wetzlar.

**OFC**
**(March 30-April 3)** San Francisco.
Contact OFC, +1 972-349-7840, **ofc@mcievents.com**; www.ofcconference.org/en-us/home.

## 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, **customerservice@spie.org**; https://spie.org/conferences-and-exhibitions/optics-and-optoelectronics.

**SPIE Defense + Commercial Sensing**
**(April 13-17)** Orlando, Fla.
Contact SPIE, +1 360-676-3290, **customerservice@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.

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

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

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

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

### Photonics North
**(May 20-22)** 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.

### 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.

### 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.

## JULY

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

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

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

## AUGUST

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

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

# Photonics Showcase

## High-Precision OEM Optical Systems

We design, engineer, and produce optics and optomechanical systems, ultra-high precision semiconductor optical sub-systems, medical and scientific instruments, ophthalmic optical sub-systems, digital cinematic projection optics, optical systems for aerospace technologies, military optical systems and consumer sports optics. We are vertically integrated and produce optics and mechanics in-house with over 1M square feet of manufacturing space.

**Meopta s.r.o.** **+420581241111**
**meopta@meopta.com** **www.meopta.com**

## PEM200 Polarization Modulation

The PEM200 has a digital controller and optical enclosures with sleek, compact designs. Benefits of using the PEM200 are increased stability at low modulation, increased signal-to-noise for short wavelength applications, modulation purity, and high sensitivity. The PEM200 allows seamless integration for applications such as astronomical research, remote sensing, materials characterization and research, polarization microscopy, and pharmaceutical research.

**Hinds Instruments Inc.** **(503) 690-2000**
**sales@hindsinstruments.com** **www.hindsinstruments.com**

## TracePro Optical Design Software


TracePro® is the go-to optical design software for lighting, displays, and imaging systems. Advanced ray tracing, stray light analysis, and optimization tools simplify complex designs. The new Sequence Editor adds sequential ray tracing, spot diagrams, and beam analysis, seamlessly integrating with CAD tools. Recent updates enhance analysis speed and CAD interoperability for photonics, aerospace, and medical applications.

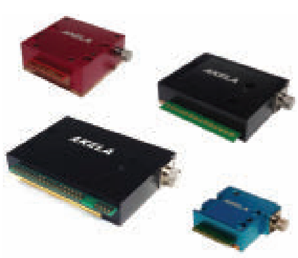
**Lambda Research Corporation** **(978) 486-0766**
**sales@lambdares.com** **www.lambdares.com**

## Beam Launchers for Quantum

Schäfter+Kirchhoff offers a new series of beam launchers – customized optical systems – for collimation and combination of fiber-guided radiation from multiple laser systems, that are compact, modular and long-term stable – ideal for launching tailored laser beams to the desired target. The variety of functions that can be integrated makes them ideal for quantum applications.

**Schäfter+Kirchhoff GmbH** **+49 40 85 39 97-0**
**info@sukhamburg.com** **www.sukhamburg.com**

## Multi-Wavelength Laser Diode Modules




Versatile lines of multi-wavelength and high-power fiber-coupled laser diode modules for medical and industrial applications combining emitters from 375 to 2000 nm. Over fifty standard module designs and wavelengths combinations. Limitless potential custom configurations. Quick prototyping. One module, multiple applications. Seamless and fast transition from pilot batches to volume production.

**AKELA Laser Corporation** **(732) 305-7105**
**info@akelalaser.com** **www.akelalaser.com**

## 6-Axis Precision Hexapods

PI hexapods are supported by powerful, easy-to-use controllers, along with extensive programming examples and software tools for simulation and workspace verification.

**PI (Physik Instrumente) LP** **(508) 832-3456**
**askpi@pi-usa.us** **www.pi-usa.us**

## Discover Precision with the VARIUS


Experience the innovative VARIUS™ Spectrometer, featuring patent-pending technology that elevates versatility and precision. Easily adapt to any challenge with its replaceable slit, achieve stray light levels as low as 0.1%, superior signal-to-noise ratios, and experience fast data transfer. We invite you to explore the VARIUS™ Spectrometer at Photonics West, booth 1740 at Avantes. Join us in discovering its potential!

**Avantes** **+31 313 670 170**
**info@avantes.com** **www.avantes.com/products/avaspec-varius**

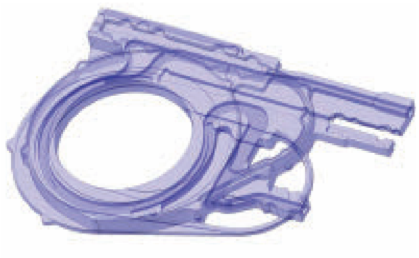
## Leader in Diamond-Like Carbon

DLC coatings are ideal for Infrared applications with their high refractive index and are recommended for use in harsh environments because of their excellent physical/chemical resistance. Intlvac's DLC system offers a unique proprietary 8-12 BBAR process. Recently developed processes include: thick DLC up to 4 μm, reduced stress, black DLC, and electrical conductivity.

**Intlvac Thin Film** **(800) 959-5517**
**sales@intlvac.com** **www.intlvac.com**

# Photonics Showcase

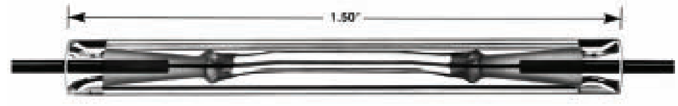
## Experienced Precision Brazing!



We have 20+ years machining complicated brazed cold plates with a specialization in aluminum cold plates. We also have experience with copper and stainless steel, as well as machining finned and dip brazed heat exchangers for passive heat exchanger systems.

**Lux Manufacturing Inc.** **(408) 617-0635**
**sales@luxmfg.com** **www.luxmfg.com**

## Norland Optical Splice




Norland's optical splice provides a high-performance connection for optic fibers in a unique one-piece design.

**Norland Products Inc.** **(609) 395-1966**
**info@norlandproducts.com** **www.norlandproducts.com**

## 872 Series Laser Wavelength Meter


The 872 Series High-Resolution Laser Wavelength Meter is ideal for the frequency stabilization of lasers. Offering a frequency resolution as high as 200 kHz, the 872 Series provides exceptional sensitivity to wavelength deviations. With a built-in PID controller and 1 kHz sustained measurement rate, the 872 Series is well suited to precisely stabilize lasers used in applications such as atomic cooling and trapping.

**Bristol Instruments Inc.** **(585) 924-2620**
**info@bristol-inst.com** **www.bristol-inst.com**

## ZEISS PGS NIR 2.5

The Plane Grating Spectrometer NIR 2.5 from ZEISS offers high-quality NIR spectroscopy, covering a broad range of 1200 to 2450 nm with a spectral dispersion of 5 nm/pixel. It uses enhanced InGaAs sensor technology for improved data rates and linearity. Custom ZEISS gratings ensure optimal NIR sensitivity and signal quality. Contact us to explore the full potential of our PGS.

**Carl Zeiss Spectroscopy GmbH** **+49 3641-64-2838**
**info.spectroscopy@zeiss.com** **www.zeiss.com/spectroscopy**

## Improving Performance in the SWIR

Discover Chroma Technology's SWIR filters, engineered for unparalleled environmental monitoring and industrial inspection precision. Detect gases, monitor pollutants, and ensure flawless quality control with filters built for exceptional results. Rely on Chroma's SWIR filters for superior performance and reliability.

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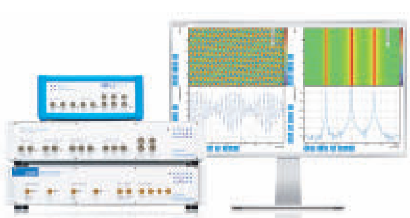
**sales@chroma.com**
**www.chroma.com/swir**

## Femtosecond Laser CARBIDE


CARBIDE is a series of femtosecond lasers combining high average power and excellent power stability. CARBIDE features market-leading output parameters without compromises to beam quality and stability. The CARBIDE is employed in top-class research centers, as well as display, automotive, LED, medical, and other industries. The reliability of CARBIDE has been proven by hundreds of systems operating 24/7 in industrial environments.

**Light Conversion** **+370 5 247 2232**
**sales@lightcon.com** **www.lightcon.com**

## Lock-in Amplifiers



Zurich Instruments Lock-in amplifiers are equipped with the LabOne® user interface, providing time- and frequency-domain signal analysis tools in the form of a scope, a real-time data plotter, a DAQ module, a spectrum analyzer, and a sweeper. Upgrade options include phase-locked loops, PID controllers, multi-demodulator and multi-frequency functionalities, boxcar averagers, and arbitrary waveform generators. Let's connect!

**Zurich Instruments** **+41 44 515 0410**
**info@zhinst.com** **www.zhinst.com**

## Picomotor™ Piezo Linear Actuators

Achieve high stability and nano-precision at target point. Newport linear actuators are designed for motorizing fine-positioning optical mounts and positioners when the smallest step sizes, exceptional precision and set-and-forget stability are required.

**MKS | Newport** **(877) 835-9620**
**sales@newport.com** **www.newport.com/f/picomotor-piezo-linear-actuators**

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## Our Broadest Tuning Yet

Unlock the full potential of your spectroscopy application by accessing the valuable fingerprint region of the mid-infrared with MIRcat™. Our enhanced MIRcat laser, equipped with Daylight-engineered QCLs, offers unparalleled wavelength coverage, allowing precise targeting of this critical region for more accurate and detailed molecular identification. Achieve deeper insights and more reliable results, all within the same trusted compact design.

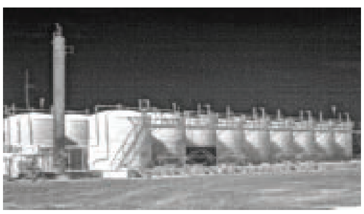
**DRS Daylight Solutions** **(858) 432-7500**
**taylor.stathopoulos@drs.com** **www.daylightsolutions.com**

## Cr Series Fixed Focal Length Lenses

These ruggedized imaging lenses are protected from shock and vibration to avoid damage while maintaining optical pointing and positioning. All individual lens elements are glued in place while robust mechanics with a simplified focus and stainless steel locking C-Mount clamp further prevent pixel shift. They are ideal for calibrated imaging systems such as measurement and gauging, 3D stereo vision, robotics and sensing, and autonomous vehicles.

**Edmund Optics** **(800) 363-1992**
**techsup@edmundoptics.com** **www.edmundoptics.com**

## 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 roadblock 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.

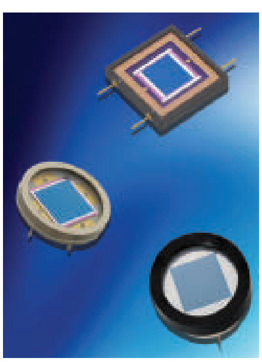
**LightPath Technologies** **(724) 272-3067**
**rschutte@lightpath.com** **www.lightpath.com/optical gasimagingoilandgas**

## Custom Precision Optics & Assemblies

For three generations, LaCroix has been dedicated to empowering our customers' success. We don't just meet the demand for precision optics – we anticipate it. From prototype to production and assembly, we can guide and grow with you every step of the way. Experience the LaCroix advantage.

**LaCroix Precision Optics** **(870) 698-1881**
**info@lacroixoptics.com** **www.lacroixoptics.com**

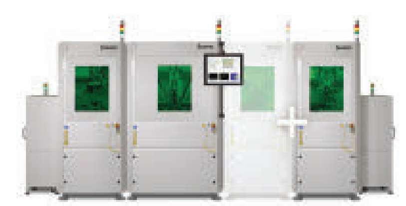
## Tetra-Lateral Two-Dimensional (PSD)



Tetra-lateral position sensing detectors are manufactured with one single resistive layer for both one and two dimensional measurements. They feature a common anode and two cathodes for one dimensional position sensing or four cathodes for two dimensional position sensing. They offer high response uniformity, low dark current, and good position linearity over 64% of the sensing area.

**OSI Optoelectronics**
**(310) 978-0516**
**sales@osioptoelectronics.com**
**www.osioptoelectronics.info/site**

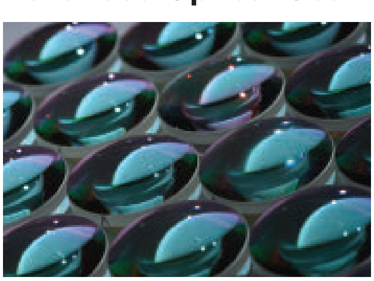
## Photonics Assembly and Test



ficonTEC is the world leader for integrated photonic device assembly and test manufacturing solutions. The individual systems are available as standalone cells or as a coherent in-line production line, at various levels of automation and at every level of process development or manufacturing scale. Manufacturing made light, scalable from lab to fab. Find us at Photonics West and tell us what you need.

**ficonTEC Service GmbH** **+49 4202-51160-0**
**info@ficontec.com** **www.ficontec.com**

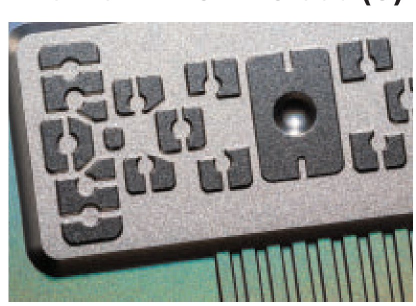
## Advanced Optical Coatings



PFG Precision Optics offers advanced optical coatings, both as a service and as part of complete custom optics fabrication. Coating offerings include AR, HR, and beam-splitting designs. With over 40 years of expertise, PFG provides coating solutions for the semiconductor, defense, research, and advanced metrology industries, ensuring precision and reliability at the highest levels. Prototype through production in the USA.

**PFG Precision Optics Inc.** **(228) 875-0165**
**sales@pfgoptics.com** **www.pfgoptics.com**

## The New LASER S 500 (U)



Inspired by 70 years of innovation in the machine tool industry, GF Machining Solutions is proud to introduce its ultimate product: the LASER S 500 (U) that takes accuracy and speed to a new level. Micro-machining and 3D surface processing become child's play with the LASER S 500 (U).

**GF Machining Solutions** **+41 76 495 06 55**
**communications.gfms@georgfischer.com** **www.gfms.com**

# Photonics Showcase

## BTS2048 Series Spectroradiometers

The BTS2048 line of spectroradiometers feature a fast response time over a wide dynamic range using three processors and electronic shutter plus input and output triggers for synchronized measurement applications. Considered scientific grade instruments in terms of linearity, stray light reduction and calibration they are compact and portable enough for use in production or field service. Complete UV, VIS or NIR spectral data is provided.

**Gigahertz-Optik Inc.** **(978) 462-1818**
**info-us@gigahertz-optik.com** **www.gigahertz-optik.com**

## Creating a Better Future Together


Hamamatsu is committed to advancing light and imaging technologies to improve lives. From healthcare to environmental solutions, we are pioneering innovations that address the world's most complex challenges. Join us at Photonics West 2025 at booth 1127, alongside Energetiq Technologies, NKT Photonics, and Fairchild Imaging to discover our collaborative efforts for a brighter future, together as One Hamamatsu.

**Hamamatsu** **(908) 231-0960**
**photonics@hamamatsu.com** **bit.ly/41pchUU**

## UV Hyperspectral Scanning System


Inno-spec GmbH, a Headwall Group company, introduces a complete UV Hyperspectral Scanning System with the BlueEye camera, automated stage, illumination, safety enclosure, and even an ozone mitigation system. Pharma PAT, art & forensics, adhesives & films, and many other uses. Learn how our new hyperspectral systems let you Collect, Train, Deploy, and Succeed with your applications!

**inno-spec GmbH** **+49 911 376691-0**
**info@inno-spec.de** **www.inno-spec.de**

## Lock-in Camera heliCam C4/C4M

The heliCam C4/C4M by Heliotis revolutionizes imaging with over one million lock-in amplifiers on a single chip. With in-pixel signal processing, the heliCam C4 achieves real-time, high-resolution dual-phase demodulation at up to 250 kHz and an impressive 21-bit dynamic range. Perfect for researchers needing massive parallel detection of weak optical signals.

**Heliotis AG**
**+41 414556700**
**web@heliotis.com**
**www.heliotis.com**

## Laser Safety Glasses

HHV AT's innovative multilayer thin-film coated Laser Safety Glasses protect users from Class 3B And Class 4 harmful lasers. High optical densities up to OD7+ for enhanced laser protection. All of the laser-coated glasses are EN208 compliant. Coatings can be done on BOROFLOAT-33 and optical filter glass from 400- to 1100-nm wavelength range. Customized shapes of glasses can be done.

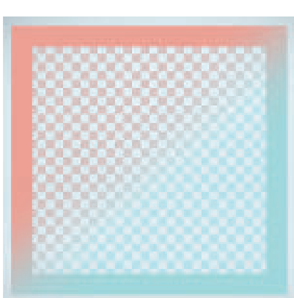
**HHV Advanced Technologies Pvt. Ltd.** **+91 80-67003700**
**infotfod@hhvadvancedtech.com** **www.hhvadvancedtech.com**

## P940 Modular Power Solution

Simplify your test bench power requirements with Highland Technology's compact and economical P940. Mix and match DC and 3-phase AC supplies, loads, alternator simulators, and more in a single 3U chassis with a unified USB and Ethernet interface with programmable monitor outputs. Featuring front panel GUI and waveform monitor outputs, synchronized multi-module control, SCPI, and fast UDP monitoring.

**Highland Technology Inc.** **(415) 551-1700**
**sales@highlandtechnology.com** **www.highlandtechnology.com**

## Patterned Thin-Film Optics



Custom photolithographic patterning service produces a wide range of complex patterned optics with geometries down to 5µm on substrates up to 18" in diameter. We provide multiple pattern stacking and gapless patterns. Metallic or dielectric materials are selected based on the application's transparent, reflective, and/or conductive opto-electrical requirements for alignment test & reference patterns, heated windows, reticles, barcodes. ISO & ITAR

**Reynard Corporation** **(949) 366-8866**
**sales@reynardcorp.com** **www.reynardcorp.com**

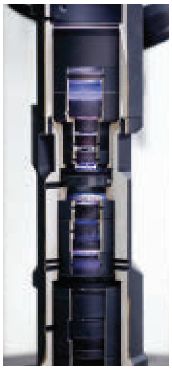
## Y Imaging Colorimetry in Perfection

Admesy's Helios Y imaging Colorimeter establishes new benchmarks for the color accuracy of imaging systems measuring Y exclusively. The Helios is designed for display measurements and is also well-suited for accurate color measurements of virtually any scene, such as automotive dashboards or functional and decorative lighting. Several unique patent pending features are incorporate to push the accuracy limits further.

**Admesy** **+31 475-600-232**
**sales@admesy.com** **www.admesy.com/series/helios**

# Photonics Showcase

## Custom High NA Objective Lens



Hyperion specializes in custom objective lenses engineered for quantum applications. Achieve high NA in a compact design with metrology-backed precision, including 2-5μm decenter & tilt correction per surface and 20μm 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.

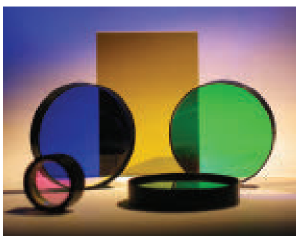
**HYPERION OPTICS USA**
**(908) 899-1918**
**rfq-us@hypoptics.com**
**www.hyperionoptics.com**

## SWIR Cameras – See the Invisible

Short-wave infrared (SWIR) cameras capture images in light ranges beyond visible light, enabling detection of objects difficult for traditional cameras or the human eye to see. With high image quality and resolution, they are ideal for semiconductor, packaging, and food industries. For example, they can detect transparent materials, inspect produce for defects and check levels in opaque containers. Choose Balluff for unmatched SWIR technology.

**Balluff Inc.** **(800) 543-8390**
**balluff@balluff.com** **www.balluff.com**

## More Signal, Less Background



Iridian's custom optical filters provide wavelength selectivity from the UV to LWIR to applications including communications (telecom/datacom/satcom), spectroscopy (Raman/fluorescence/molecular diagnostics), sensing and imaging (gas detection/Earth observation/lidar). With high transmission and deep and broad blocking, our custom filter solutions and multizone filter arrays are designed and manufactured to optimize technical and commercial needs in our customers' systems.

**Iridian Spectral Technologies Ltd.** **(613) 741-4513**
**istsales1@idexcorp.com** **www.iridian.ca/product-custom-filters**

## Hyperfine One Spectrometer

Compact 250 to 1000 nm spectrometer with 1 nm resolution at all wavelengths Leveraging LightMachinery's world class design and manufacturing for higher sensitivity Onboard image processing and serial data output with a easy to use user interface The right choice whenever a brighter, faster, or wider spectrum is required. The wide range and high sensitivity enable high speed process control for spectroscopic measurements from UV to NIR

**LightMachinery Inc.** **(613) 749-4895**
**gsenechal@lightmachinery.com** **www.lightmachinery.com**

## Multi-Axis Fiber Alignment System

The FiberMax®HP 3- to 6-axis photonics alignment platform is built on Aerotech's ANT nanopositioning product line. It is designed to meet the demanding needs of critical photonics alignment in a highly automated, 24/7 production environment with no compromise in speed, accuracy, and resolution.

**Aerotech Inc.**
**+1 (412) 963-7470**
**sales@aerotech.com**
**www.aerotech.com/industries/optics-and-photonics**

## Fiber Focusers and Accessories

Our FC10 Fiber Collimator paired with our Focusing Modules gives micron size spots and eliminates extra optical mounts. From 1:1 imaging of fiber's MFD to longer focal lengths, small spots can be generated from near UV to 2 microns. Besides focusing, polarizers, lines and other optic modules can be attached for a compact optical module. These can be customized for a complete optical assembly and be made very compact.

**Micro Laser Systems Inc.** **(714) 898-6001**
**info@microlaser.com** **www.microlaser.com**

## The NYFORS SMARTSPLICER


The NYFORS SMARTSPLICER offers $CO_2$ laser glass-processing capabilities designed to produce high-power and sensitive photonic components and complex structures. It offers contamination-free fiber array splicing, ball lensing, end-capping, and many other challenging processes. NYFORS also provides automated high-precision solutions for fiber preparation, such as stripping, cleaving, recoating, and end-face analyzing. NYFORS also offers custom workcell automation solutions.

**NYFORS** **+46 8712-1021**
**sales@nyfors.com** **www.nyfors.com**

## High-Quality Optical Coatings

Evaporated Coatings Inc. is a professional and experienced resource for your Thin-Film Optical Coating requirements. ECI has been supplying high-precision optical coatings for more than 60 years — from minute biomedical and fiber optic components to defense and aerospace optics. ECI manufactures optical coatings for glass, plastic, molded polymer optics, fiber optic devices, LED lighting components, crystals, and semiconductor materials.

**Evaporated Coatings Inc.** **(215) 659-3080**
**sales@evapcoat.com** **www.evaporatedcoatings.com**

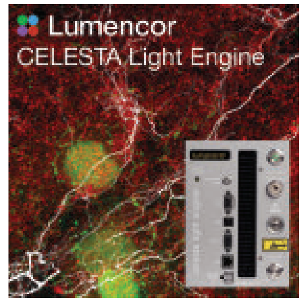
# Photonics Showcase

## Liquid Light Guides


Liquid Light Guides are flexible, unbreakable, and very durable, and they have significantly better transmission, more homogeneous illumination, and a larger aperture than fiber bundles at lower costs! They are the perfect solutions for applications that demand uniform, high-intensity light. We offer four different series designed for diverse spectra ranging from ultraviolet to infrared and a broad selection of end fittings.

**Lumatec GmbH** **+49 89-742822-0**
**sales@lumatec.de** **www.lumatec.de**

## CELESTA Light Engine




CELESTA Light Engine houses seven lasers in a turnkey illuminator for fluorescence confocal spinning disk microscopy and spatially resolved transcriptomics. 1000 mW/color from the end of an optical fiber is powerful, intense, quiet, reproducible and consistent. High-end imaging and OEM instrumentation are well supported. Ask about customization.

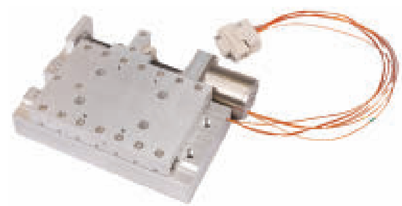
**Lumencor Inc.**
**(503) 213-4269**
**info@lumencor.com**
**www.lumencor.com**

## GoldenEye: The Ultimate Snapshot Imager


BaySpec's GoldenEye™ is the only Snapshot hyperspectral imager covering 400 to 1100 nm. Using BaySpec's FT-PI proprietary technology, this novel imager features high sensitivity and is most suitable for low-light-level applications, such as fluorescence imaging.

**BaySpec**
**(408) 512-5928**
**sales@bayspec.com**
**www.bayspec.com**

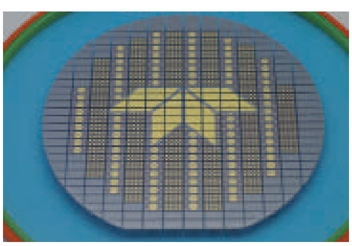
## New! UHV Micropositioning



The MMP-UHV50 is an ultra-high vacuum (UHV) micropositioning system. Linear motion with 50 mm travel, 190nm minimum step size and high native accuracy and repeatability. Designed to ensure full compatibility with UHV applications, including overheat protection, zero power mode, and bakeable to 100°C. The MMP-UHV50 is modular and a 2kg load limit. System includes the Micro-DriveUHV controller with software.

**Mad City Labs Inc.** **(608) 298-0855**
**sales@madcitylabs.com** **www.madcitylabs.com**

## MEMS Micromirror Manufacturing



Teledyne MEMS has decades of experience and provides MEMS manufacturing services for datacenter, telecom and Lidar applications. Bulk micromachined geometric tilt mirrors offer critical dimension control, precise layer alignment, and film stress stability, and many optional capabilities. Surface micromachined diffractive switching arrays offer small vertical aspect ratios, high speed, high channel count, and high optical power management.

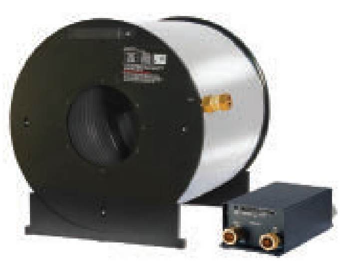
**Teledyne MEMS** **(780) 431-4400**
**mems_sales@teledyne.com** **www.teledynemems.com**

## Ultrafast Fiber Lasers: <50 fs, 2 W

HÜBNER Photonics proudly announces the next generation of the VALO femtosecond lasers. The new Tidal delivers pulse durations of typically 40 fs at 2 W of output power. Due to the exceptional peak power and the integrated dispersion pre-compensation unit it is an ideal tool for nonlinear applications like high harmonic imaging, broadband terahertz generation, and nonlinear wafer inspection.

**HÜBNER Photonics** **+46854591230**
**sales@hubner-photonics.com** **www.hubner-photonics.com**

## 150-kW High Power Laser Sensor



The Ophir® 150-kW Very High Power Laser Sensor measures power levels to 150 kW. The water-cooled calorimetric sensor delivers exceptional accuracy and dependable performance over the range of 900-1100nm. Extremely low back reflection ensures operational safety. Designed for high-power fiber laser development and testing, directed energy systems, and industrial applications such as cutting and drilling.

**MKS Ophir** **(435) 753-3729**
**sales.ophir.usa@mksinst.com** **bit.ly/41nQsFr**

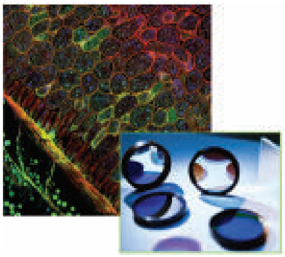
## Optical Machinery System Supplier


No matter what type of optical component you want to process, OptoTech is your system supplier for cutting edge processing machines, vacuum coating systems and measuring technology. Our machines and technologies have been shaping the optical industry for almost 40 years and we are not going to stop pushing the boundaries of processing optics. See for yourself how OptoTech can make a valuable contribution to the success of your company.

**OptoTech Optical Machinery Inc.** **(215) 267-0957**
**sales-precision-america@optotech.net** **www.optotech.net**

# Photonics Showcase

## ODiate® Fluorescence Filter Sets



ODiate® Fluorescence Filters and Filter Sets are engineered for advanced fluorescence and microscopy applications, delivering exceptional precision and performance. Designed to produce brighter images, optimized signal-to-noise ratios, and consistent spectral performance, ODiate leverages MKS Newport's cutting-edge thin-film coating platform for unmatched reliability and consistency.

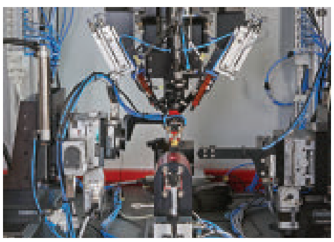
**MKS | Newport** **(877) 835-9620**
**sales@newport.com** **www.newport.com/f/odiate-fluorescence-filter-sets**

## Ion Beam Patterning of Slanted SRGs

Ion beam processes are perfect for etching slanted surface relief gratings (SRG) either directly into waveguides or into master stamps for NIL. scia Systems' RIBE process creates SRGs with constant slant angles, using reactive gases to control material selectivity and etch rate. Substrates are tilted to achieve the desired angle and structure design. By using reactive ion beam trimming, slant angle and etching depth across the substrate can vary.

**scia Systems GmbH** **+49 371335610**
**m.gebhardt@scia-systems.com** **www.scia-systems.com**

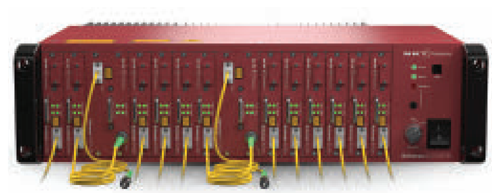
## Active Alignment and Assembly



The NanoGlue, NanoWeld, and NanoSolder series are partly or fully automated production stations for demanding alignment and low-shift assembly procedures in opto-electronics industry. The linear axes work with 5-nm resolution, and angular rotation resolution is below 0.0005°. Long travel ranges facilitate the loading and unloading procedures while the modular architecture allows for fast and reliable customization. Visit us at Photonics West, booth #4605.

**nanosystec GmbH** **+49 6078-782540**
**sales@nanosystec.com** **www.nanosystec.com**

## Modular Laser Systems for Quantum



Have you always dreamed about designing your own laser system for quantum applications? Now you can! Mix and match our modular building blocks to create the laser system you need for your quantum sensing, quantum computing, or quantum metrology projects. Pick your wavelength and power. The low noise, narrow linewidth, and industrial reliability are standard.

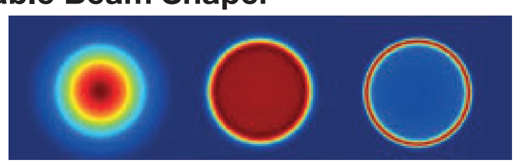
**NKT Photonics** **+45 4348 3900**
**sales@nktphotonics.com** **www.nktphotonics.com**

## Thin-Film Services Since 1988

We can provide high quality and quick turnaround of thin-film requirements by customers. They include evaporated and sputtered coatings and circuit fabrication. Indium bumps for flip chip bonding is a new service. AR and enhanced reflection coatings in the visible and infra red. Coatings for soldering and brazing applications. Abrasion and wear resistant coatings. Please visit our website and send as an email for your particular requirements.

**THINFILMS Inc.** **(908) 359-7014**
**am@thinfilmsinc.com** **www.thinfilmsinc.com**

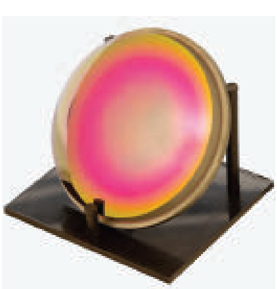
## Variable Beam Shaper



The Variable Beam Shaper is an advanced refractive optical element engineered to transform a single mode Gaussian beam into one of 3 different output profiles - Gaussian spot, flat top circular spot or a ring shaped spot. It enables users to achieve dynamic beam shaping in applications such as laser welding or laser additive manufacturing and allows a new level of process enhancements and benefits to be realised.

**PowerPhotonic Ltd.** **+1383 825 910**
**sales@powerphotonic.com** **www.powerphotonic.com**

## Optical Coatings



Our customers choose us because we can reliably deliver the highest quality optics at expedited timeframes and with reduced risk, because we not only have one of the largest teams of optical engineers and state-of-the-art manufacturing facility and technologies at our disposal but because we own the entire manufacturing process. This includes an advanced cleanroom where we routinely generate coatings for some of the most demanding markets.

**Optimax Systems Inc.** **(585) 265-1020**
**sales@optimaxsi.com** **www.optimaxsi.com**

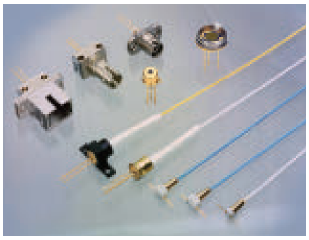
## Near Infrared 3D Sensing

A fast and accurate measurement solution, Radiant's Near-Infrared (NIR) Intensity Lens system is an integrated camera/lens that measures the angular distribution and radiant intensity of 850 or 940 nm* near-infrared (NIR or near-IR) emitters. Manufacturers of 3D sensing technology can apply the NIR Intensity Lens solution for angular measurement of NIR LEDs, lasers, and structured light patterns produced by Diffractive Optical Elements.

**Radiant Vision Systems** **(425) 844-0152**
**info@radiantvs.com** **www.radiantvisionsystems.com**

# Photonics Showcase

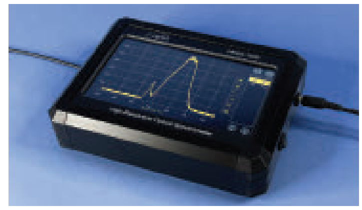
## Fermionics InGaAs Photodiodes



Fermionics Opto-Technology provides indium gallium arsenide (InGaAs) photodiodes and InGaAs-related devices. Fabricated with planar-passivated technology, our devices provide superior and reliable performance. High-speed photodiodes are ideal for analog/digital communication systems, instrumentation, and fiber optic sensors. Ask about our large area InGaAs photodiodes with superior responsivity from 800 to 1700 nm for sensing/instrumentation tasks. Our devices are also widely used in various medical applications.

**Fermionics Opto-Technology** **(805) 582-0155**
**ingaas@fermionics.com** **www.fermionics.com**

## Handheld Optical Spectrometers



OZ Optics offers a handheld optical spectrometer for ultraviolet to near-infrared wavelengths. The design features a special transmission grating and custom coatings for exceptional sensitivity and signal-to-noise ratios. A touchscreen display and intuitive user interface provide ease of use, while a USB interface enables detailed computer analysis. An OEM version is offered for custom applications.

**OZ Optics Ltd.** **(613) 831-0981**
**sales@ozoptics.com** **www.ozoptics.com**

## Design. Prototype. Scale.


FTI provides American-made diamond turned or molded polymer optics, including micro-optics, aspheres, freeforms, and PIR in the UV, VIS, and IR range. Request your ruler kit and book a meeting at Photonics West to explore which optical approach may best suit your project. FTI's optical expertise, extensive catalog, and custom capabilities can help ensure your project's success.

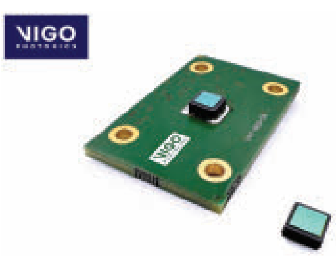
**Fresnel Technologies Inc.** **(817) 926-7474**
**info@fresneltech.com** **www.fresneltech.com**

## GLIDER Mid-IR External Cavity


The GLIDER mid-infrared external cavity is designed for single-mode operation with wide spectral tunability. It uses Alpes Lasers QCL or ICL broad gain chips which can cover up to 25% of their central wavelength selected in the range 3.2 microns to 13.7 microns. The system can combine up to four chips and includes drivers and software for a complete light source.

**Alpes Lasers** **+41 32 729 9510**
**sales@alpeslasers.ch** **www.alpeslasers.ch**

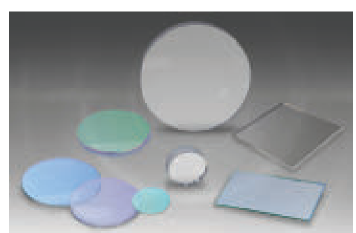
## SMD 5 µm




PVA-5-d1-SMD series are RoHS-compliant, uncooled, MWIR detectors in a compact, surface-mount ceramic SMD package. They are compatible with automatic soldering and pick-and-place stations. These detectors feature band-pass optical filters, ensuring high responsivity for detecting MWIR gases. Applications include medical diagnostics, quality control and environmental protection. These detectors are also available integrated into detection modules.

**VIGO Photonics S.A.** **+48 22 733 54 10**
**info@vigophotonics.com** **www.vigophotonics.com**

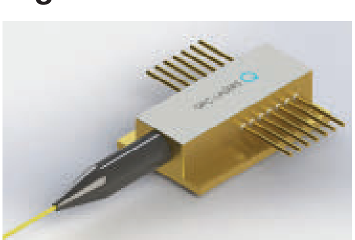
## High-Volume Optics from 0.2 µm-15 µm



PG&O's new capabilities include cost-effective, high-volume, precision optical components up to 100,000 parts per month with timely delivery. The high-quality optical components operate from 0.2 µm – 15 µm. Our recently installed PR Hoffman 5400 double-sided polishing machine provides exceptional surface quality on substrates up to 250 mm diam. and allows us to polish parts in days, rather than weeks. Call us today at 714-540-0126 to learn more.

**Precision Glass & Optics (PG&O®)** **(714) 520-0126**
**info@pgo.com** **www.pgo.com**

## High-Power Gas-Sensing Diodes



QPC Lasers offers the world's highest power narrow-linewidth diodes for sensing applications, including the detection of methane at 1.65 µm. They have powers beyond 500 mW and can be frequency modulated. They are packaged in thermoelectrically cooled PM single-mode fiber-coupled butterflies and free space configurations. Other applications include wind lidar and free space communications.

**QPC Lasers Inc.** **(818) 986-0000**
**info@qpclasers.com** **www.qpclasers.com**

## High-Performance Sub-ns Lasers


Teem Photonics offers sub-ns microchip pulsed lasers in 1064, 532, 355, 266, and 213 nm. Trusted by OEMs and research labs for their long lifetime, compactness, and cost-effectiveness, our lasers excel in biomedical applications, sensing and ranging, semiconductor inspection, and more — driving innovation in diverse photonics fields.

**Teem Photonics** **+33 4 76 04 05 06**
**sales@teemphotonics.com** **www.teemphotonics.com**

# Photonics Showcase

## Siskiyou TPI Series Adjustment Screw

Our 100TPI-0.5d differential adjustment screw has the industry's best resolution for a manual drive at 20µm/revolution and the smallest package size for a differential adjustment screw. In addition, we offer higher resolution non-differential adjustment screws, from 20tpi to 170tpi. Custom variations have been available from our U.S.-based manufacturing facility since 1972.

**Siskiyou Corporation** **(877) 313-6418**
**sales@siskiyou.com** **www.siskiyou.com**

## Scanner for Additive Manufacturing

The new excelliSCAN 30 ARRAY is a particularly flexible and compact scan head that is precisely tailored to the requirements of the AM industry. The particularly narrow design makes this system ideal for use in multi-head systems. Several scanning systems can work together in a space-saving manner with a very large image field overlap, thus significantly reducing process times. High precision and drift stability is ensured by digital encoders.

**SCANLAB GmbH** **+49 89 800 746 0**
**info@scanlab.de** **www.scanlab.de**

## AFL's LAZERMaster® LZM-125A+

The LAZERMaster LZM-125A+ Series is a splicing and glass processing system that uses a $CO_2$ laser heat source to perform splicing, tapering (to create MFAs), lensing, or other glass shaping operations with glass diameters of 2.0 mm or less. The high resolution optical analysis system works in conjunction with on-board firmware for fully automatic splicing, tapering and other glass shaping processes.

**AFL**
**(864) 433-5423**
**lucas.mays@aflglobal.com**
**www.aflglobal.com/en**

## Turn-key PIC (SiPH) Test Solutions

The TS2000-IFE is part of MPI's PIC (SiPH) 200 and 300mm wafer test solutions family. Its scalability allows for testing any design at any wavelength, as well as combined electrical testing. Single-fiber or multichannel (FAU) testing in both R&D and production settings, along with its Measmatic and SENTIO® software suites and integrated calibration, enable fully automated and autonomous testing, supporting any third-party test instrumentation.

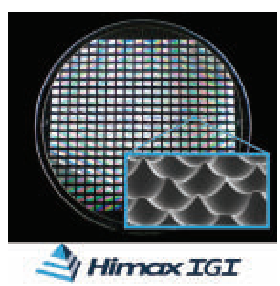
**MPI Corporation** **(408) 770-3650**
**info@mpi-corporation.com** **www.mpi-corporation.com**

## CENTUM® C3

Sheetak's CENTUM® C3 thermoelectric coolers leverage a patented architecture to achieve industry-leading multi-stage performance in the most compact form factor on the market. It's designed for use in various optoelectronic applications, imaging sensors and analytical instrumentation, but our team is always on hand to create custom, optimized designs to fit your unique needs. Contact us to find your solution today!

**Sheetak Inc.** **(512) 577-1081**
**info@sheetak.com** **www.sheetak.com**

## Wafer-Level Optics




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

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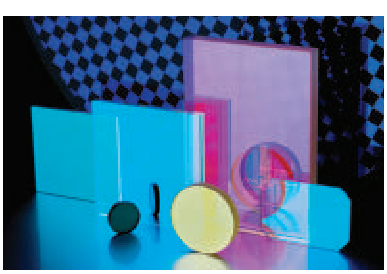
**sales@himaxigi.com** **www.himaxigi.com**

## SIRRUS™ PVD Platform



Alluxa's innovative, next-generation SIRRUS™ plasma physical vapor deposition (PVD) platform offers full spectral coverage from ultraviolet (200 µm) to infrared (14 µm). The proprietary process enables optical filters with the steepest edges, highest transmission, and deepest blocking available while maintaining high performance, precision wavelength control, and extremely uniform coatings.

**Alluxa Inc.** **(855) 425-5862**
**info@alluxa.com** **www.alluxa.com**

## WinCamD-GCM GigE CMOS Beam Profiler


Using the same sensor as DataRay's WinCamD-LCM (11.3 × 11.3 mm active area, 4.2 Mpixels, 5.5 × 5.5 µm pixels, global shutter), the WinCamD-GCM utilizes a GigE Vision® connection for long-range applications (cable lengths up to ~100m) and can be easily scaled and integrated into existing networks, for scalable GigE Vision beam profiling with DataRay's powerful, familiar, full-featured software.

**DataRay Inc.**
**(831) 215-2200**
**sales@dataray.com**
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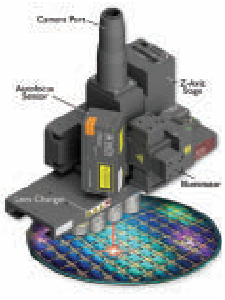
# Photonics Showcase

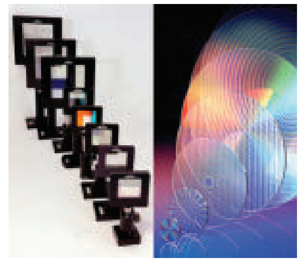
## PFA-LN Dynamic Adaptive Aufofocus



WDI's NEW PFA-LN sensor provides continuous focus on multi layer, varied substrate, pattered and mixed reflectivity surfaces. It features an improved design with higher speed, greater accuracy and flexible integration making it ideal for semiconductor, flat panel display, optical metrology applications. PFA-LN can be used alone or with WDI's new high-performance modular microscope system including lens changers, Z-stages and illuminators.

**WDI Wise Device Inc.**
**(905) 415-2734**
**info@wdidevice.com**
**www.wdidevice.com**

## Large-Size Switchable Planar Optics



Planar optics technology pioneered by BEAM is over 99% efficient in VIS to MWIR bands with up to 8" sizes. Overcoming the deficiencies of metasurfaces, BEAM's flat lenses, prisms, beam shapers, vortices are haze-free and allow AR coatings for high throughput due to their planar continuous structure. Fixed or switchable between multiple optical states, they enable non-mechanical beam steering for LiDAR and adaptive glasses for AR/VR applications.

**BEAM Engineering for Advanced Measurements Co.**
**(407) 734-5222**
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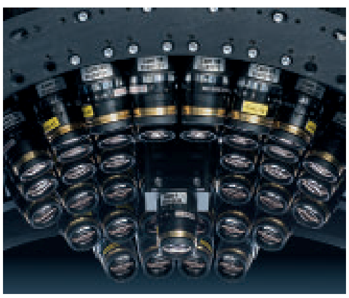
## Traceable Image Quality Measurement



The world's benchmark image quality testing from TRIOPTICS provides unparalleled control over your optical production processes by delivering correlation and traceability from R&D all the way through production. Optimized for accuracy, flexibility, and traceability from lab to fab. Visit TRIOPTICS at Photonics West, booth 1640… See what´s new!

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## InGaAs Avalanche Photodiode Series

The enhanced C30645 and C30662 InGaAs Avalanche Photodiodes from Excelitas are high-speed, high-gain devices offering high quantum efficiency, high responsivity, high resistance to over-illumination, and now with significantly lower noise in the 1000 nm to 1700 nm spectral range. They provide better Signal-to-Noise-Ratios and increased detection range from the same laser output power, making them ideal for eye-safe range-finding and LiDAR systems.

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## Micro Injection Molded Optics

Micro polymer optics for data communications, imaging, sensors, diagnostics, and a wide variety of high-tech applications. Micro injection molding is an enabling technology for miniaturized, tight tolerance, high-volume thermoplastic molded components. Accumold micro molding has served the industry for more than 30 years.

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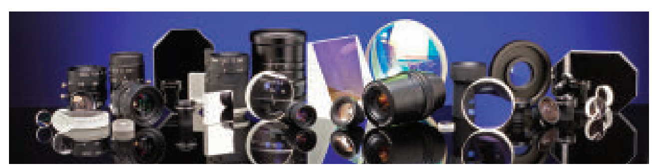

Westech Optical designs, manufactures and distributes precision lenses and lens assemblies. Westech offers a wide choice of stock, modified stock and custom lens designs. Applications include security, surveillance, medical instruments, noncontact measurement, laser and lidar. Don't pay catalog prices for OEM optics. Contact Westech.

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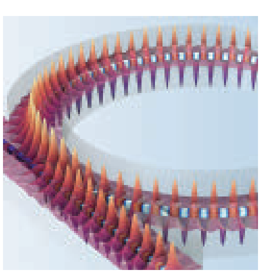

COMSOL Multiphysics® is a software environment for creating physics-based models and standalone simulation apps. Add-on products provide specialized functionality for electromagnetics, structural, acoustics, fluid flow, heat transfer, and chemical simulations. Interfacing products offer a unified workflow 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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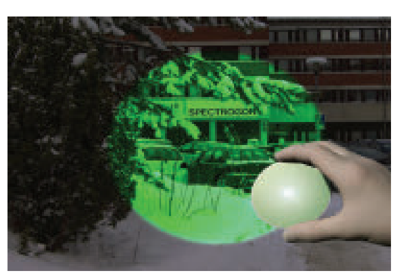
## IR Filters for Thermal Imaging



Spectrogon manufactures infrared filters and windows with high transmission, high rejection outside the passband, while maintain excellent coating uniformity for thermal imaging and gas detection applications such as cryogenically cooled IR detectors and uncooled microbolometers. Our filters and windows range in dimension from Ø6.0 to Ø200.0 mm, with dicing capabilities down to as small as 1.0 × 1.0 mm.

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**Robert L. Gordon**
Account Executive
Voice: +1 413-499-0514, Ext. 207
Fax: +1 413-443-0472
robert.gordon@photonics.com

South Central U.S., Southeastern U.S., Midwest, CT, ME, NH, NJ, NY, PA, RI, & VT
**José D. Amor**
Account Executive
Voice: +1 413-499-0514, Ext. 108
Fax: +1 413-443-0472
jose.amor@photonics.com

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

**Reprint Services**
Voice: +1 413-499-0514
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**Mailing Address**
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# Liquid crystals so good, they're a scream!

When Edvard Munch completed his famed painting "The Scream" in 1893, he probably didn't expect it to have such a profound and lasting effect on the cultural zeitgeist. Just as likely, he probably never imagined that it would at one point hold the record for the most expensive work ever sold at auction; the painting fetched a cool $120 million back in 2012.

Thankfully, contemporary museum goers can see this expression of Munch's personal anxieties, as access to the painting is still attainable for the rest of us plebians who can't afford to casually drop millions of dollars on a canvas. The painting is on public display at the National Museum of Oslo, Norway.

For those who don't have the means to plan a trip to the painting's current home, a recent advancement in liquid crystals could provide a view of the work that you won't even find in Oslo. Researchers from Dartmouth College and Southern Methodist University (SMU) have designed a molecular switch that can trigger shape changes in liquid crystals that allow them to reflect different colors. So far, the study has created reproductions of Munch's "The Scream" as well as Vincent van Gogh's "The Starry Night."

The switch in question is made up of the organic molecule triptycene and a class of compounds, called hydrazones, that can flip on and off with a pulse of light, which functions as a stimulus. The researchers demonstrated that these hydrazones can be attached to triptycene in such a way that the molecule's symmetry breaks, making it chiral. When chiral triptycene interacts with a liquid crystal molecule, it sets a chain of events into motion that causes other liquid crystal molecules to fall in line, rearranging themselves in twisted, DNA-like helices.

Once in helical form, the liquid crystals reflect ambient light at different wavelengths based on their pitch, or how far apart the coils in their helical structure are spaced — stretching and compressing the helix triggers vivid color changes. This is similar to what happens when, say, a chameleon changes color or a painter whitewashes a canvas after getting all of the colors wrong.

The reproductions were made using this technique, along with a microscope from an SMU lab rejiggered into a mini slide projector. In a process reminiscent of multicolor screen printing, the researchers used the projector to beam light through a series of stencils on a makeshift screen made of liquid crystals doped with chiral triptycene. New colors were added by shining the light for varying lengths of time on parts of the screen left exposed by the stencil.

Though the liquid crystal paintings aren't permanent, the technique's ability to enable colors to remain on the pattern for multiple days has researchers excited. Advancements such as liquid crystal lasers, display screens that could be easily printed and erased, and microscopic tags that could, for example, be added to bank notes to deter counterfeiters, could become a reality in the near future with this newfound molecular switch.

But while applications such as these are useful, a lingering question remains: Can they be deployed to elicit a case of existential dread in a museum viewing room? Perhaps we'll just have to wait and see.

The research was published in *Nature Chemistry* (www.doi.org/10.1038/s41557-024-01648-0).

Edvard Munch's "The Scream" **(left)** compared to the Dartmouth and Southern Methodist University (SMU) reproduction made via a molecular switch.

Image courtesy of Dartmouth College.