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Developing Tomorrow's Workforce

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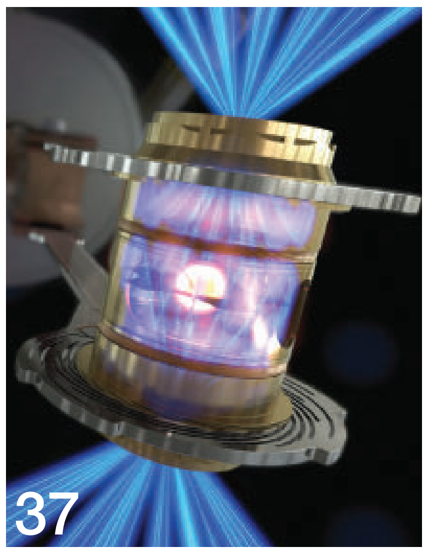
Inside This Issue

August 2024 volume 58 issue 8

Features



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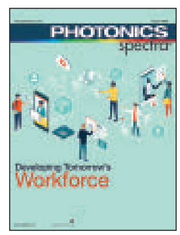
Departments

Columns

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



The Cover

Workforce development initiatives aimed at cultivating talent in support of occupations at all reaches of the photonics industry are adapting to the distinct needs of different sectors. Image courtesy of iStock.com/elenabs. Cover design by Senior Art Director Lisa N. Comstock.

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Editor's Note

Escalating efforts to meet workforce demands

Regional clusters are a hallmark of the North American photonics landscape. The cluster model, by its nature, enables individual regions to spearhead scientific progress in the technology areas that drive economic opportunity.

On a larger scale, this model ensures that the photonics ecosystem on this continent retains influence from each of the individual regions that compose it. Think Rochester, N.Y., and optics, or Arizona's "Optics Valley" and astronomy. The optics hotbed of Central Florida, which serves as the backdrop of this issue's cover story, is synonymous with optical technologies used in the aerospace and defense sector. The Colorado Photonics Industry Association and Montana Photonics Industry Alliance, fostering advancements in quantum and semiconductor technologies, respectively, have also featured in this magazine in recent issues.

The beauty of the cluster model, and indeed much of its value, extends beyond individualism. Clusters work in harmony to drive progress in support of a shared industry. They do not exist in a vacuum.

A parent industry is not the only thing that clusters share. Workforce needs run through the entire industry. And not only in North America.

The featured stories in this issue delve into distinct elements of workforce development and related initiatives. The necessary training, credentialing, and upscaling of viable talent advances critical knowledge far beyond any singular technology area or region. This critical knowledge also reaches beyond any one segment of the population.

The approaches that industry changemakers in Central Florida have adopted (and which contributing editor James Schlett explores in his feature article on page 32) are just some of the current undertakings targeting the workforce. The Netherlands-based photonic chip accelerator PhotonDelta, in announcing its plans last month to open a U.S. office, cited the need to bolster the workforce in Europe, and the U.S. PhotonDelta said its forthcoming efforts may include university exchange programs.

The plans of PhotonDelta, of course, point to another challenge in workforce development: cultivating a workforce for emergent technologies, such as those that factor into integrated photonics and semiconductor technologies.

One approach, perhaps under-considered, involves taking steps to familiarize students with relevant technologies before the students reach high school. As he writes in this issue, it is a thought that Kevin McComber, cofounder and executive director of the Spark Photonics Foundation, has himself turned into action.

jake.saltzman@photonics.com

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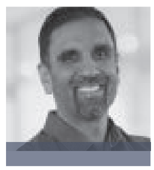
Contributors

Ken Barat
Ken Barat is a certified laser safety officer with 30 years of experience addressing laser safety for end users internationally. He has written 11 texts on the subject and espouses the motto "safety through cooperation." Page 63.

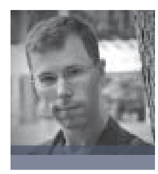
Klein Johnson
Klein Johnson has been working in the field of VCSEL technology since the early 1990s, first with Honeywell and later as cofounder of Vixar. He currently leads VCSEL R&D activities at ams OSRAM. Page 55.



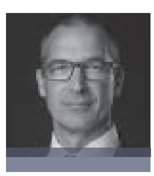
Sanjay Gangadhara
Sanjay Gangadhara is the senior program director for optics at Ansys. He works closely with the product management and R&D leadership teams to define the long-term product vision and business strategy for the Ansys optics portfolio. Page 43.

Kevin McComber
Kevin McComber is the cofounder and CEO of Spark Photonics, an integrated photonics design firm, as well as cofounder and executive director of the Spark Photonics Foundation, a nonprofit engaged in STEM outreach. Page 29.

Amirhossein Ghods
Amirhossein Ghods is a senior staff scientist at ams OSRAM. He leads the EPI design activities for NIR III-V surface-emitting lasers targeted for a variety of 3D-sensing and automotive lidar applications. Page 55.



James Schlett
Contributing editor James Schlett is an award-winning author, poet, and journalist. He is the former editor of *BioPhotonics*. Page 32.



Lukas Gruber
Lukas Gruber is a director of business development at Leonardo Electronics US Inc. With more than 25 years of experience in photonics, he has held many positions, from fundamental research at Lawrence Livermore National Laboratory to product development, manufacturing, and general management. Page 37.

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. Page 49.

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High-Performance PDH Locking with Reconfigurable Instrumentation

The Pound-Drever-Hall (PDH) method is ubiquitous in fields, including spectroscopy and atomic physics, that require laser frequency stabilization. PDH systems are traditionally assembled manually from various components, and often present challenges for researchers due to time constraints and adaptability issues, leading to maintenance difficulties and signal distortion. Liquid Instruments provides a pedagogical introduction to the PDH technique and creates a system using reconfigurable, FPGA-based instrumentation. Multiple instruments, including the Moku Laser Lock Box, combine into a bespoke environment, emulating a real optical system.
Presented by Liquid Instruments.
To view, visit www.photonics.com/w1006.

The Heart of Gas Sensors: Novel IR Detectors for Gas Analysis

VIGO Photonics' Jędrzej Mijas discusses optical gas analysis in the MIR, emphasizing the selection of the proper detector for each gas sensing technique. The most important gaseous species to detect are methane, ammonia, nitrous oxides, and sulphur oxides, and techniques for accurate detection, in various applications, are explored. Mijas also addresses the pros and cons of various methods, including nondispersive infrared (NDIR), tunable diode laser absorption spectroscopy (TDLAS), and Fourier transform. He touches on the novel IR detectors manufactured by VIGO, showcasing the specific features that make them the best fit for analyses. He describes both high-end mercury cadmium telluride (MCT) detectors tailored for gas analysis, plus cost-effective and RoHS-compliant III-V superlattice detectors.
Presented by VIGO Photonics.
To view, visit www.photonics.com/w1028.

Beam Steering with Galvanometers: Common Configurations and Their Uses

Galvanometer scanning systems are highly configurable and are used in applications including lidar, microscopy, and laser materials processing. Choosing the correct configuration for an application requires the consideration of many factors. Carol Borsa from Thorlabs compares commonly available configurations and discusses the merits of each, providing key insights into specifications on data sheets and guiding users to suitable solutions. This presentation also covers basic integration steps and requirements, plus tools for finding the limits of a system. Participants will gain insights into best practices when choosing a system and will have an opportunity to learn to use other available equipment to integrate confidently.
Presented by Thorlabs.
To view, visit www.photonics.com/w1014.

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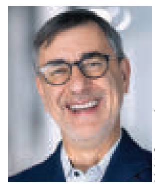
Light Conversion
Arrigoni.

The editors of *Photonics Spectra* and *BioPhotonics* magazines invite you to the Scientific Lasers Summit, an online webinar series showcasing the continuous innovation of laser technologies. The one-day summit premieres Sept. 18 and all presentations will remain accessible on demand following the event.

Join industry experts at Menlo Systems, Novanta, NKT Photonics, Light Conversion, and more to better understand cutting-edge technologies driving innovation and technical information for enhancing laser performance, such as achieving stable carrier-envelope phase (CEP) and gigahertz repetition rates.

Registration is free and unlocks essential data and insights necessary for decision-making, optimization, troubleshooting, and innovation within laser performance. Attendees can engage directly with presenters through a summit chat box — an opportunity to pose questions, share experiences, and contribute to the collective efficiency of the photonics community.

Website

To learn more about the program, visit **www.photonics.com/SL2024**.

On the Pulse of Time:
Recent Advancements in Femtosecond Fiber Lasers
Jaroslaw Sperling, Menlo Systems

Advanced Femtosecond Lasers:
Stable CEP and Gigahertz Repetition Rates
Albrecht Bartels, Novanta

Versatile Broadband Tunable Lasers
for Cutting-Edge Scientific Research
Deepak Nair, NKT Photonics

Ytterbium-Based Lasers for High-Energy
and Power Applications
Marco Arrigoni, Light Conversion

Upcoming Summits

Sensors & Detectors — *November 13*

Polymer Optics — *December 4*

Register today at
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LIVE
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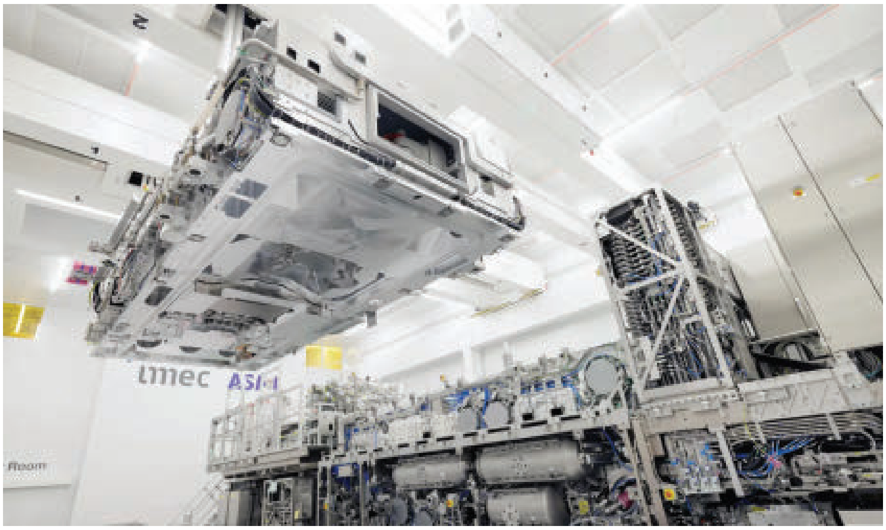
ASML and imec debut joint lithography lab

ASML and imec have opened the jointly run High NA EUV Lithography Lab in Veldhoven, Netherlands. The lab will provide logic and memory chip makers as well as advanced materials and equipment suppliers with the first prototype High NA EUV scanner and surrounding processing and metrology tools.

The collaborators said that they expect leading chip manufacturers to use the facility to gain early access to the technology as they seek to develop high numerical aperture (NA) extreme ultraviolet (EUV) use cases before adopting the scanners in their production fabs to reduce risk. High-volume manufacturing with High NA EUV is expected to begin as early as 2025.

"High NA EUV is the next milestone in optical lithography, promising the patterning of metal lines/spaces with 20-nm pitch in one single exposure and enabling next generations of [dynamic random-access memory] chips," said imec president and CEO Luc Van den hove. The technology is set to improve yield and reduce cycle time and carbon emissions compared to existing multi-patterning 0.33 NA EUV systems.

In addition to providing early access for process development, access will also be provided to the broader ecosystem of material and equipment suppliers as well as to imec's High NA patterning program.



imec

ASML and imec's joint High NA EUV Lithography Lab provides access to ASML's prototype 0.55 numerical aperture (NA) extreme ultraviolet (EUV) lithography machines, capable of printing 10-nm-dense lines supporting chip fabrication.

Preparations for the 0.55 NA EUV scanner and its associated infrastructure began in 2018. Since then, ASML and ZEISS developed specific solutions related to the scanner's source, optics, lens anamorphicity, stitching, reduced depth of focus, edge placement errors, and overlay accuracy. In addition, imec, in cooperation with its supplier network, prepared the patterning ecosystem, including the development of advanced resist and underlayer materials, photomasks, metrology and inspection techniques, anamorphic imaging strategies, optical proximity correction, and integrated patterning and etch techniques.

The preparatory work recently resulted in first exposures, which showed, for the first time, 10-nm dense lines (20-nm pitch) printed in Veldhoven on metal oxide resists using the 0.55 NA EUV prototype scanner.

EU effort achieves initial graphene photonic integrated circuit

The European Union (EU)-funded Graphene-Based All-Optical Technology Platform for Secure Internet of Things (GATEPOST) project presented its first photonic integrated chip. The graphene-on-silicon nitride chip is designed initially with nine layers, according to Leonardo Del Bino, cofounder of Akhetonics GmbH. Del Bino presented the device design in a presentation at a meeting of the project's eight stakeholders at the EurA AG headquarters in Ellwangen, Germany.

The chip, Del Bino said, can be thought of as a cake with each layer made up of different ingredients, and each layer with a mask representing a specific material at a specific point in the cake.

The Horizon Europe-funded GATEPOST project seeks to develop and produce graphene-based chips to revolutionize existing computer technology and information technology security, according to Mindaugas Lukosius of IHP GmbH, and a lead partner on the project. GATEPOST intends to integrate graphene and 2D materials into silicon nitride using standard CMOS processes. Taking place under the auspices of the EU's Graphene Flagship program, the project began last

October and will run for three years, funded with €5.4 million ($5.8 million).

The GATEPOST chip is now being manufactured in the experimental pilot plant at IHP GmbH at the Leibniz Institute for Innovative Microelectronics. According to Del Bino, some elements of the current design will be included in the project's final result, which will build on the current simplified version.

The project's first papers were presented at the Optical Fiber Communications Conference and Exhibition 2024 (OFC 2024). The project partners are IHP GmbH Leibniz Institute for Innovative Microelectronics; Akhetonics GmbH; Hewlett Packard Enterprise; Aristotle University of Thessaloniki; Enlightra; Fraunhofer Heinrich Hertz Institute; EurA AG; and imec.

Coherent names CEO

Coherent Corp. appointed Jim Anderson CEO. He is succeeding Vincent "Chuck" Mattera in the position and will also be made a member of the Coherent board.

The appointment comes after Mattera announced his retirement as chairman and CEO in February, pending the hiring of a successor.

Anderson joins Coherent from Lattice Semiconductor, where he served as president, CEO, and a member of its board of directors. Prior to Lattice, he was vice president and general manager of Advanced Micro Devices' Computing and Graphics business group, and he has held leadership positions at companies including Intel, Broadcom, and LSI Corporation.

Anderson serves on the boards of Entegris, EdgeQ, and Lumotive as well as on the board of directors of the Semiconductor Industry Association, the MIT Sloan Americas, the Electrical and Computer Engineering advisory board at Purdue University, and the Dean's Advisory Board for the College of Science and Engineering at the University of Minnesota.

Coherent

Jim Anderson, CEO of Coherent Corp.

This month in history

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

1994

Soreq Nuclear Research Center and its commercial arm, Isorad Ltd., developed a compact blue laser capable of a continuous output power of 3.6 mW at 427 nm by doubling a standard gallium arsenide diode laser. The device was based on an integrated potassium titanyl phosphate (KTP) waveguide that included a quasi-phase-matching section and Bragg reflector section.

2004

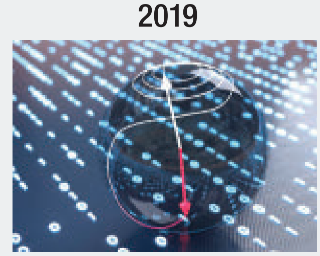
Scientists at Fraunhofer Institute for Applied Solid State Physics (IAF) and the National Research Council in Ottawa, Ontario, developed quantum-well infrared photodetectors with the ability to characterize mid-infrared pulses in the picojoule range. They created the artificial three-level system using the narrowband characteristics of intersubband transitions.

2014

A laser device developed at the Polish Military University of Technology's Institute of Optoelectronics was shown to detect the presence of alcohol vapors inside a moving car. The results showed that the presence of the vapors was detected at concentrations of 0.1% and greater.

2019

An international team of researchers discovered how to perform superfast data processing using light pulses instead of electricity. The team used magnets to create faster data processing speeds without high energy costs, succeeding in navigating the magnetization of a magnet to a new orientation in one-trillionth of a second and costing a single photon's worth of energy.



AmeriCOM adds Keene State College to workforce development network

The American Center for Optics Manufacturing (AmeriCOM) partnered with New Hampshire's Keene State College, marking the workforce training initiative's first partnership with a postsecondary four-year institution, and fifth partnership with an institution of higher learning. The Keene State collaboration aims to increase capacity for work-ready technicians in optics manufacturing as well as to expand opportunities for Keene State students, faculty, and regional employers in precision manufacturing.

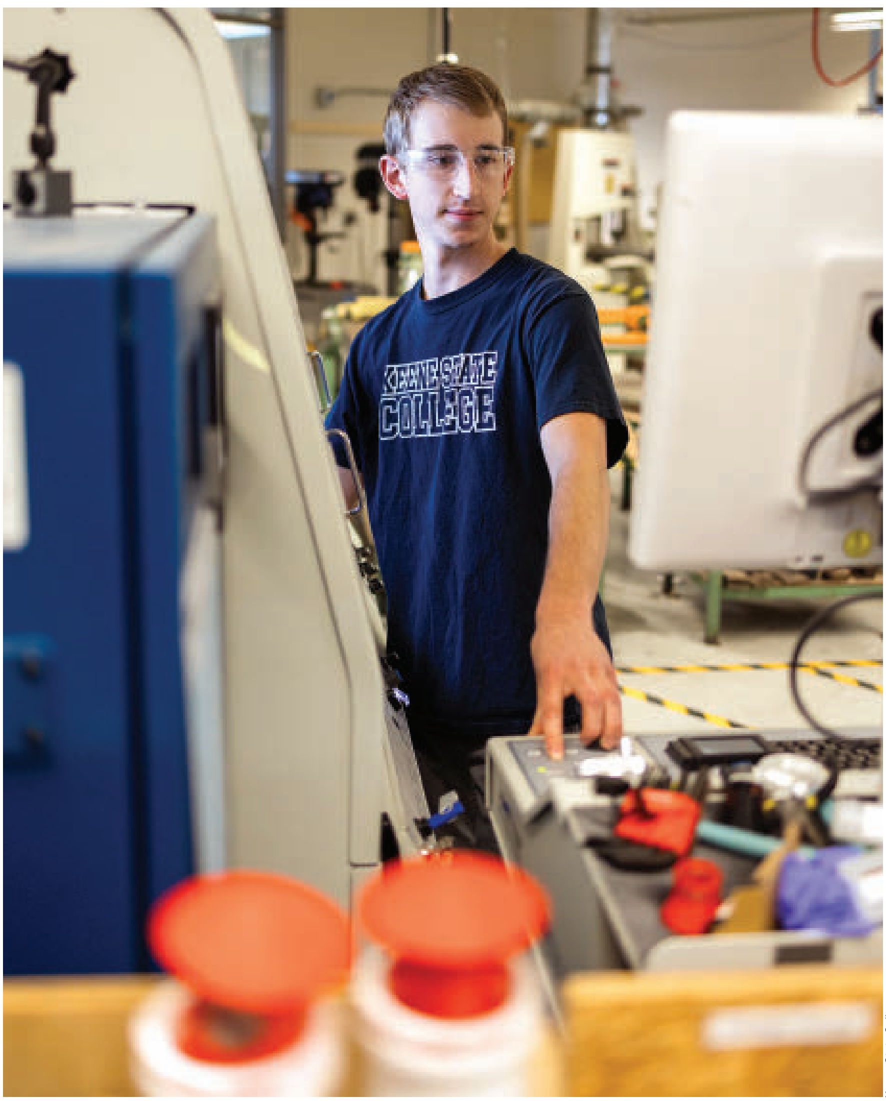
As an initiative of the U.S. Department of Defense, AmeriCOM aims to promote workforce training at the technician level and address critical gaps in defense systems, the optics supply chain, and future industry needs. AmeriCOM's core initiative is the Defense Precision Optics Workforce Development and Technology Ecosystem Project. This effort merges partners in industry, education, nonprofit, and government sectors to expand workforce training programs, undertake research, expand the precision optics manufacturing base, and secure the national precision optics supply chain.

AmeriCOM's higher education partners are Sussex County Community College (New Jersey); Front Range Community College (Colorado); Valencia College (Florida); and Monroe Community College (New York). The initiative creates a network of ecosystems supported by regional optics industry clusters and workforce training organizations with the purpose of growing educational opportunities by building optics labs, increasing curriculum development efforts, and recruiting and training teachers and students.

In alignment with these pursuits, Keene State College president Melinda Treadwell said the partners will develop and expand curricula, support dual enrollment for high school students, and create upskilling and tailored training for existing regional employers and employees. Keene State already offers an integrative degree in sustainable product design and innovation. The program combines industrial design, project management, and manufacturing engineering technologies. Students can also take classes with optical applications and earn a microcredential in the discipline.

The partnership with AmeriCOM follows Keene State's receipt of a $3 million grant that will be used in conjunction with a $100,000 gift to construct a teaching and training precision optics lab to be called the Kingsbury Center for Diamond Turning Excellence.

Keene State graduate Nathan Priebe earned a degree in sustainable product design and innovation. He works full-time at AMETEK Precitech in Keene, N.H., in manufacturing engineering.



Keene State College

11.6%

— the estimated compound annual growth rate of the global optical switches market by 2029, according to Mordor Intelligence

Atom Computing

Atom Computing CEO Robert Hays **(left)**, and Export and Investment Fund of Denmark (EIFO) CEO Peder Lundquist.

Atom Computing lands investment, expands overseas

Quantum computing developer Atom Computing received a 70 million DKK ($10.2 million) investment from the Export and Investment Fund of Denmark (EIFO). This money, along with a newly formed partnership with Danish officials, will help the company to establish its European headquarters in Copenhagen, Denmark.

Atom Computing's approach uses optically trapped neutral atom arrays to build scalable gate-based quantum computers. According to the company, the approach provides the scalability, fidelity, and long-coherence times necessary to meet next-generation demands in a faster time frame compared to other approaches.

"In Denmark, Atom Computing employs quantum research that began over 100 years ago at the Niels Bohr Institute and continues to this day at Danish universities and NATO's Deep Tech Lab — Quantum," Atom Computing CEO Rob Hays wrote in a blog post discussing the partnership.

EIFO's investment is its first with a non-Danish company. It was made in collaboration with Atom Computing and Invest in Denmark, an organization promoting national investments. The decision supports the country's National Strategy for Quantum Technology and the Quantum Information and Sciences Technology cooperation agreement between Denmark and the U.S.

Black Semiconductor raises $275 million

Graphene chip developer Black Semiconductor raised €254.4 million ($275.4 million) in funding. The startup is developing a method to build networks of graphene-based chips to speed network communications and facilitate optical chip-to-chip connections. The company said that it plans to use the funding to accelerate R&D initiatives, establish pilot line manufacturing capabilities, and boost the company's workforce.

Specifically, the investment will enable the company to advance its 300-mm wafer pilot production facility, according to company cofounder and CEO Daniel Schall. The company plans to open a pilot manufacturing facility in Aachen, Germany, by 2026 to demonstrate integration of graphene into electronic chips, with mass production planned for 2031.

According to Black Semiconductor, the platform provides a significant lowering of manufacturing costs by reducing the number of production steps by more than half. The technology has applications in data centers, generative and embedded AI, and autonomous driving.

Black Semiconductor's funding breakdown comprises €228.7 million in public funding from the German Ministry of Economic Affairs and Climate Action and the state of North Rhine-Westphalia over the next seven years. The company secured an additional €25.7 million in equity funding in a round led by Porsche Ventures and Project A ventures.

Quandela launches pilot line for qubit devices

Quantum computing company Quandela is establishing a pilot line for high-performance photonic qubit devices. Located at The Photovoltaic Institute of Île-de-France (IPVF), the line is expected to produce more than 2000 devices per year during the next two years.

The company aims to use the pilot line to boost device manufacturability and performance to accelerate the deployment of error-corrected quantum computers. At full capacity, it is projected to produce 10,000 devices per year, with qubit density increasing to hundreds of devices per square millimeter.

The manufacturing plant features a qubit identification tool for testing qubit properties at cryogenic temperatures in minutes, selecting the most performant qubits for further processing. Probing the quantum properties of hundreds of nanometer-size structures and collecting high-volume data while mapping uniformity provides fast feedback for optimizing the fabrication process, Quandela said. The process enables yields between 40% and 70% with low process variation.

The solid-state quantum dot photon source is key to the company's technology platform. Based on research by Quandela's chief science officer, Pascale Senellart, the sources boast an efficiency >50%.

According to Quandela, competing approaches use light sources that generate photon pairs with efficiencies of around 1% to 3%. Quandela's approach has the potential to reach close to 100% as it continues to be refined, the company said.

Using a first-of-its-kind approach, a semiconductor quantum dot is included in a micron-size optical cavity and aligned with <100-nm precision, leveraging a proprietary technology that enables identification of randomly placed quantum emitters, according to the company. An optical lithography step is then undertaken at cryogenic temperature, which allows the size and shape of the optical cavity to be tailor-made to the chosen emitter.

Quandela opened its first quantum computer factory last year. The company delivered two quantum computers to industrial customers, and it raised around $55 million last year to expedite expansion and increase production.

Briefs

VIGO Photonics, a producer of uncooled infrared photon detectors, signed an agreement with the **National Center for Research and Development** to cofinance the HyperPIC — photonic integrated circuits for mid-infrared applications — project up to €102.9 million ($111.3 million) under the European Funds for a Modern Economy program. The HyperPIC project aims to develop and implement PIC technology to operate in the mid-infrared range to create a production line providing a complete value chain for these systems.

Basler AG acquired 25.1% of the shares in **Roboception GmbH**, an intelligent 3D sensor technology developer. The two companies have worked togethersince 2021, including on the development of 3D image processing solutions that enable robotic systems to reliably capture and analyze their environment. According to Basler CFO/COO Hardy Mehl, the current investment will fuel development of Roboception's 3D vision technology for applications such as logistics and factory automation. Financial details of the transaction were not disclosed.

The **University of Rochester's Laboratory for Laser Energetics** (**LLE**) completed a $46 million building expansion that began in August 2022. The 66,600-sq-ft building houses 15,500 sq ft of laboratory space and will enable construction of the AMICA laser system, prototyping of the National Science Foundation OPAL lasers, and the creation of next-generation targets, diagnostics, and optics for national security efforts.

Innosuisse, the Swiss Innovation Agency, awarded **Lightium AG** a 2.67 million CHF ($2.9 million) grant to accelerate commercialization of Lightium's proprietary thin-film lithium niobate platform. Lightium aims to open beta access to its foundry services in the fourth quarter of 2024, with capabilities ranging from rapid prototyping to volume production. The company said that it will use the Innosuisse funds to transfer its manufacturing process to a commercial CMOS fab, enabling volume production.

Neutral-atom quantum computing technology developer **QuEra Computing** is doubling its footprint in Boston by adding a new building. The addition, QuEra said, addresses growing demand for its quantum computers in the U.S., Europe, and Asia.

MicroAlign, a spinoff of the Eindhoven University of Technology, closed a €1 million ($1.07 million) seed funding round to accelerate the commercialization of high-accuracy fiber arrays. Funding will be used to expand its R&D staff and facilities. Applications of the technology include quantum

Fusion startup Xcimer raises $100M, plans laser prototype

Fusion energy startup Xcimer Energy raised $100 million in a series A financing round. The company plans to use the funds to establish a new facility in Denver, where it will build a prototype laser system to advance the development of its laser-driven inertial fusion.

The company also plans to expand its technical team in Denver, where it recently moved most of its employees.

Xcimer has also hired a senior vice president of engineering, Giovanni Greco, who will lead the company's engineering efforts beginning with the design, development, and manufacturing of the prototype laser system.

Xcimer's laser architecture, the company said, will produce up to 10× higher laser energy at 10× higher efficiency, and >30× lower cost per joule than the National Ignition Facility (NIF) laser system that achieved fusion scientific breakeven in 2022. According to Xcimer, its planned prototype will include the world's largest nonlinear optical pulse compression system.

The company's goal is to extend the proven science of inertial fusion to an industrial scale via its high-energy laser system and combine it with key technologies and innovations from multiple fields.

Xcimer Energy

Xcimer Energy will use funds raised from its series A financing round to establish a facility in which it will build a prototype laser system for laser-driven inertial fusion.

According to the company, it is building on laser technologies originally pursued for the Strategic Defense Initiative (called Star Wars) defense programs of the 1980s to enable much higher laser energies. This in turn enables scaling the fusion performance achieved on the NIF to much higher gain, as well as other simplifications to the design of a laser fusion power plant.

In 2023, Xcimer was selected for a $9 million award from the Milestone-Based Fusion Development Program of the U.S. Department of Energy (DOE). Xcimer is also involved in the DOE's three inertial fusion energy hubs, in the Inertial Fusion Energy Science and Technology Accelerated Research (IFE-STAR) initiative.

computing, data communication, and artificial intelligence. The round was led by DeepTechXL and PhotonVentures, the venture capital arm of PhotonDelta.

Fraunhofer IPMS hosted German president Frank-Walter Steinmeier and French president Emmanuel Macron during a three-day French state visit to Germany. As part of the visit, leadership from the French research institute **CEA-Leti** and Fraunhofer IPMS signed a memorandum of understanding for further collaboration between the entities in microelectronics, quantum technologies, and solar and hydrogen technologies.

BlueHalo was awarded a $95.4 million contract by the U.S. Army Space and Missile Defense Command for advanced direct energy prototype development as part of the Laser technology Research Development and Optimization program through the Aviation & Missile Technology Consortium. BlueHalo will conduct continuous system performance improvement, research, and prototyping based on the company's counter-unmanned aerial systems technologies and data received through active deployment of its LOCUST laser systems.

Q*Bird, a provider of quantum networking equipment, raised €2.5 million ($2.7 million) to accelerate its growth in the quantum security market. The company is the developer of a quantum cryptography product, which is deployed under a large-scale trial at the Port of Rotterdam (Netherlands). The company expects to launch the product later this year.

Optical communications technology company **Lightwave Logic** has collaborated with **Advanced Micro Foundry** (**AMF**) to develop polymer slot modulators using AMF's silicon photonics platform. The companies previously teamed to develop electro-optic polymer slot modulators using AMF's standard manufacturing process flow on 200-mm wafers.

Flexible solar panel MIT spinout company **Active Surfaces** has raised $5.6 million in an oversubscribed pre-seed funding round. The funding will go toward scaling the company's laboratory-fabricated 4- × 4-in. photovoltaic devices with roll-to-roll semiconductor printing technologies to enable mass production of thin, flexible solar materials of any size. The devices, Active Surfaces said, can be integrated into virtually any surface.

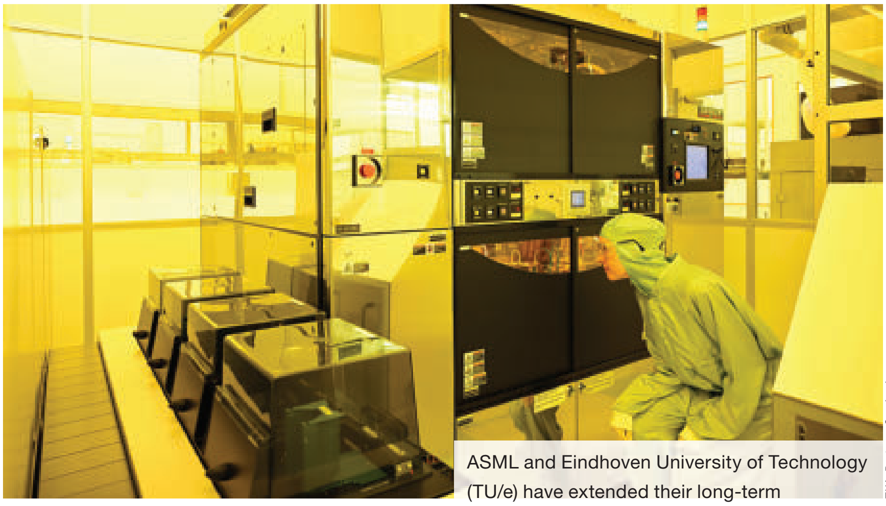
ASML, university partner commit to $195M for semiconductor R&D

ASML and Eindhoven University of Technology (TU/e) signed an agreement to expand their existing collaboration over the next ten years, with $195 million in investments. The financing is targeted to support semiconductor research as well as research and training in areas including plasma physics, mechatronics, optics, and AI, based on common road maps. The expanded collaboration will also support the establishment of a cleanroom at TU/e.

Per the agreement, ASML will invest €80 million (approximately $87 million) into the partnership during the next ten years. Its total investment in support of the cleanroom building, as well as the to-be appointed doctoral students, TU/e said, is expected to amount to more than €100 million.

The agreement, TU/e said, is the elaboration of a memorandum of understanding signed last year by ASML and the university. The pact is also in line with the €2.5-billion Project Beethoven initiative, which is spearheaded by the government of the Netherlands and the Brainport Eindhoven region to boost semiconductor production, innovation, and talent.

The collaboration also aligns with the university's own Future Chips flagship, spurred by Project Beethoven, under which the university aims to boost the development of chip technology.


TU/e Bart van Overbeeke

ASML and Eindhoven University of Technology (TU/e) have extended their long-term collaboration. Per the agreement, the pair will invest heavily in semiconductor research and talent generation, including the establishment of a new cleanroom facility.

People in the News


Intel

O'Buckley.

Intel Corporation has appointed **Kevin O'Buckley** senior vice president and general manager of Foundry Services, the customer service and ecosystems operations division of Intel Foundry. He succeeds **Stuart Pann**, who will retire at the end of May and remain with the company as an adviser to support the transition. O'Buckley joins Intel with more than 25 years of semiconductor industry experience, most recently serving as senior vice president of hardware engineering for the Custom, Compute, and Storage Group at Marvell Technologies. He joined Marvell as part of its 2019 acquisition of Avera Semiconductor, where he served as CEO.

In a series of personnel changes, Jabil has named **Michael Dastoor** CEO. Dastoor previously served as CFO and interim CEO and succeeds **Kenneth Wilson** in his new position. **Gregory Hebard**, most recently senior vice president, treasurer, was appointed CFO. The actions follow the completion of an investigation related to corporate policies, which Jabil initially disclosed this spring, and which the company said did not relate to and does not affect its financial statements or financial reporting. Separately, the company appointed **Fred McCoy** executive vice president, operations, and **Steve Borges**, **Matt Crowley**, and **Andy Priestley** executive vice presidents of global business units.


Coractive

Yang.

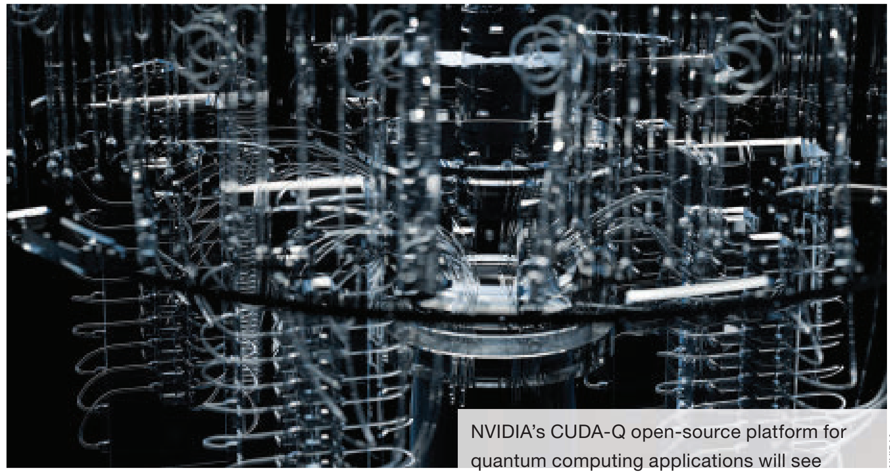
Fiber optics manufacturer and specialty fiber technology developer Coractive named **Michael Yang** CEO. He succeeds **Jean-Noel Maran**, who held the position for more than three years. Yang brings 20 years of management experience to Coractive, having worked at GfK as the national general manager, at Amazon as category lead, and has held roles at companies including Dell and Siemens.

Metalenz, a meta-optics technology company, has appointed **Gaurav Aggarwal** vice president of software and systems engineering and **Mari-Anne Gagliardi** vice president of operations. Before joining Metalenz, Aggarwal was director of backend software engineering at Snorkel AI and has held engineering leadership roles at Broadcom, Immedia/Blink, Samsung Research, and Facebook (Meta Platforms). Most recently, Gagliardi served as director of operations at Qorvo Power Device Solutions and as vice president of operations for United Silicon Carbide Inc., where she focused on developing the company's silicon carbide product supply chains.

Syntec Optics has named **Dean Rudy** CFO. Rudy brings more than 30 years of experience in financial and operational leadership. He has prior CFO experience with Auction Direct USA, Vanguard Printing, and Ben Weitsman & Son of Rochester.

Refeyn, a developer of mass photometry technology, named **Fiona Coats** chief marketing officer. Coats most recently served as the head of marketing for Sartorius' lab products and services division and has experience in leadership positions in marketing at MESO SCALE DIAGNOSTICS and Thermo Fisher Scientific.

NVIDIA strikes quantum supercomputing partnership agreements



NVIDIA's CUDA-Q open-source platform for quantum computing applications will see deployment across three sites, in Poland, Japan, and Germany.

NVIDIA

NVIDIA forms partnerships with quantum computing centers in Germany, Japan, and Poland, which will each adopt the company's open-source NVIDIA CUDA-Q platform to power their respective quantum processing units (QPUs).

The CUDA-Q open-source platform is designed for integrating and programming QPUs, graphics processing units (GPUs), and central processing units (CPUs) in one system through a unified and open programming model. NVIDIA said that CUDA-Q enables GPU-accelerated system scalability and performance across heterogeneous QPU, CPU, GPU, and emulated quantum system elements.

The platform is to be deployed at the Poznan Supercomputing and Networking Center (PSNC) in Poland in collaboration with London-based ORCA Computing. The PSNC's high-performance computing data center is equipped with two ORCA PT-1 Series quantum photonic systems in conjunction with NVIDIA GPU-based clusters.

The integration of CUDA-Q at PSNC is expected to accelerate work in a range of scientific and application areas including biology, chemistry, and machine learning.

In March, ORCA and NVIDIA reported the integration of the CUDA-Q platform with an ORCA PT-1 QPU. The companies demonstrated an algorithm for image generation using a hybrid generative adversarial network approach. According to ORCA, the output of the quantum processor was fed to neural networks running on GPUs to produce higher-quality data.

Meanwhile, in Japan, CUDA-Q has been integrated into the National Institute of Advanced Industrial Science and Technology's ABCI-Q, which uses the NVIDIA Hopper architecture. The supercomputer is powered by more than 2000 NVIDIA H100 Tensor Core GPUs in 500+ nodes interconnected by the NVIDIA Quantum-2 InfiniBand. The site is also set to deploy a neutral-atom quantum computer from QuEra Computing. This deployment is scheduled to take place in 2025.

The QPU integrated with ABCI-Q will enable researchers at the Tokyo-based institute to investigate quantum applications in AI, energy, and biology, using rubidium atoms controlled by laser light as qubits to perform calculations.

In addition, Germany's Jülich Supercomputing Centre (JSC), at Forschungszentrum Jülich, installed IQM's Spark quantum computer to complement its JUPITER supercomputer as part of the JUNIQ quantum computing infrastructure. The five-qubit system is designed for basic experiments and applications in teaching at universities and research institutes. In addition to CUDA-Q, the system will also include the NVIDIA GH200 Grace Hopper Superchip, designed for artificial intelligence and high-performance computing applications.

imec-led pilot line to support early-stage semiconductor tech

imec and European and global equipment and materials suppliers will establish the NanoIC pilot line, in collaboration with partners CEA-Leti, Fraunhofer-Gesellschaft, VTT Technical Research Centre of Finland, Center for Surface Science and Nanotechnology (CSSNT, Romania), and Tyndall Institute. With the pilot line, the goal is to develop beyond-2-nm systems-on-chip in support of European industry. The NanoIC line is to be constructed as an extension of existing imec pilot line facilities.

The initiative is set to receive €2.5 billion ($2.7 billion) through a combination of public and private contributions. The line is expected to enable companies to explore the most advanced chip technology solutions for their future applications, imec said. With the pilot line, imec aims to lower this threshold by offering early-stage process design kits (PDKs). Startups, small- and medium-size enterprises, universities, and design and system companies can use design pathfinding PDKs for prototyping of advanced technology components on top of commercially available foundry wafer. Foundries and integrated device manufacturers can evaluate innovations in process flows and equipment, for example. This would support derisking for new features before internal investments are made, thereby improving the speed and efficiency of process development, according to imec.

The pilot line will also benefit from the development of a pan-European design platform combined with access to a network of competence centers, offering training and support to boost design skills. The design infrastructure is expected to link the technology and design communities to accelerate development and reduce time-to-market for products.

The line's funding will be provided in part by European Union funding programs, such as Horizon Europe and Digital Europe, through the Chips Joint Undertaking and Flanders, with a total of €1.4 billion in indicative public funding. The grant agreement with the Chips Joint Undertaking is currently ongoing and will be signed later this year. Private contributions will be made by several industry partners, including ASML, and are set to amount to €1.1 billion. The foundational investment will be leveraged further through strong contributions from the European Union and global industry to run projects on the pilot line.

ZEISS to establish photonics and optics business unit

Carl Zeiss AG (ZEISS) will establish a dedicated photonics and optics business unit within the ZEISS Group starting in the 2024/2025 fiscal year. The unit will combine seven smaller, specialized units within the ZEISS Group, which will operate as independents.

The umbrella unit will include the ZEISS Group's micro-optics, spectroscopy, planetariums, and simulation projection solutions businesses from its current shared production unit as well as the cinematography, mobile imaging, photo, and optics business for hunting and nature observation, currently under its consumer products business unit.

The restructuring, the company said, will not result in changes for customers regarding products, services, or contacts. In addition, ZEISS said that it plans to acquire companies it has identified as having high growth potential, and to incorporate these acquisitions under the newly formed ZEISS Photonics & Optics umbrella.

ZEISS holds all subsidiaries within Zeiss Group, including Carl Zeiss Meditec AG, Carl Zeiss Vision GmbH, Carl Zeiss SMT GmbH, Carl Zeiss IMT GmbH, and Carl Zeiss Microscopy GmbH. The ZEISS Group has approximately 43,000 employees across 50 countries.

Technology News

Blurred light delivers 3D-printed, high-quality optics

OTTAWA, Ontario — Researchers from the National Research Council of Canada developed a 3D-printing method, called blurred tomography, that can be used to rapidly produce microlenses with commercial-level optical quality. By adding optical blurring effects to the light beams used in the 3D-printing approach, the researchers achieved the production of optically smooth surfaces.

The speed and simplicity of the method could enable the approach to be used for the design and fabrication of a variety of optical devices.

According to Daniel Webber of the National Research Council of Canada, the researchers expect the affordability of the tomographic 3D printer, as well as the materials used in the method, to offer value as a cost-effective and swift prototyping technique for optical components. “Also, the inherent freeform nature of tomographic 3D printing could enable optical designers to simplify designs by replacing multiple standard optics with printed optics that have complex shapes,” Webber said.

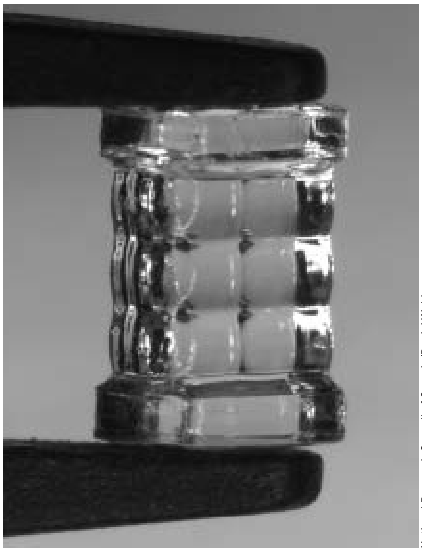
In demonstrations, the researchers made a millimeter-size plano-convex optical lens with an imaging performance comparable to a commercially available glass lens. They also showed that the method can produce optical components that are ready to use in just 30 min.

Tomographic volumetric additive manufacturing is a relatively new manufacturing approach that uses projected light to solidify a light-sensitive resin in specific areas. It allows an entire part to be printed at once without any support structures. However, existing tomographic methods cannot directly print imaging-quality lenses because the pencil-like beams used cause striations that lead to small ridges on the component’s surface. Although post-processing steps can be used to create smooth surfaces, these approaches add time and difficulty, which remove the rapid prototyping advantage associated with tomographic printing.

“Blurred tomography can be used to make freeform designs in a low-cost manner. As the technology matures, it could allow much quicker prototyping for new optical devices, which would be useful for anyone from commercial manufacturers to garage-based inventors,” Webber said.

The researchers are working to improve component accuracy by optimizing the light patterning method and incorporating material parameters into the printing process. The researchers also want to introduce automation to make the system sufficiently robust for commercial use.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.519278).


National Research Council of Canada/Daniel Webber

A Canadian research team developed a 3D-printing method, called blurred tomography, that can rapidly produce microlenses with commercial-level optical quality. The team used the technique to print a microlens array, shown being held by a set of tweezers.

Chip-scale erbium laser points to portable integrated systems

LAUSANNE, Switzerland — At the crossroads of growing demand for both fiber lasers and chip-scale lasers, researchers at École polytechnique fédérale de Lausanne (EPFL) developed a chip-integrated erbium-doped waveguide laser that meets the performance of fiber-based lasers. It combines wide wavelength tunability with the practicality of chip-scale photonic integration.

Fiber lasers are commonly favored for their stable high-quality beams and high output power as well as their efficiency, low-maintenance requirements, durability, and smaller size compared to gas lasers. The increased demand to miniaturize these sources to chip-scale led the EPFL researchers to use erbium as the gain source and construct a meter-long, on-chip optical cavity based on an ultralow-loss silicon nitride PIC. According to Yang Liu, a researcher in EPFL’s Laboratory of Photonics and Quantum Measurements, the researchers integrated micro-ring resonators that extended the optical path without enlarging the device.

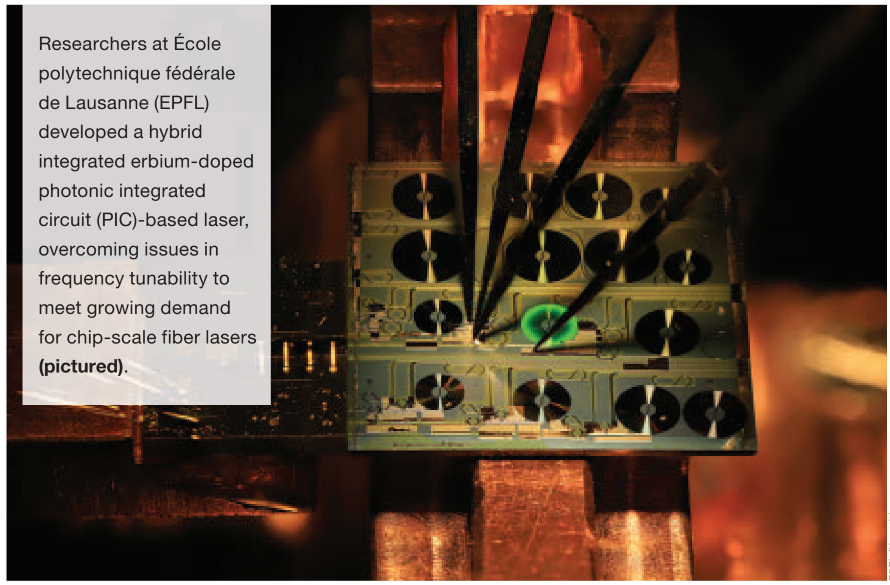
The researchers implanted the circuit with high-concentration erbium ions to selectively create the active gain medium necessary for lasing. Finally, they integrated the circuit with a III-V semiconductor pump laser to excite the erbium ions to enable them to emit light and produce the laser beam.

To refine the laser’s performance and achieve precise wavelength control, the researchers engineered an innovative intracavity design featuring micro-ring-based Vernier filters, a type of optical filter that can select specific frequencies of light. The filter allows dynamic tuning of the laser's wavelength across 40 nm within the C- and L-bands. This surpasses legacy fiber lasers in metrics gauging both tuning and low spectral spurs, or unwanted frequencies, while remaining compatible with current semiconductor manufacturing processes.

The design supports stable, single-mode lasing with a narrow intrinsic linewidth of 50 Hz. It also allows for significant side mode suppression — the laser's ability to emit light at a single, consistent frequency while minimizing the intensity of other frequencies (side modes). In practice, this allows "clean" and stable output across the light spectrum for high-precision applications.

With output power exceeding 10 mW and a side mode suppression ratio >70 dB, the chip-scale source is well suited for coherent applications, such as sensing, gyroscopy, lidar, and optical metrology. Further, the ability to produce chip-scale erbium fiber lasers could reduce overall costs and increase accessibility for portable integrated systems across telecommunications, medical diagnostics, and consumer electronics. It could also scale down optical technologies in applications such as lidar, microwave photonics, optical frequency synthesis, and free-space communications.

The research was published in *Nature Photonics* (www.doi.org/10.1038/s41566-024-01454-7).



Researchers at École polytechnique fédérale de Lausanne (EPFL) developed a hybrid integrated erbium-doped photonic integrated circuit (PIC)-based laser, overcoming issues in frequency tunability to meet growing demand for chip-scale fiber lasers **(pictured)**.

EPFL/Yang Liu

Fiber optic gyroscope monitors risk in active volcanoes

FLORENCE, Italy — Researchers from the Consiglio Nazionale delle Ricerche Istituto Nazionale di Ottica (CNR-INO), the National Institute of Geophysics and Volcanology (INGV), and the Italian Space Agency (ASI) built a prototype fiber optic gyroscope for high-resolution, real-time monitoring of ground rotations caused by earthquakes in the active volcanic area of Campi Flegrei in Naples, Italy. The device is expected to provide greater insights into seismic activity in the region, which could help improve risk assessment and early warning systems.

In the study, researchers reported preliminary observational data gathered from the rotational sensor over the course of five months. The sensor, based on a 2-km-long fiber optic gyroscope, detected noise and ground rotations from small to medium local earthquakes.

Gyroscopes detect and measure changes in orientation or angular velocity — the rate at which an object rotates. For example, in smartphones, simple gyroscopes detect and measure the device's orientation and rotation. To

A fiber optic gyroscope for monitoring linear and rotational activity in Earth's crust caused by seismic activity. Based on the Sagnac effect, the gyroscope is formed from fibers wound around an aluminum spool.

Consiglio Nazionale delle Ricerche Istituto Nazionale di Ottica (CNR-INO)/Saverio Avino measure rotation in seismic waves from an earthquake or volcanic activity, the researchers developed a more complex gyroscope based on the Sagnac effect, which occurs when light traveling in opposite directions around a closed loop exhibits different travel times. This leads to measurable interference patterns in the light that depend on the rotation rate of the loop. By measuring the light interference, the angular velocity can be detected with high resolution.

"Our labs are located in the heart of an active volcanic area, thus creating a natural source of earthquakes," said research team leader Saverio Avino from CNR-INO.

"Because we experience small/medium earthquakes almost every day, we can measure and acquire a large number of data on ground rotations, which can be successively analyzed to study seismic and volcanic phenomena of the Campi Flegrei region."

According to Avino, seismic activity incites linear and rotational movements that can be detected on the Earth's surface. Rotations, he said, are generally small and not typically monitored. The ability to capture them would grant a more complete understanding of Earth's internal dynamics and seismic sources.

Naples, a city of ~3 million people, has three active volcanoes. The area is covered by a grid of multiparametric sensors that provide real-time monitoring of physical and chemical parameters used to study seismic and volcanic activity.

The researchers assembled a prototype fiber optic rotational sensor using standard laboratory instrumentation and components. In experiments, the optical sensor was kept in a controlled laboratory environment in a building that sits on top of a volcano caldera — a large depression formed when a volcano erupts and collapses.

"This first version of the system showed a resolution comparable to other state-of-the art fiber-optic gyroscopes," said paper first author Marialuisa Capezzuto, from CNR-INO.

The research was published in *Applied Optics* (www.doi.org/10.1364/AO.518354).

Laser patterning raises soft electronics' operation possibilities

CHEONAN, South Korea — As micro- and optoelectronics move beyond foldable and rollable devices into an era of stretchable devices for electronic textiles, health care, and other applications, it is essential to develop small, elastic energy storage devices. Using a laser ablation patterning technique, researchers from the Korea Institute of Industrial Technology and Pohang University of Science and Technology (POSTECH) fabricated deformable micro-supercapacitors (MSCs) for storing energy in soft electronic devices.

The work addresses the need for energy storage systems in emerging stretchable devices for health monitoring, among other applications. MSCs offer customizable form factors, reliable performance, efficient use of space, and easy integration with electronic components. However, the solid metals that are typically used to collect the current in MSCs, such as gold, have limited stretchability, restricting deformation potential.

To fabricate an MSC capable of bending and stretching without breaking or losing functionality, the researchers selected a liquid metal, eutectic gallium-indium (EGaIn) alloy, as the current collector. EGaIn has high conductivity and, due to its liquid nature, is easily deformable. However, fabricating high-density interdigitated patterns with EGaIn to ensure high energy storage performance has proved to be a challenge.

To shape the EGaIn, the researchers used graphene as the material for the electrode and polystyrene-block-poly (ethylene-co-butylene)-block-polystyrene copolymer (SEBS) as the material for a flexible substrate. They fabricated EGaIn film with a uniform thickness on the SEBS substrate using a brushing method. They then coated graphene onto the EGaIn film and fabricated an interdigitated graphene-EGaIn electrode using laser ablation.

The researchers optimized the laser ablation process to ensure that the complete ablation of both the graphene and the EGaIn occurred without damaging the SEBS. During laser irradiation, the graphene and EGaIn film absorbed the laser light at a wavelength of 355 nm, while the SEBS material did not absorb any light. In this way, the team achieved selective ablation of the graphene-EGaIn electrode without losing the flexibility of the substrate.

The energy storage performance of MSCs depends on the areal density of the interdigitated electrodes. Ideally, the gap between neighboring interdigitated electrodes should be minimized for as long as the electrodes maintain mechanical and electrical stability under deformation.

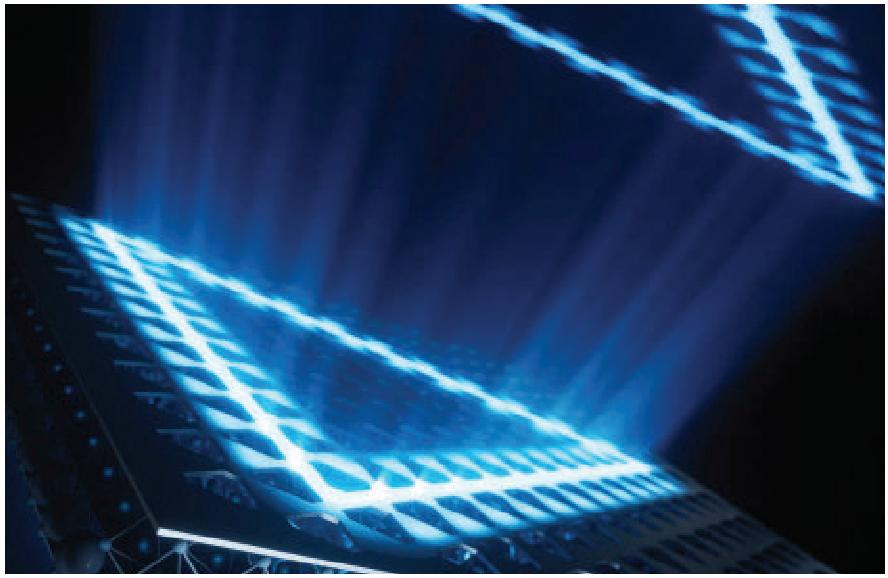
By carefully controlling the gap between neighboring interdigitated electrodes and the mass loading of graphene, the researchers achieved a high areal capacitance of 1336 $\mu F\ cm^{-2}$ with reliable rate performance.

The researchers stretched and shrank the MSC for 1000 cycles without impairing energy storage performance. To demonstrate the feasibility of using the MSC as a deformable power source, the researchers fabricated a soft electronic system comprising serial and parallel connected MSC arrays integrated with LEDs. Because of the liquid characteristics of the EGaIn current collector and the flexibility of the SEBS substrate, the MSC demonstrated a strong energy storage performance, and the soft electronic system demonstrated stable operation under various mechanical deformations, including folding, stretching, wrinkling, and twisting.

The researchers believe that the laser ablation technology could be used to pattern various electrode materials, including carbon materials, metal oxides, and Mxene(s), for deformable, high-performance energy storage systems.

The research was published in *npj Flexible Electronics* (www.doi.org/10.1038/s41528-024-00306-2).

Photonic insulator enhances study of light-matter interactions


Rensselaer Polytechnic Institute

A graphical rendering of the photonic topological insulator. The device, as thin as a human hair, could help physicists better understand the nature of matter and light in disciplines including laser and quantum physics.

TROY, N.Y. — Researchers from Rensselaer Polytechnic Institute (RPI) created a device as thin as a human hair that could help physicists better understand the nature of matter and light. The researchers created the device with a photonic topological insulator. This material can guide photons to interfaces specifically designed within the material, while also preventing light from scattering through the material itself.

Using this property, topological insulators can cause many photons to behave coherently, as if they were a single photon.

Exciton-polaritons — the hybrid quasiparticles of excitons and photons — have the potential to serve as a tunable, nonlinear platform for studying topological phenomena. However, due to limitations in materials, experimental observations using an exciton-polariton platform have been unable to enter the nonlinear condensation regime.

RPI researchers used halide perovskites with a valley Hall lattice design to create a polariton lattice that operates in a strong light-matter interaction regime. The lattice-based topological insulator can operate at room temperature without any external magnetic field and can be used to explore topological phenomena without the need for bulky, expensive equipment.

According to professor Wei Bao, the team's insulator works at room temperature — signifying a major advancement.

"Previously, one could only investigate this regime using big, expensive equipment that supercools matter in a vacuum. Many research labs do not have access to this kind of equipment, so our device could allow more people to pursue this kind of basic physics research in the lab," Bao said.

To fabricate the device, researchers followed the technique that is used to build semiconductor chips, layering different kinds of materials to form a structure with the desired properties. They grew ultrathin plates of halide perovskites made of cesium, lead, and chlorine ($CsPbCl_3$) and etched a polymer with a pattern on top of the perovskite layer. They sandwiched the perovskite and polymer layers between sheets of oxide materials, forming a lattice ~2-μm thick and 100 μm in length and width.

The polariton lattice features a large bandgap of 18.8 meV and exhibits strong nonlinear behavior, with clear long-range spatial coherence across the critical pumping density.

When the researchers shined a laser on the device, a triangular pattern appeared at the interfaces in the material, indicating the topological characteristic of the laser.

The photonic topological insulator can also be used as a quantum simulator and may help improve efficiency in lasers. Further, the parameters and material composition of the photonic topical insulator can potentially be tailored to study topological phenomena related to other interquasiparticle interactions.

The research was published in *Nature Nanotechnology* (www.doi.org/10.1038/s41565-024-01674-6).

WGM resonators get sensitivity and portability boost for in-field use

TUCSON, Ariz. — Whispering gallery mode (WGM) resonators enable many biochemical applications, owing to the high sensitivity, rapid response, and label-free characteristics that these structures provide. Applications range from early diagnostics and prognostics to food and water quality inspection, to chemical threat sensing and hazardous gas detection.

Although the WGM microtoroid resonator has been shown to be one of the most sensitive biochemical sensors in existence, capable of detecting single molecules, the tapered optical fiber used to evanescently couple light into the resonator has been a barrier to commercializing this sensor for field work. The fiber must be precisely aligned with the microtoroid for phase matching and efficient energy transfer. However, this component is fragile and susceptible to mechanical vibrations due to fluid flow and air currents.

In recent work, researchers at the University of Arizona developed a design that eliminates the need for a tapered optical fiber altogether. The researchers designed a free-space coupling system for microtoroid resonators that uses a single objective lens with a digital micromirror device (DMD) for light injection, scattered light collection, and imaging the microtoroid.

The DMD, which filters out some of the present stray light, can be used to select a region of interest. The use of a single objective lens allows for a more compact system, a cheaper design, and easier alignment.

The DMD reflectivity spans 700 to 2500 nm, and the system's optical components are designed for use in the NIR band. However, the system design is compatible with other WGM mode resonators and wavelengths, although at other wavelengths, some components may need to be replaced to fit the application.

Using 100-μm diameter microtoroids, the researchers achieved quality factors as high as 1.6 × 108. Electromagnetically induced transparency-like and Fano resonances were observed in a single cavity, which the researchers attributed to indirect coupling in free space. These resonances enhanced the sensitivity of the resonator. Also, the large coupling area — ~10 μm in diameter for a numerical aperture equal to 0.14 — removed the need for precise positioning.

The team is adapting the system for biosensing detection in aqueous environments and is multiplexing the sensors to enable simultaneous, multitarget detection. The researchers believe the work could also help expand WGM microtoroid resonators for spectroscopy applications.

The research was published in *Light: Science & Applications* (www.doi.org/10.1038/s41377-024-01418-0).

Quantum optical sensor aims to increase MRI scan quality, speed

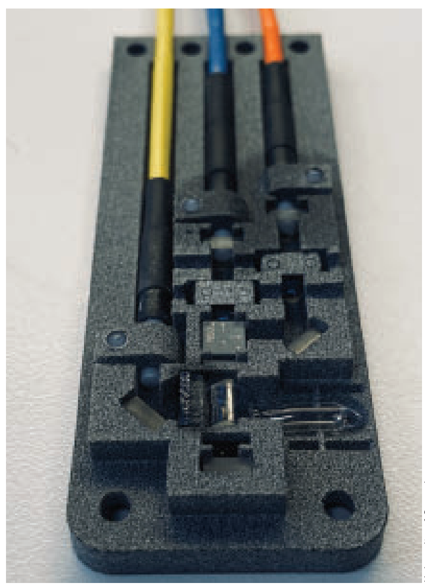
COPENHAGEN, Denmark — Researchers at the Danish Research Center for Magnetic Resonance (DRCMR) and the Niels Bohr Institute at the University of Copenhagen developed a quantum optical magnetometer to help spot flaws in MRI scans. This sensor aims to increase the longevity of MRI scanners and improve their quality and lower costs. MRI scanners provide 3D images of exceptional quality, though the strong magnetic fields used to create these images have fluctuations that can introduce errors and disturbances in scans.

Consequently, these machines need frequent calibration to maintain their image quality. Additionally, scanning methods such as spiral sequences, which could reduce scanning time(s), are not feasible due to the magnetic field's high levels of instability.

In theory, this problem could be corrected by adding a sensor to read and map changes in the magnetic field. Doing so would allow errors to be corrected computationally.

In practice, however, this has been difficult to implement due to interference from electrical-based sensors and the metals used in cables.

The newly developed optical sensor is based on saturated absorption spectroscopy on the extreme angular-momentum states of the cesium D2 line. It has four small, separate field sensors that are distributed in the MRI scanner. One of these probes remains out of range of the magnetic field and acts as a control. The system sends laser light through fiber optic cables to the four sensors located in the scanner.


University of Copenhagen

The prototype of the optical sensor, which is operational at Hvidovre Hospital near Copenhagen, Denmark, where it will be fine-tuned after test data is collected.

Inside the sensors, light passes through a small glass container that holds the cesium gas. At a certain frequency, the gas absorbs the light, and a resonance is created in the cesium atoms. The electrons in the cesium atoms oscillate more while absorbing the light, and the light is then re-emitted as the electrons fall back into place. The light dims and the gas vapor gets brighter. If the cesium is exposed to a magnetic field, the frequency of the light will change according to the strength of the field.

When fluctuations in the magnetic field occur, the optical sensor maps the location of the disturbance in the field and registers how the disturbance has affected the strength of the field. The resulting data is used to identify errors in the MRI scan. Corrections to disturbed and faulty images could be made based on the data collected by the four sensors, ensuring the MRI image is accurate.

The optical sensor offers continuous readout, a high sampling rate, and sensitivity and accuracy in the parts per million (ppm) range. All support electronics and optics for the system are fitted into a single, 19-in. rack to make it compact, mobile, and robust. The field sensors are fiber-coupled and made from nonmetallic components, allowing them to be easily and safely positioned inside a 7 tesla (T) MRI scanner.

The researchers demonstrated the capabilities of the optical sensor by measuring two different MRI sequences. To highlight the system's potential applications in medical MRI, they showed how it can be used to reveal imperfections in the gradient coil system.

According to Hans Stærkind, the primary designer of the sensor, MRI scanners already produce high-quality images.

"But with the help of my sensor, it is imaginable to use the same amount of time to produce even better imagery — or spend less time and still get the same quality as today," he said.

"A third scenario could be to build a cheaper scanner that, despite a few errors, could still deliver decent image quality with the help of my sensor," he said.

A prototype of the sensor is currently operational at Hvidovre Hospital at DRCMR.

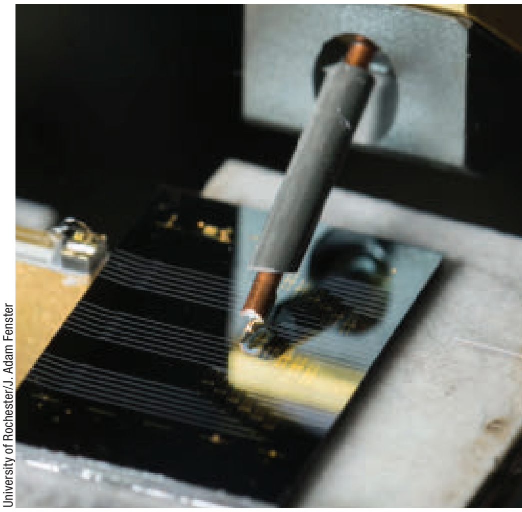
The research was published in *PRX Quantum* (www.doi.org/10.1103/PRXQuantum.5.020320) and *Physical Review X* (www.doi.org/10.1103/PhysRevX.13.021036).

On-chip laser showcases self-sustained comb operation

ROCHESTER, N.Y. — Optical frequency combs have been transformational for metrology, spectroscopy, atomic clocks, and other applications. Their utility outside of lab and industrial settings, however, has yet to be realized due to the difficulty of developing frequency comb generators at the microchip scale.

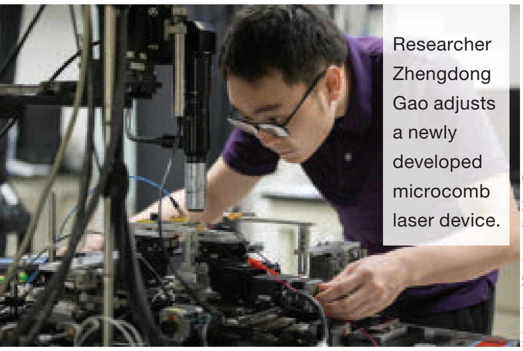
Now, due to a method introduced by researchers at the University of Rochester, a path to applying microcomb lasers to fields, including telecommunications and optical computing, is within reach. The lasers, developed by Rochester professor Qiang Lin and his team, benefit from a simple design and resolve long-standing challenges that have prevented the commercial adoption of microcombs.

While there has been progress in prototyping microcombs, there has been limited success producing viable versions that can be applied in practical devices. Obstacles preventing this success include low power efficiency, limited controllability, slow mechanical responses, and the



University of Rochester/J. Adam Fenster

University of Rochester researchers created a chip-scale microcomb laser with an innovative design that allows users to control the optical frequency comb simply by switching on a power source.



Researcher Zhengdong Gao adjusts a newly developed microcomb laser device.

University of Rochester/J. Adam Fenster

need for sophisticated system preconfiguration.

According to Jingwei Ling, a Ph.D. student in Lin's lab and lead author of the paper, previous approaches have usually relied on a single-wavelength laser injected into a nonlinear converter that can transfer the single wavelength into multiple wavelengths, thereby forming the optical comb.

"We eliminated the single wavelength because that's going to degrade the system's efficiency," Ling said. "We instead have all the comb itself being amplified in a feedback loop inside the system, so all the wavelengths get reflected and enhanced inside a single element."

The researchers initiated comb generation using resonantly enhanced electro-optic modulation. A resonantly enhanced optical Kerr effect served to expand the comb bandwidth and phase-lock the comb lines, and an embedded III-V optical gain stabilized and sustained the comb operations. The researchers fed the resulting coherent microwave back to the electro-optic comb to further enhance the mode-locking and allow self-sustained comb operation. To achieve this, the researchers integrated a III-V gain element with a thin-film lithium niobate photonic integrated circuit to create a III-V/lithium-niobate comb laser. They combined active electro-optic modulation with passive four-wave mixing in a dispersion-engineered, high-Q laser cavity to enable the on-demand generation of a mode-locked soliton microcomb.

While the microcomb laser unifies architectural and operational simplicity, the obstacles of electro-optic reconfigurability, high-speed tunability, and multifunctional capability must be overcome before the technology can be implemented — particularly in fabrication methods. The researchers, however, are hopeful that their devices can find use in other applications, including telecommunications systems and lidar.

The research was published in *Nature Communications* (www.doi.org/10.1038/s41467-024-48544-2).

Light-matter discovery challenges understanding of photon momenta

IRVINE, Calif. — A research team at the University of California, Irvine (UC Irvine), working with researchers at Kazan Federal University, discovered that photons can gain substantial momentum when they are confined to nanometer-scale spaces in silicon — in a process similar to how momentum is obtained by electrons in solid materials. The light-matter discovery could make silicon a more effective medium for optoelectronics applications, including solar energy and semiconductor lasing.

Although bulk silicon does not naturally emit light, silicon that is porous and nanostructured can produce detectable light after being exposed to visible radiation. This phenomenon, although not fully understood, fueled the study on photon momentum in silicon. The researchers reported the discovery during their investigation of structural photoemission in silicon glass.

"Silicon is Earth's second-most abundant element, and it forms the backbone of modern electronics," said Dmitry Fishman, director of Laser Spectroscopy Laboratories at UC Irvine. "However, being an indirect semiconductor, its utilization in optoelectronics has been hindered by poor optical properties."

The work of the UC Irvine-led team builds on discoveries of luminary physicists Arthur Compton and C.V. Raman. In 1923, Compton discovered that gamma photons possessed sufficient momentum to strongly interact with free or bound electrons. "In our experiments, we showed that the momentum of visible light confined to nanoscale silicon crystals produces a similar optical interaction in semiconductors," Fishman said.

Raman's further investigations in 1928 led to the discovery of what is now known as the vibrational Raman effect and Raman scattering.

For its recent investigation, the team produced silicon glass samples ranging in clarity from amorphous to crystalline. They exposed a 300-nm-thick silicon film to a tightly focused, continuous wave laser that was scanned to write an array of straight lines. In areas of the film where the temperature did not exceed 500 °C, a homogeneous, cross-linked glass was formed. In areas where the temperature surpassed 500 °C, a heterogeneous semiconductor glass was created. The differences in the silicon film allowed the team to observe how the electronic, optical, and thermal properties of silicon glass varied on the nanometer scale.

Based on their experiments, the researchers found that light emission in silicon glass is the result of electronic Raman scattering. "But unlike conventional vibrational Raman, electronic Raman involves different initial and final states for the electron, a phenomenon previously only observed in metals," said Eric Potma, a professor at UC Irvine.

The researchers attribute photoemission in the disordered system to the presence of an excess electron density in states within the forbidden gap (Urbach bridge) where electrons occupy trapped states. Transitions from gap states to the conduction band are enabled through electron-photon momentum matching. The researchers discovered that this momentum matching resembles Compton scattering but is observed for the visible light spectrum and driven by the enhanced momentum of a photon confined within nanostructured spaces.

The researchers' experiments demonstrated the role of photon momentum in the optical response of solids that display disorder on the nanoscale.

The research was published in *ACS Nano* (www.doi.org/10.1021/acsnano.3c12666).

Growing the Photonics Workforce Demands an Early Start

BY KEVIN MCCOMBER
SPARK PHOTONICS

Industry workforce reports and popular news stories have made it clear: There is a glaring need to increase the number of workers in photonics and in the semiconductor industry more broadly. In 2021, MIT researchers projected that U.S.-based middle-skilled and select lower-skilled positions within the photonics industry would grow from around 58,000 to nearly 85,000 by 2030[1]. In 2023, the Semiconductor Industry Association (SIA) projected that the U.S. semiconductor industry will add 115,000 jobs by 2030. At current rates of degree completion, however, the association said that ~67,000 of these positions could go unfilled.

Students from Doherty Memorial High School in Worcester, Mass., are introduced to college-level courses during a visit to Worcester Polytechnic Institute.

Latent potential in K-12

The need to add talent in the semiconductor industry and related disciplines is evident beyond the cleanrooms. From my position as CEO of Spark Photonics Design, an integrated photonics design services company, the most obvious discrepancy of this multipronged challenge pertains to the dynamic that exists between skilled workers and the types of programs that are essential to cultivate talent. There are numerous workforce development initiatives either deployed or still emerging for semiconductors and photonics. Since companies, understandably, seek to fill their open positions in the near term, many firms gravitate toward certificate- or degree-earning programs, students, and graduates. These programs typically serve a population of college/university students as well as those who have already entered the workforce.

In doing so, such efforts almost entirely overlook the K-12 demographic and, as a result, address only a small portion of the potential talent funnel.

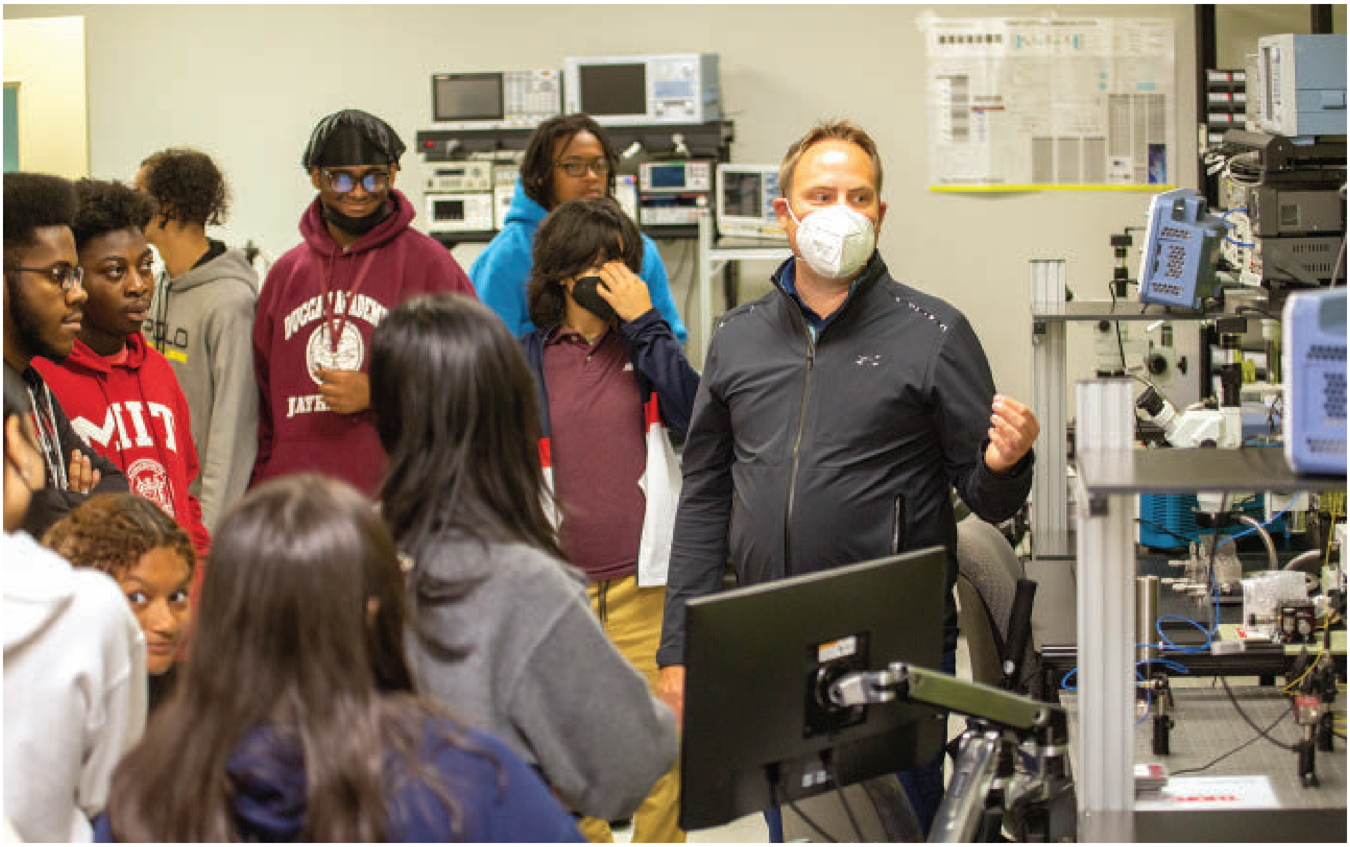
How small is this portion of the funnel? According to the National Center for Education Statistics (NCES), in 2021 ~62% of the U.S.' high school graduates enrolled in college. Of all postsecondary certificates and degrees awarded in the 2021 to 2022 school year in the U.S., ~18% were in STEM fields.

This means that from the end of high school to the completion of a certificate or degree, ~90% of graduates opt to pursue careers outside of STEM. One way to cut into this number and help build the STEM workforce is to reach students long before their high school graduation.

Another critical area to target is the clear disparities that exist among the recipients of STEM certificates and degrees across demographic groups. Addressing these disparities could be transformational for the STEM workforce, including those who work with semiconductors.

For example, in the 2021 to 2022 school year, men earned nearly two-thirds of all STEM degrees and certificates, according to NCES figures. Driving up the number of women receiving their STEM certificates and degrees to be on par with their male counterparts would add approximately 230,000 more STEM graduates — a value that would represent a 29%

All images courtesy of Spark Photonics Foundation.



Students from John J. Duggan Academy in Springfield, Mass., examine integrated photonics measurement equipment during a visit to Western New England University.

increase in the number of STEM graduates overall.

Further, studies show that most students choose their disciplines to pursue during or before the eighth grade[2]. Students typically select high school classes based on these interests. The importance of presenting STEM opportunities to students by or before eighth grade is obvious, and there is enormous opportunity to grow the photonics and semiconductor workforce in elementary and middle school.

Fertile ground in photonics

Founded in 2019, the nonprofit Spark Photonics Foundation aims to engage young people in the fields of photonics and semiconductors. While we have easily identified workforce trends, solutions have been more difficult to decipher, given the need to fully develop and implement programming. For example, the underrepresentation of girls and women in STEM is a disparity that largely originates prior to high school. This signals an enormous opportunity for growth in the field of semiconductors, and particularly for photonics — a discipline that is often completely unknown in K-12. By contrast, many K-12 students are already familiar with or even working with electronics, often in quite sophisticated ways. Since photonics typically presents as an untapped technology area for K-12 students, there is rarely any degree of prior knowledge or experience. This creates a level playing field and makes it easier to engage students who might otherwise feel intimidated by their peers' expertise in certain subject matter.

Moreover, photonics is a discipline that students can observe in action, eliminating the hypothetical application of the science and making it "real." This only adds to the prospect of engagement.

Teachers, school administrators, and parents also have good reasons to showcase the potential of a career in photonics to their students. Beyond the high demand for jobs in the field, the industry also boasts well-above-average entry-level wages. According to U.S. Bureau of Labor Statistics data, degrees in electrical/electronic engineering closely align with the content associated with photonics; those with an associate degree in this focus have a median salary of $72,800 and those with a bachelor's degree have a median salary of $109,010. Both are significantly higher than the median U.S. salary of $59,540. White House reports from 2022 further show that, compared to other manufacturing professions, semiconductor manufacturing pays >20% higher wages on average.

Headwinds for K-12 workforce efforts

Unfortunately, the idea of addressing photonics/semiconductor workforce needs at the K-12 level is met with skepticism in many cases. Often, these doubts concern the viability of implementing photonics-focused programming for K-12 students — and not the merits of the argument. The most common challenge is that K-12 teachers (in U.S. public schools) lack the time to implement new programming. To be sure, many school curricula are predetermined and aim to prepare students for standardized testing.

In other instances, professionals in both industry and academia may contend that semiconductor and related scientific disciplines are too technically challenging to introduce to K-12 students. It is important to note that exposure to photonics/semiconductors in K-12 is not so much about a deep understanding of the technology as it is about an awareness of the technology's possibilities. The Spark Photonics Foundation's Spark-Alpha program introduces K-12 students to photonics by focusing on applications of integrated photonic sensors. The program enables students to devise product ideas and ways that the technology may ultimately be deployed.

An additional common refrain is that K-12 schools lack the funds for new programming. School budgets are typically fully allocated, and long budget cycles often indicate that adding programming requires extended effort.

But for some institutions, substantial external funding does flow into the school system — and often on shorter cycles than their regular budget(s). Highlighting the benefits of programs such as these can be crucial to unlocking more resources to build up curricula. Given the need for more workers to aid in the production of semiconductors, which is an increasingly popular topic of discussion, it is becoming easier to make the case for more STEM programming.

Actions we can take together

There are several steps that those in all reaches of the photonics ecosystem can take to capitalize on this opportunity in workforce development.

First, in academia, adopting a goal that gives students the tools needed to graduate and pursue meaningful careers should be supplemented with placing priority on growing the ranks of incoming students pursuing specialized certificate and degree programs in semiconductors and photonics. Engaging K-12 students in ways that pique their interests and impress a range of opportunities upon them are effective target outcomes from active engagement initiatives.

Showing not only the results of a STEM career but also the journey to such a career must be a greater focus of outreach efforts for schools. In contrast to showcase-style events, project-based learning activities enable students to actively drive their education and work collaboratively to complete a task, often with many creative potential end uses.

Under the workforce development umbrella, the role of the government is often tightly tied to funding. In many state- and federally subsidized programs working in and/or with semiconductors, workforce development is a required component. Often, however, technical requirements of many funded programs are lengthy, while the workforce development component is only briefly touched upon. Workforce development at the K-12 level is rarely required, and yet every workforce initiative is influenced by the results of K-12 education. Adopting a holistic view of the workforce would command that state and federal leaders include focused, direct, and specific requirements for K-12 educational outreach when dispersing funds to worthy applicants.

Finally, workforce development is a long-term investment. Too many professionals in our field, including many of my peers, view the idea of workforce development as equivalent to college internships or apprenticeships that streamline employee hiring as rapidly as possible. Instead, we need to simultaneously grow the next generation of technicians and engineers and allow ourselves to be guided by efforts that will pay off down the road.

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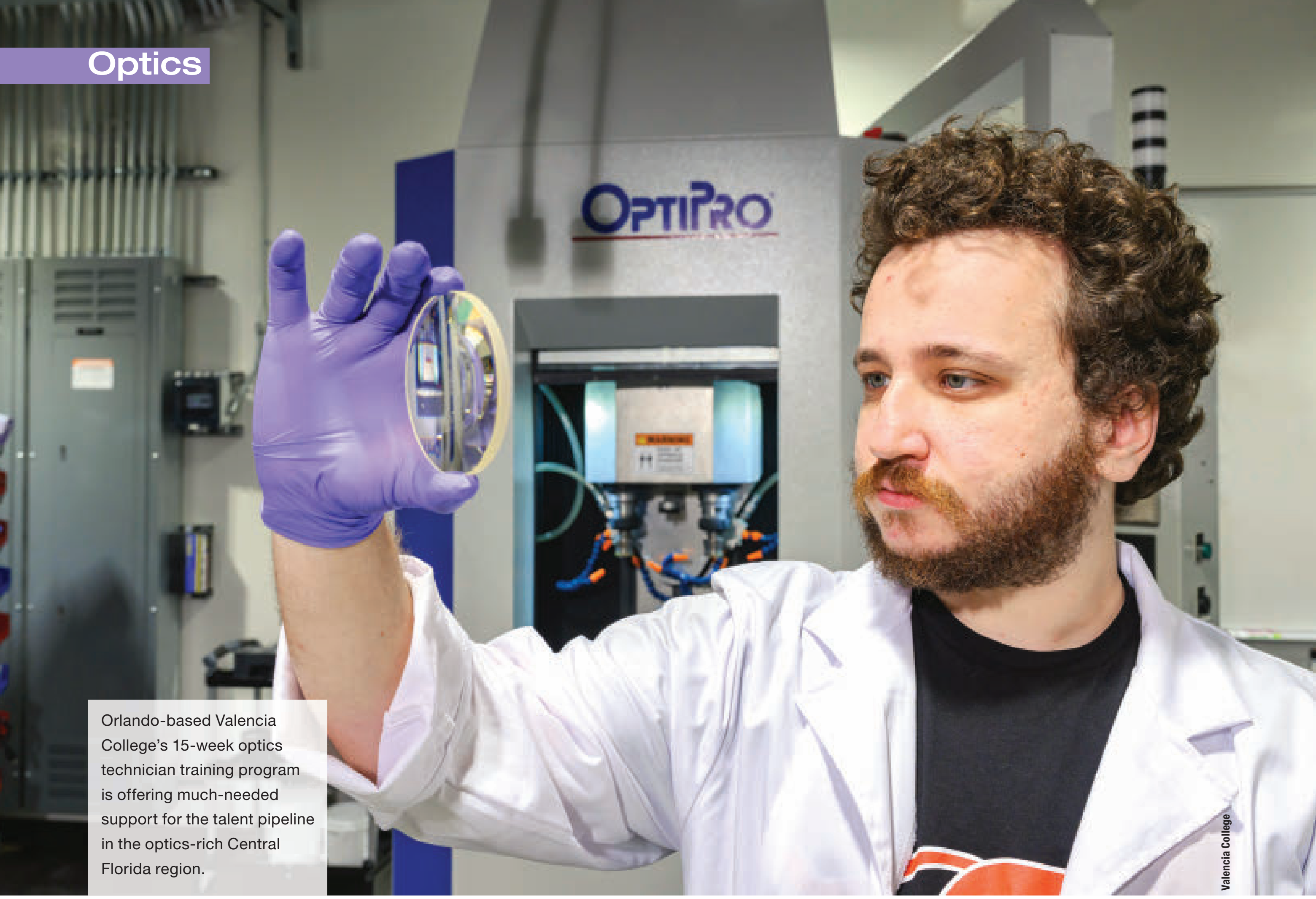


Orlando-based Valencia College's 15-week optics technician training program is offering much-needed support for the talent pipeline in the optics-rich Central Florida region.

Valencia College

A 15-Week Technician Program Bolsters Central Florida's Optics Ecosystem

A program to facilitate Central Florida's optical technician talent pipeline adds a critical dynamic to a region that is already a top producer of optical engineers.

BY JAMES SCHLETT
CONTRIBUTING EDITOR

The metropolitan areas of Orlando and Tampa, Fla., experienced the fourth and fifth largest annual population gains, respectively, in the U.S. in 2023, according to the U.S. Census Bureau. Charles Middleton, CTO of microwave photonics startup Critical Frequency Design, has been indirectly affected by this mass influx of new residents to Central Florida.

Critical Frequency Design is in Melbourne, about an hour's drive southeast from Orlando, on Florida's Space Coast. Since its launch five years ago, Critical Frequency Design has more than doubled its team of photonics engineers and currently has 30 people on its payroll. The company expects this number to reach 40 by the end of the year.

Though the startup does not yet employ any photonics or optical technicians, Middleton plans to hire three to five during the next three years as the company develops its manufacturing capabilities.

While the company is committed to growth, Central Florida's booming housing market has complicated the development of a robust pipeline of qualified workers for small and mid-size companies. Middleton referred to the case of a recent graduate of an out-of-state doctoral program, who accepted an offer of an engineering position from the company only to relinquish the opportunity after struggling to secure housing. The recent graduate ultimately accepted a position in Georgia.

Competition from major photonics-related defense contractors further hinders smaller employers' abilities to fill open positions. The recruitment of homegrown talent is vital to the growth plans of Critical Frequency Design as well as dozens of other Florida-based companies serving the optics and photonics industry.

To help meet this need, Orlando-based Valencia College launched a 15-week optics technician training program last September. Although Florida already has five higher education institutions that award photonics and optics-related certificates or degrees, the Valencia College program stands as the first of its kind in the state.

"It is the technician roles that are being vocally requested," said Barron Mills, executive director of the Florida Photonics Cluster. The organization comprises 75 members, spanning industry and academia, and aims to foster the growth of Florida's optics and photonics industry through partnerships with economic development organizations, state universities, community colleges, and local and state governments.

"Engineers with [a] bachelor's are still a need, but folks to work the manufacturing process and quality control are the greater desire right now. Employers would love for those folks to have an associate degree, but the excitement about the 15-week course shows that they mainly just want quality individuals that they know can be trained," Mills said.

Regarding technician hiring prospects in his industry, Middleton agrees. "We have a better chance of getting technicians if they already live here and can get the training they need to do the job," he said.

Revamping the pipeline

Central Florida is a sizeable optics hub, and it is no surprise that the state — largely driven by the Orlando region — is a leader in awarding undergraduate degrees in optics-related fields. Only New York-based schools awarded more bachelor's degrees in optics/optical sciences and laser and optical engineering than those in Florida in 2022. In New York, the combination of the University of Rochester and the Rochester Institute of Technology contributed to these results. In Florida, meanwhile, the University of Central Florida's College of Optics and Photonics (UCF CREOL) in Orlando led the field, according to data from the

Charles Middleton is CTO of microwave photonics startup Critical Frequency Design. The company is increasing its work in photonic integrated circuit (PIC) design, packaging, and testing. Engineers in these disciplines typically hold a master's-level degree.

Critical Frequency Design

Integrated Postsecondary Education Data System (IPEDS).

New York schools also led the nation in awarding photonics-related associate degrees, with Monroe Community College (MCC), located outside Rochester, N.Y., awarding 21 in laser and optical technology. Indian River State College in Fort Pierce, Fla., awarded 16 associate degrees in electrical/electronic engineering technologies in 2022, according to IPEDS' data. Indian River has an electrical/electronic engineering technologies program with a specialization option in lasers and photonics.

The comparison of Orlando to Rochester also indicates the prominence of optics and photonics in regional- and state-level industry. Fifty optical instrument and lens manufacturing establishments operated in Florida in 2021, the most recent year that data was reported for this North American Industry Classification System (NAICS). Of those manufacturers, more than half were based in the East Central (Orlando) and West Central (Tampa Bay) regions. New York has 48 optical instrument and lens manufacturing establishments, and its Rochester metropolitan area has 23, according to data from the U.S. Bureau of Labor Statistics.

In many regards, the existing talent pipelines that benefit industry in both states were designed in response to the needs of optics and photonics employers in their respective regions. At the same time, these degree-awarding institutions also directly contribute to the growth of optical instrument and lens manufacturing firms, either through spinout companies, with origins in technology developed at the universities, or via industry attraction efforts. For example, information technology company CACI International recently opened its 13,000-sq-ft facility in Orlando for the manufacturing of laser communications for national security and commercial space missions.

Where New York pulls ahead of Florida is in the certification of laser and photonics technicians. In 2022, MCC lifted New York to second among U.S. states for laser and photonics certificate awards, trailing only behind Michigan. Florida ranked outside the top five for these certification awards, even with four community colleges statewide offering these certificate awards in 2022.

"Optics manufacturing is late to the advanced-manufacturing training game," said Josanne DeNatale, national marketing and workforce development operations director for the American Center for Optics Manufacturing (AmeriCOM). The initiative of the U.S. Department of Defense is to promote workforce training at the technician level and assess and address critical gaps in defense systems as well as the optics supply chain and future industry needs.

"AmeriCOM, as it was originally conceived by a group of forward-thinking people in the optics industry, saw that precision optics manufacturing needs to emerge into the advanced manufacturing programs that have long been in place at community colleges across the country," DeNatale said.

Industry ties

Valencia College's newly launched program provides 15 weeks of training in optics fabrication, optical assembly, photonics, and fiber optics. The program debuted with AmeriCOM providing $1.5 million for equipment, and program leadership has worked closely with AmeriCOM and MCC to develop and optimize the initiative. Valencia has also partnered with several photonics companies with operations in Central Florida for this project, including Lockheed Martin, LightPath Technologies, Ocean Insight, Critical Frequency Design, Jenoptik, and Chronos Photonics.

"Not every student has two years to get a degree to enter a new career field. We specifically try to uplift students in distressed areas in our community so they can earn a family-sustainable wage," said Carolyn McMorran, Valencia College's assistant vice president of professional and continuing education. The college's precision optics program, she said, is the sixth accelerated-skills training program in advanced manufacturing that school administrators added to its roster.

"The request for this program came from Lockheed Martin and other local employers who were struggling to hire entry-level technicians," McMorran said.

Additionally, the need for a rapid onboarding to new, higher-paying career opportunities was a major factor behind Valencia's decision to pursue the new 15-week program. Some students in the program already have a bachelor's degree and are pivoting careers. Many students come from low-paying jobs, in industries including hospitality, food service, and ride sharing.

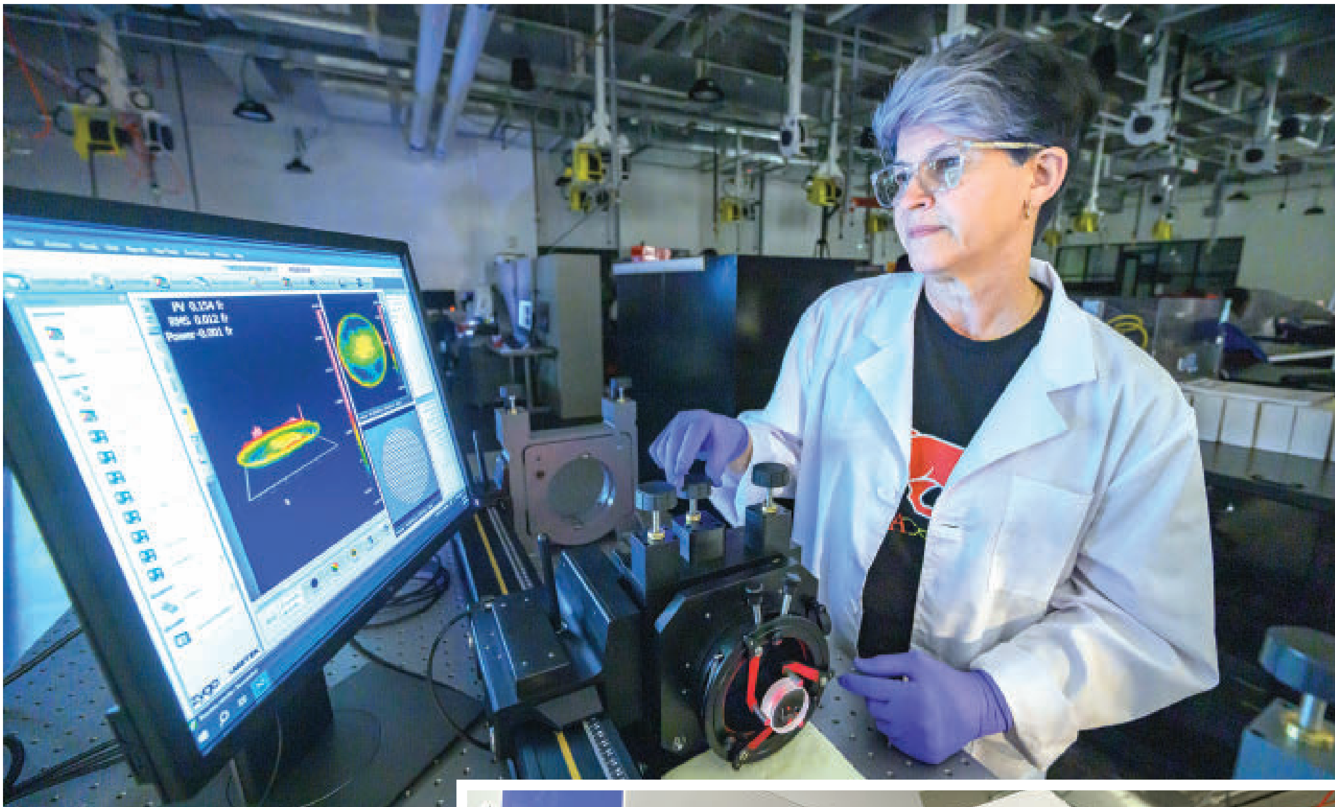
Long-term gains

Valencia's 15-week course is credentialed, though not credit-bearing. This is different from offerings from other schools within AmeriCOM's network of partners, which currently includes five institutions of higher learning. Credit-bearing programs allow students with one-year certificate programs to apply earned credits toward the completion of a two-year associate degree. In addition to the credential program, Valencia offers a laser and photonics technician certificate. Additional Florida institutions that offer similar certification programs include Hillsborough Community College, Indian River State College, and Pensacola State College.

"Every college is hoping to be able to implement the 15-week credential — not 'certification' — model," DeNatale said. "The 15-week model works because of how its recruiters build relationships with prospective students and because of how it nimbly responds to the industry needs in its community. All community colleges do this. It is in their charter. But Valencia does it with emerged skill."

"As a manufacturing company, it is useful for our technicians to have a basic theoretical understanding of optics coupled with hands-on experience using industry equipment (production and test)," said Mark Palvino, vice president of global sales and marketing at LightPath Technologies. "Our needs align well with the curriculums offered by Valencia College and other like-photonics certificate programs."

LightPath, a precision optical elements, assemblies, and custom-designed imaging solutions OEM, employs nearly 20 optical technicians at its Orlando facility. Palvino said one of LightPath's biggest challenges in attracting and retaining optics talent stems from the competition of larger companies that are better positioned to offer higher salaries and more appealing benefit packages as well as more opportunities for career advancement. Middleton cited similar challenges that stem from



Valencia College

The U.S. Department of Defense-funded American Center for Optics Manufacturing (AmeriCOM) provided $1.5 million for equipment for Valencia College's precision optics lab. The facility is located at the college's Osceola Campus in Kissimmee, Florida, outside Orlando.

Valencia College

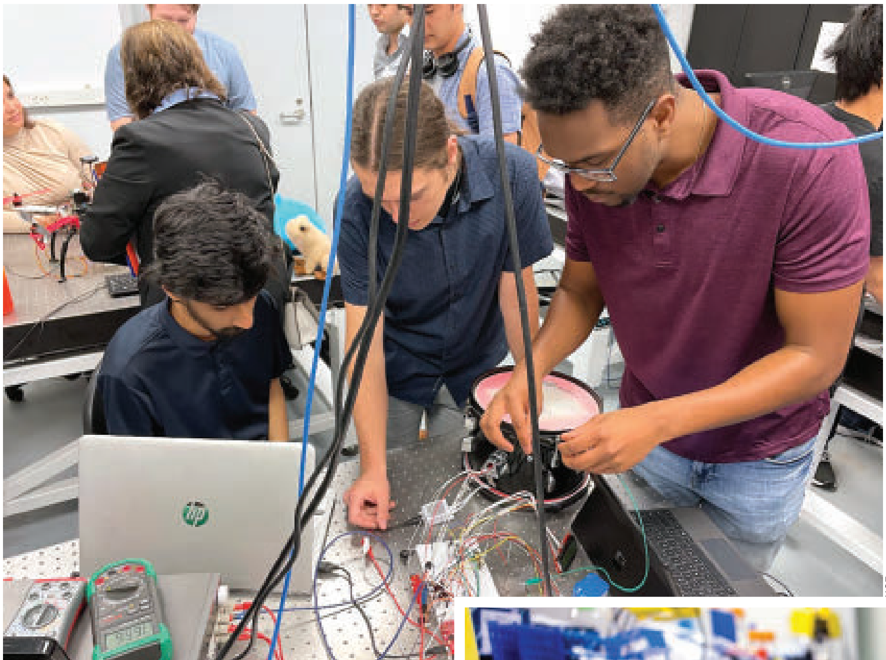
competition with large defense contractors, such as Northrop Grumman and L3Harris, with Orlando-area operations.

According to Palvino, relationships with UCF CREOL and Valencia College can provide access to a common pipeline of skilled graduates and potential research collaborations. However, upskilling is also critical to recruitment and retention at LightPath.

"On-the-job training programs can help develop talent internally, improving retention rates," Palvino said.

Several U.S.-based optical instrument and lens manufacturers outside of Florida — Optimax, Archer Optx, and LaCroix Precision Optics are among them — partner with community colleges for precision optical manufacturing technician apprenticeships. According to McMorran, Valencia is more focused on pre-apprenticeship programs than bona fide apprenticeship pathways. Pre-apprenticeship programs last a few weeks or months and provide courses that teach the basic skills required for entry into a U.S. Department of Labor-registered apprenticeship, which could last several years.

Common job titles for students who complete the Valencia program include optics fabrication technician and optics



UCF

According to David Hagan, dean of the University of Central Florida's College of Optics and Photonics (UCF CREOL), companies are increasingly recruiting employees with skills in lens design and thin films and optical materials. The college is considering adding electives in these areas to complement and support its existing courses and degree offerings.

UCF

technician. In 2023, 14 students completed Valencia's optical technology program. The college is on track to train up to 40 technicians this year.

Filling every need

The optics-related positions that LightPath struggles the most to fill are process and quality engineers. These positions carry a minimum requirement of a bachelor's degree or equivalent in role-specific experience.

Certain Central Florida schools are looking to precisely accommodate those needs, said David Hagan, the dean of UCF CREOL. Companies are increasingly recruiting employees with skills in lens design and thin films and optical materials from UCF CREOL, he said. According to Hagan, it is likely that the college's undergraduate program will add more electives targeting those areas.

There are other areas of focus: Middleton said that Critical Frequency Design is increasing its work with photonic integrated circuits (PICs), for example, and that the company needs more employees with experience in PIC design, layout, packaging, and testing. "These positions typically require at least a master's degree, but we have hired a few people with bachelor's degrees and provided additional training," Middleton said.

At the bachelor's level, and driven by industry feedback, UCF CREOL recently introduced project-based learning opportunities for students to complete at the end of each of six laboratory courses. It also added a course for first-year students to serve as an introduction to photonic engineering design. And UCF CREOL's master's program recently introduced a fully online offering that serves many professionals in the optics industry.

Currently, the school is exploring the rollout of its own optical technician program to accommodate and ultimately retain students who struggle with courses, such as calculus.

"We envisage a hands-on program in photonics that the student can complete in four years that will prepare them for a technician-level job in the photonics industry," Hagan said.

"We do not intend to recruit students into this program directly, as it would be better for most to attend Valencia instead."

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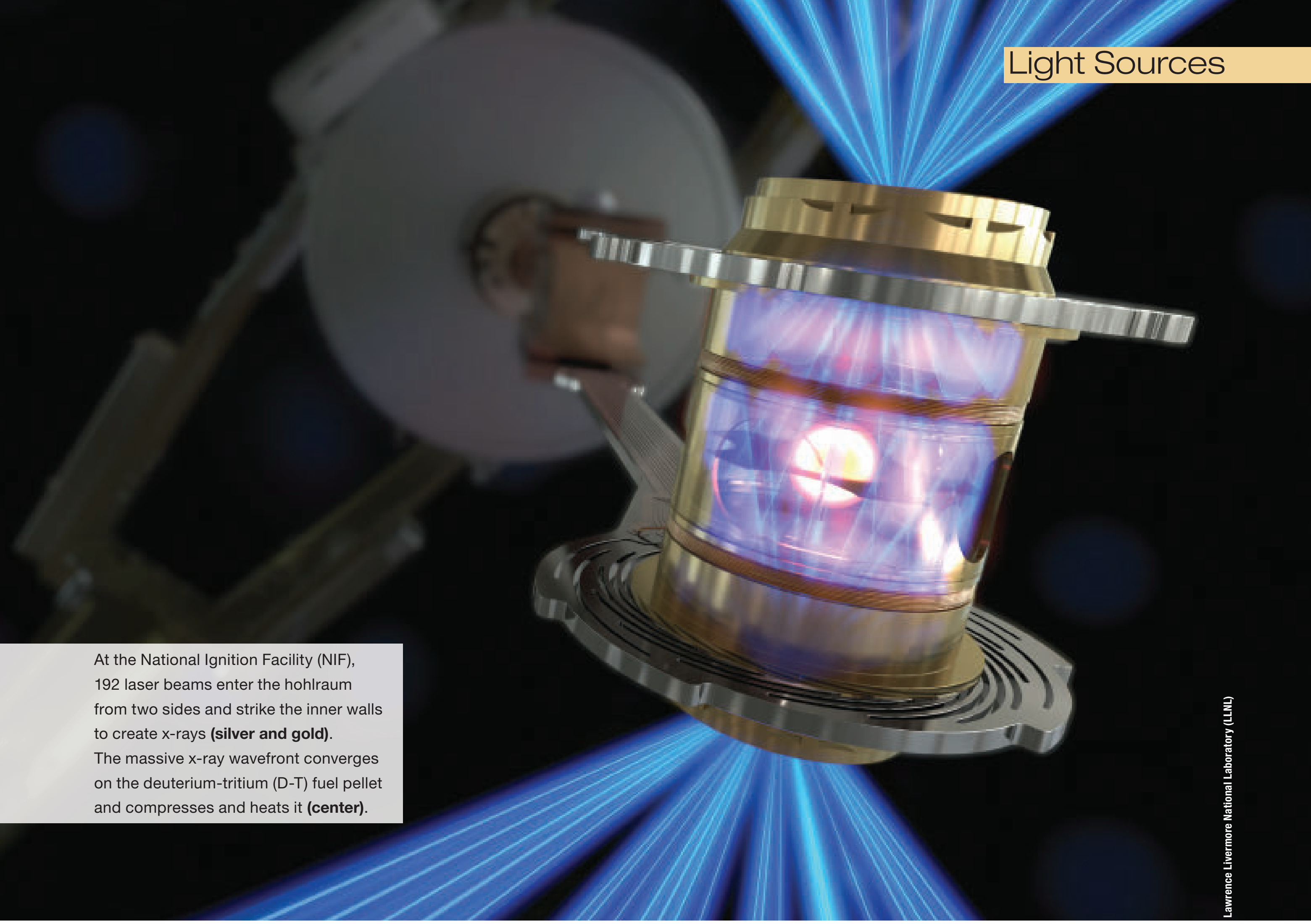


At the National Ignition Facility (NIF), 192 laser beams enter the hohlraum from two sides and strike the inner walls to create x-rays **(silver and gold)**. The massive x-ray wavefront converges on the deuterium-tritium (D-T) fuel pellet and compresses and heats it **(center)**.

Powerful Tailwinds Support Fusion Energy's Commercialization Road Map

The pursuit to harness fusion energy is shifting from fundamental research to engineering. High-power pump laser diodes hold the key as an enabling technology to achieve energy gain.

BY LUKAS GRUBER
LEONARDO ELECTRONICS US INC.

Fusion energy has promised for decades to offer a clean, carbon-free, safe, and virtually limitless source to power the planet. Now that Lawrence Livermore National Laboratory (LLNL) scientists on Dec. 5, 2022, have achieved "net target gain" at the National Ignition Facility (NIF), this promise is ever more tangible. Net target gain refers to a controlled fusion reaction that produces more energy than was supplied to the target to initiate it. This demonstrated ability to obtain more energy from a controlled fusion reaction than the amount that was supplied — just as it happens in the sun and the stars — reinvigorated the quest for viable fusion reactors.

The significance of the NIF team's achievement cannot be overstated. This advancement not only heightened the interest in the fusion process for the scientific community and public but also demonstrated that the underlying physics of laser-driven inertial fusion energy (LD-IFE) can now be understood. The several subsequent successful ignition shots since December 2022 have reinforced this understanding.

This milestone, as well as many related technical developments that preceded and followed the NIF result, has sparked the private sector's renewed interest in the fusion space. With the aim of advancing and harnessing the immense commercial potential of fusion energy technologies, numerous companies worldwide are on the path to developing working reactors. Others are targeting the underlying technologies required to enable and improve the next iteration of fusion sources.

In each case, the efforts that are driving fusion science forward are focused on a collaborative, modular approach to achieve new milestones on the road to commercialization. High-power pump diodes are positioned at the heart of these advancements as well as the further development of practical fusion reactors.

Fusion basics

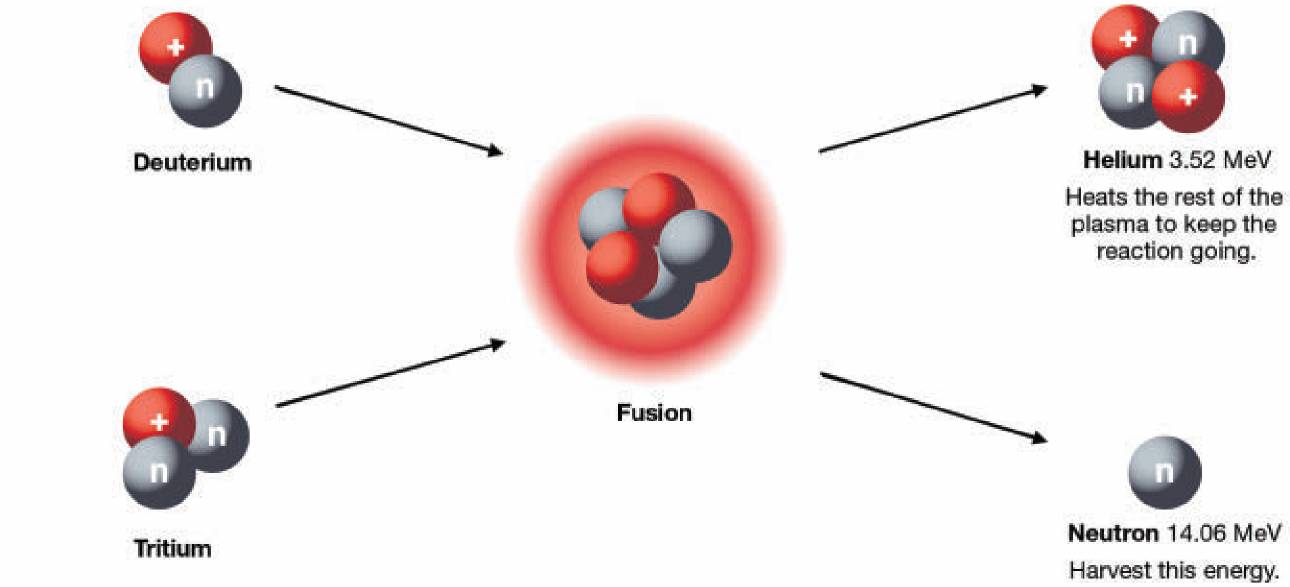
Currently, fusion industry players are opting to pursue several distinct approaches to harness fusion. The two main approaches — magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) — are favored by most companies within the fusion space.

The most common mechanism involves fusing nuclei of deuterium (D) and tritium (T) to yield an alpha particle, or helium nucleus, and a free neutron. The total mass of all particles after the reaction decreases slightly compared to the total mass before the reaction. This difference in mass (Δm) is converted directly into energy (E) according to Einstein's theory of special relativity, $E = \Delta m \cdot c^2$, where c is the speed of light. Most of this energy is carried away by the neutron in the form of kinetic energy.

Three conditions must be met in a plasma to produce net energy through fusion. First, the positively charged nuclei must be energetic enough to get so close that the strong force overcomes their electrostatic repulsion and draws them together. This requires a sufficiently high temperature. Next, the nuclei must have a high-enough probability of colliding. This requires a combination of high density or sufficiently long confinement time.

The considerations around this final condition are multifaceted: If the density is low, the confinement time must increase to allow for enough fusion collisions. If the confinement time is short, then the density must be increased to ensure sufficient interaction between plasma particles. The product of these three parameters — pressure, confinement time, and temperature — called the triple product, must exceed a certain value (the Lawson criterion) to achieve fusion.

The only place in which the Lawson criterion is met naturally is within stars, where gravitation creates extreme densities and high temperatures, and the confinement time is close to infinity. As a result, building a fusion reactor requires creating conditions that are similar to those occurring at the center of the sun. MCF typically achieves long confinement times but lower densities, whereas ICF tends to have short confinement times but extremely high densities. In both cases,



Leonardo Electronics US Inc.

A fusion reaction using deuterium (D) and tritium (T) as fuel, resulting in helium and an energetic neutron as reaction products. The helium nucleus, or alpha particle, typically contributes to further heating in the fusion plasma and the energetic neutron can be harvested to convert its energy into heat and ultimately drive a steam turbine.

very high temperatures (~10× the temperature of the sun's core) are required to spur a successful fusion.

To meet the Lawson criterion in IFE, an external energy source, often a very powerful laser, is applied to a small fuel pellet containing the D-T fuel, which becomes rapidly compressed and heated. This causes the pellet to implode and reach enormous pressures and temperatures for brief occurrences, enabling fusion reactions.

Satisfying the Lawson criterion in magnetic confinement systems (MFE), such as the tokamak or stellarator, involves using powerful magnetic fields to contain and control a hot plasma. In contrast to LD-IFE, researchers pursuing MFE are in turn pursuing fusion by attaining extended confinement times at low pressure.

For both approaches based on D-T fuel, the alpha particle typically stays in the plasma and contributes its energy, further helping to heat the reaction. The neutron, on the other hand, typically escapes the reaction volume and hits the wall of the chamber. There, its energy can be harvested and converted to heat.

An industry takes shape

Many technological developments have served to establish market opportunities for companies at all reaches of the commercial fusion landscape. Compact, high-temperature superconducting magnets, high-peak power laser diodes, and, most critically, net target gain are among the individual technology areas and target goals driving early arrivers to the fusion industry. While their technological approaches and commercial goals vary, each is driven by the pursuit of a share of a multitrillion-dollar energy market.

Simultaneously, dozens of organizations, both public and private, are now actively involved in the development of fusion energy concepts. Participants in these groups include international collaborations and consortia, national laboratories, R&D centers, and private companies.

While the advancements of each industry player contribute to sustained progress in fusion science, individual milestones and benchmarks, in many cases, are longstanding. In MCF, for example, the Joint European Torus (JET) set the record of gain, Q, in a tokamak experiment. The group achieved the high mark of $Q = 0.67$ in 1997 (compared to $Q = 2.34$ at the NIF). And today, the JET has been shut down following Brexit as well as to focus on rejuvenation of the U.K.'s fusion program.

More recently, the megaproject of the International Thermonuclear Experimental Reactor (ITER), led by a consortium of 35 countries, is driving steady progress in its build, despite schedule and budget overruns. In industry, the startup company Commonwealth Fusion Systems is a leader in the field, due to funding of more than $2 billion and the successful development of a compact, high-temperature superconducting magnet that holds promise for achieving energy gain in a much smaller device footprint.

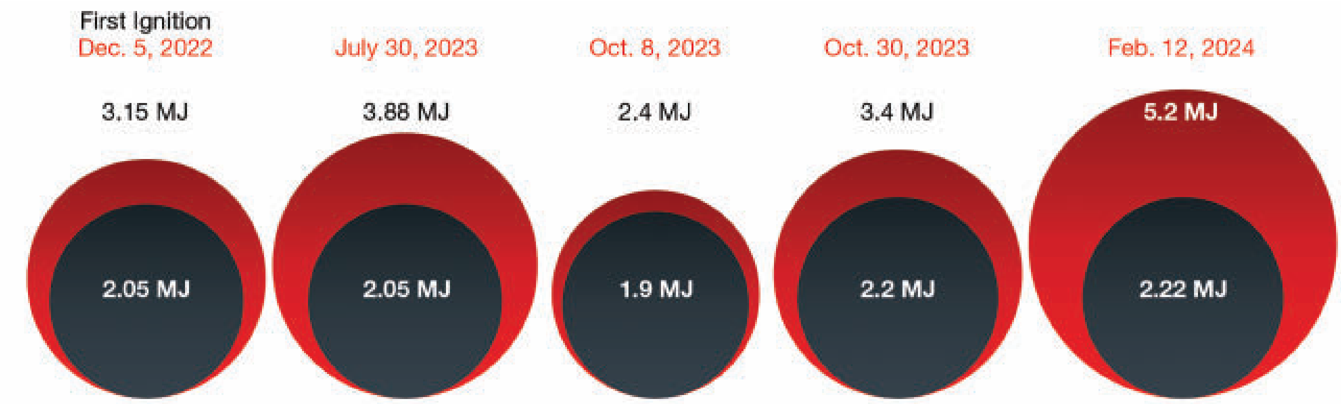
On the ICF side, beyond the 2022 achievement of ignition and net target gain by the NIF, four subsequent repetitions of this achievement since the flagship result have sustained the momentum. This wave of excitement and success is reaching the industry sector, where California-based Longview Fusion Systems is applying the same physics used for the NIF result. The company aims to improve the efficiency of the laser driver in its technical approach by replacing flash lamps with laser diodes. Additional startups targeting ICF and using efficient high-peak power laser diodes include Focused Energy, Marvel Fusion, and HB11 Energy.

Amid the launch and the recent success of members of the fusion industry, the Fusion Industry Association (FIA) is facilitating the process of enabling commercial fusion energy use to become a reality. The FIA, encouraged by the plurality of approaches, is aiming to bridge fusion companies, organizations in the fusion supply chain, investors, regulators, and policymakers. The FIA brings fusion companies under its umbrella as well as the supply chain feeding this industry.

Consortia: the road map to practical fusion

As the FIA provides an organized approach to the complex regulatory and policy backbone of this nascent industry, the technological developments themselves require an organized path toward successful commercialization of product technologies and solutions. Although fusion efforts of various reach are now active in Australia, Canada, China, France, Germany, Italy, Japan, Russia, South Korea, the U.K., and the U.S., the collaborative nature of the industry suggests that leadership in one facet of fusion science is apt to benefit the entirety of the industry.

The 2022 White House summit on "Developing a Bold Decadal Vision for



Lawrence Livermore National Laboratory (LLNL)

The progression of all ignition shots at the National Ignition Facility (NIF) dating from December 2022 to February 2024.

Commercial Fusion Energy," for example, preceded the announcement by the U.S. Department of Energy (DOE) of its plans to fund three hubs to accelerate IFE science and technology. These hubs comprise members from academic institutions, national and international labs, commercial entities, philanthropic organizations, and private IFE companies. The hubs are the Science & Technology Accelerated Research for Fusion Innovation & Reactor Engineering (STARFIRE), led by LLNL; the Inertial Fusion Energy-Consortium on Laser-Plasma Interaction (LPI) Research (IFE-COLoR), led by the University of Rochester's Laboratory for Laser Energetics (LLE); and the Inertial Fusion Science and Technology (RISE), led by Colorado State University. While each hub focuses principally on many different aspects of fusion, the use of resources provided by the different entities is a common thread. This multipronged approach demonstrates the importance of pursuing fusion with the expertise and resources from diverse stakeholders.

Similarly, this past spring, Japan announced the creation of a consortium as part of its Moonshot program. The initiative will include government organizations and private companies with the shared goal of developing advanced technologies in fusion and defining a path for commercialization. In April, Germany unveiled the PriFUSIO consortium, led by the Fraunhofer Institute for Laser Technology ILT (Fraunhofer ILT). The effort unites fusion startups, medium- and large-size companies, and semipublic research centers to advance their missions. Critically, not all members are solely pursuing advancements in fusion science — a fact that highlights the importance and shared pursuit of fusion science progress across a variety of disciplines.

While the funding for these consortia is modest, their operation represents a multifaceted approach, providing crucial expertise in many technical aspects. These consortia can serve as nucleation points for idea-sharing and discussion on how to best approach the commercialization of IFE. Additional collaborations can also emerge from these groups, which may provide this blossoming industry with added direction, especially in identifying cost drivers, pursuing the standardization of technical solutions, and advocating for relevant investments.

Next steps

The seminal achievement of target gain in laser-driven IFE answered difficult physics questions for this specific approach and has signaled a degree of optimism within the fusion community. Still, several technological questions are unanswered in the domain of LD-IFE, and, indeed, for all fusion approaches.

To advance LD-IFE specifically, companies and organizations must improve the cost and manufacturability of targets; develop appropriate target injection and tracking methodologies; mitigate optics damage; and improve laser diode cost.

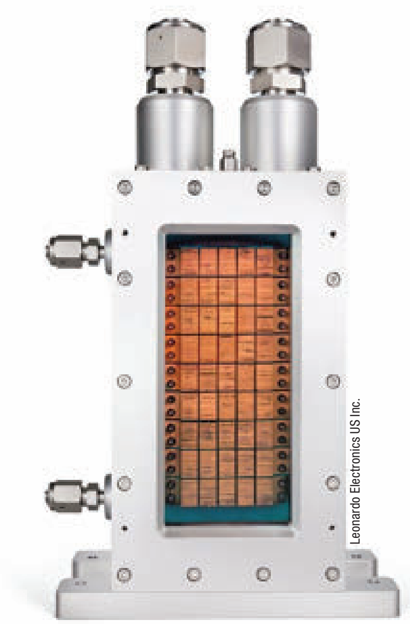
Still, several prominent technology questions must be answered for all the approaches. Experts must find, for example, the optimal materials for the reactor wall (first wall) that faces the fusion reaction and is most heavily bombarded with neutrons. They will also need to validate solutions for the fuel cycle at reactor scale. As a result, educating a workforce to sustain this industry is a pressing matter.

With the relevant consortia in place, legitimate opportunity exists to facilitate and create industry standards to govern the use of technologies that are required in fusion power plants. Such standards can align a variety of individual solutions and create efficiencies in supply chain, manufacturing technologies, and devices. This consolidation of solutions should subsequently drive cost savings through economy of scale.

Ultimately, to move the industry forward in the most substantial fashion, a facility is needed to serve as a proving ground to explore existing technologies, develop new ways to solve existing questions, and exercise the supply chain. A recent call for papers from the DOE's Office of Fusion Energy Science triggered a multitude of white papers focused on this need. The final selection for funding did not include any laser-driven facilities, though new funding opportunities are continuing to be announced, and the industry is simultaneously gaining momentum.

The importance of diodes

One key limitation in the NIF laser system, and other extreme-power laser sources, directly involves the technology used for pumping gain media. The amplifier stages of the NIF laser are pumped with flashlamps — a relatively inefficient method, and one that produces large amounts of waste heat.


Leonardo Electronics US Inc.

A 900-kW laser diode module built in 2016 by Leonardo, as it is used to pump the main amplifier in the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) installed at Extreme Light Infrastructure (ELI) Beamlines in Prague.

Replacing flashlamps in a NIF-like facility with laser diode pumping is an achievable step toward raising the efficiency of the entire system by at least one order of magnitude to a level that may enable energy break-even. The increased efficiency and thus reduced waste heat allows the operation of the laser system at the required shot rate of 10 Hz or more, compared to 1 Hz, or much less, for flashlamp pumping. It should also be noted that laser diodes are expected to represent the single most significant cost of an item in such a facility. As a result, the future of LD-IFE (incorporating diode-pumped, solid-state lasers) is dominated by both the cost and performance success of laser diodes.

Fortunately, progress in this technology area is underway. For example, in 2016, Leonardo delivered five laser diode modules, each with 800-kW output, to the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) project. This laser is designed to produce petawatt pulses with an energy of 30 J or more and pulse widths of <30 fs at a 10-Hz repetition rate. At the time of this delivery, the technology and performance of the HAPLS laser diode arrays marked a significant technological leap. Progress has only continued since then. If Leonardo were to build HAPLS-like laser diode arrays today, these arrays would be able to deliver >2 MW each with an unchanged form factor.

Fusion research has not been the only driver behind the development of advanced laser diode sources such as these. As with many other areas of laser and photonics technology, the defense industry, as well as science applications, created a pull that equally moved the technology forward, benefiting the fusion industry.

Fusion in reach

The pursuit of fusion energy, once a scientific curiosity, is now a burgeoning industry that is on the brink of revolutionizing global energy. With groundbreaking achievements, such as the net target gain at the NIF, paired with advancements in laser diode technology, the pathway to practical fusion energy is clearer than ever. Collaborative efforts from international consortia, private sector investments, and technological innovations are accelerating progress.

As a result, the fusion industry holds the promise of providing safe, abundant, and carbon-free energy. Industry players and those offering their solutions and support continue to tackle the relevant technological challenges. The future of fusion energy shines brightly, heralding an era of sustainable power.

Meet the author

Lukas Gruber is a director of business development at Leonardo Electronics US Inc. With more than 25 years of experience in the photonics industry, he has held many positions, ranging from fundamental research at Lawrence Livermore National Laboratory to product development, manufacturing, and general management; email: Lukas.Gruber@Leonardo.us.

Rigorous multiphysics simulation of airflows surrounding a high-speed aircraft are required to ensure the accurate performance of system sensors under a variety of environmental conditions.

Visualizing Brilliance:

Exploring Optical Design Through Simulation

With heightened demand for higher-quality, lower-cost optical designs, simulation techniques are enabling engineers to design products with unparalleled accuracy and efficiency.

All images courtesy of Ansys.

BY SANJAY GANGADHARA
ANSYS

From medical devices to precision instruments used for industrial manufacturing, innovative optical technologies are being increasingly integrated into products across numerous industries. The micro- and macroscopic optical components constructed from these advanced technologies — including freeform optics, diffractive optics, and metasurfaces — must perform well under all operating conditions.

As a result, the design of optical and optically enabled products for robust manufacture requires systems-level engineering, and successful designs are only possible with the aid of multiscale, multiphysics simulation.

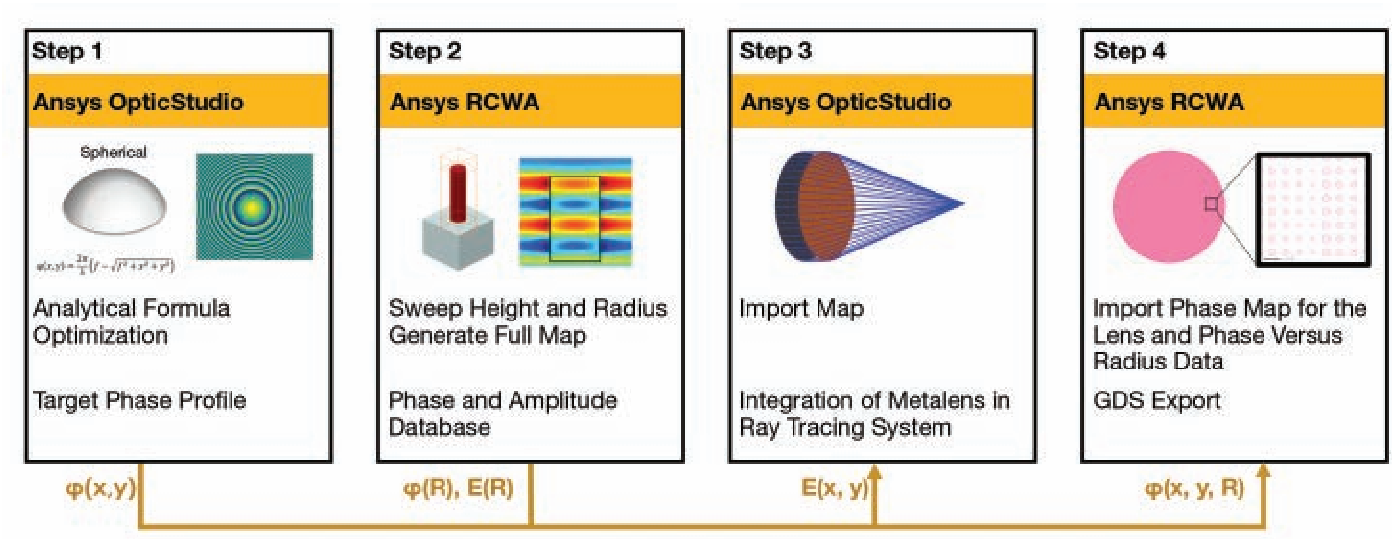
Product design factors

Miniaturization is a powerful force behind nearly all modern products. Today, these products are smaller, lighter weight, and lower cost than ever before. Optics, by their nature, provide vast functionality in a small form factor. As such, they are a critical element in the drive toward miniaturization in modern product designs. For example, a camera lens in a smartphone can effectively capture scenes as large as the Himalayas with a piece of glass or plastic the size of a penny.

Cost also plays an important role in optical design, especially when considering systems that must be produced in large volumes. For such systems, cost is related to how much it takes to manufacture the optics as well as how reliably those optics can be manufactured and the stability of their performance under all operating conditions. The same smartphone camera lens that costs $0.01 a unit, for example, may represent the ideal nominal design. But, if half of the fabricated units are discarded because they do not perform to specification — as the result of challenging manufacturing requirements — and another third do not perform well when placed inside of the product packaging or when exposed to direct sunlight, the true cost has increased by a factor of five or more.

Several advanced technologies are driving the next generation of optical and optically enabled products. Freeform optics represent the first step beyond traditional lenses and mirrors, enabling higher levels of aberration control and light manipulation through additional degrees of freedom. Diffractive optics leverage the interaction of light with microstructures at wavelength scales to enable the creation of components that can precisely direct and disperse light for specific applications. And metasurfaces, which are constructed from nanoscopic,

The current class of endoscopes requires high resolution in a compact form factor. Metalenses are a modern and increasingly popular solution to this and other requirements for designers.



The multistep sequence shows the full design workflow for a metalens-based endoscope, with each step requiring different simulation software. Geometric ray tracing characterizes the desired performance of the metalens within the device; electromagnetic simulation characterizes the responses of meta-atoms, while the target phase and the meta-atom response is used to define an arrangement of meta-atoms that form the metasurfaces of the metalens and produce a layout for fabrication. The phase profile of the "real" metalens is sent back to ray tracing for validation; and a Graphic Design System (GDS) file for the metalens is created to enable manufacturing of the lens.

pillar-shaped building blocks called meta-atoms, placed on top of a dielectric surface, are on the cusp of redefining the interface between light and material, offering ultrathin yet powerful ways to control optical behavior.

In all cases, these pioneering technologies are critical in achieving the goal of miniaturization that is helping to reshape optical design, unlocking possibilities previously confined to the realm of science fiction.

Simulation in modern product design

It is often challenging to understand the right technology for an application as well as how to maximize the value of the technology within the design. Building physical prototypes can provide insight into some of these questions but is a costly and time-consuming option. This is especially true as designs incorporate more advanced technologies, such as free-form optics and/or metasurfaces.

Simulation enables engineers to subject their designs to a variety of scenarios, identifying weaknesses and optimizing designs before the first prototype takes physical form. This process is not merely about safeguarding against failure; it is an essential requirement for achieving the desired performance and reliability of an optical design.

Although advanced technologies are already established in helping to create smaller optics, they do not yet represent a complete solution for optical design. For example, while metasurfaces may be used to create an eye-tracking system in a virtual reality (VR) headset, macroscopic optical components, such as lenses and mirrors, are still needed for other parts of the headset design. Simulation must therefore be able to model systems that include optics at multiple scales, from microscopic to macroscopic.

Multiscale simulation must also be able to model the performance of those optics at full-system level, accounting for the effects of the real-world environment on the performance of the optics. For example, the introduction of "stray light" into the system, from unintended light sources, can have a significant effect on the system. And, for systems designed to produce images for human consumption, such as cameras or VR headsets, multiscale simulation must accurately model the response of the human eye to those images to simulate human vision.

Although multiscale simulation is an important starting point, the addition of multiphysics simulation is necessary to truly understand the performance of optics embedded inside of modern products. Through multiphysics simulation, designers achieve a better understanding of how the optics will perform when manufactured and integrated into a full product as well as how product performance will be affected by potential errors in the fabrication and assembly processes. Mechanical stresses introduced by the product packaging, or by thermal loads resulting from the presence of nearby electronics — and circulating airflows that may be introduced to mitigate those thermal loads — are additional variables for which multiphysics simulation can deliver key insights.

Simulation techniques and tools

Several techniques exist for optical simulation. On the macroscopic scale, geometric raytracing remains a reliable method for determining how light interacts with components such as lenses, mirrors, and prisms. While it is common to trace rays from the light source to one or more sensors in the system (forward ray tracing), it can be beneficial to instead trace rays from a sensor to the source. This approach (reverse ray tracing) is useful in cases in which the sensors are small, and it is computationally efficient to model the system in reverse.

Even at macroscopic scales, wave effects that are ignored by geometric ray tracing can be important considerations.

As light comes to focus, or propagates through small but finite apertures, it will behave in a different manner than that described by rays. The behavior of light emitted from a coherent source, that then propagates over a long distance, will also be influenced by the wave nature of light. In these circumstances, techniques such as Fourier propagation and/or Gaussian beam decomposition can be used to model light.

As component sizes become smaller, electromagnetic simulation is often required to accurately characterize the performance of the optical system. Full solution(s) of Maxwell's equations can be conducted using finite difference time domain (FDTD) or finite element method (FEM) simulation. In many cases, system properties enable simpler solutions. For example, when modeling diffractive optics or metasurfaces with regular periodic structures, rigorous coupled wave analysis (RCWA) is often sufficiently accurate to characterize the performance of the component, even as the component is embedded in a larger system.

Engineers have the option to use several commercially available tools to perform optical simulations. Ansys, Synopsys, Lambda Research, and Photon Engineering are among some of the companies offering multiple solutions at the macroscopic scale. On the microscopic scale, Ansys, Synopsys, and Photon Design offer a suite of solutions.

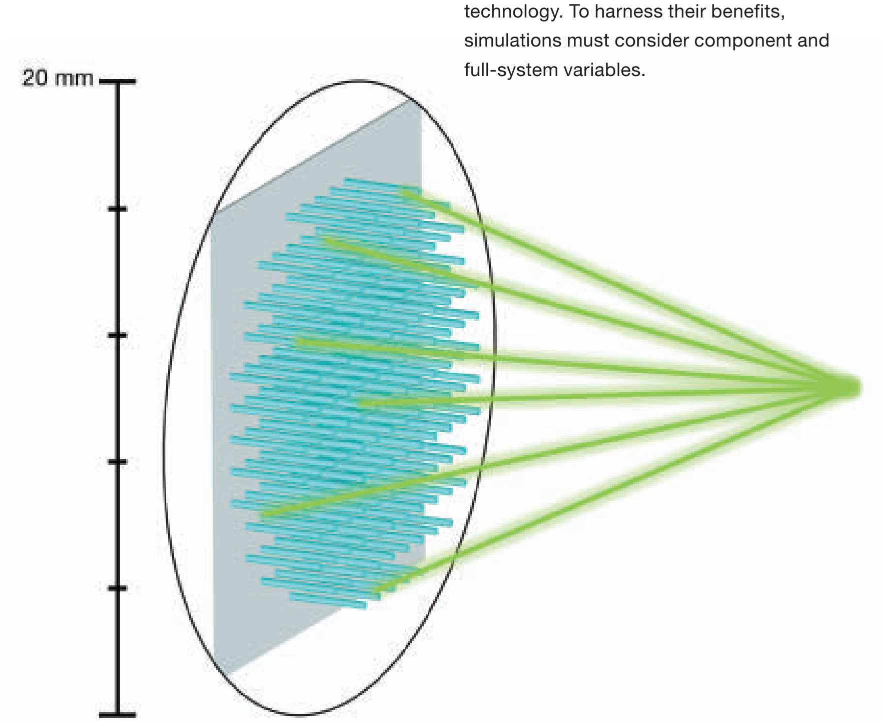
There is also a push from smaller players to move simulation to the cloud, with offerings such as KostaCLOUD for ray tracing and Flexcompute for electromagnetic simulation. As the larger players in the industry begin to follow suit, the ability to conduct heavy computational workloads required for multiscale, multiphysics simulation across distributed compute clusters and graphical processing units will dramatically accelerate the optical design process. Distributed cloud computing is essential to enable multiscale, multiphysics simulation in a realistic time frame; such simulation requires significantly more computational resources than traditional single-scale, single-physics simulation. Therefore, it will be crucial for driving innovation in the next generation of optical and optically enabled products.

Design example: medical endoscope

The miniaturization of system design is key to the development of advanced medical diagnostics, in support of both invasive and noninvasive devices. For example, medical endoscopes have traditionally been limited in clinical applications by their relatively large size and low resolution. To improve performance and increase the use potential of these devices, metalenses are being considered in favor of macroscopic optics, such as ball lenses or gradient index lenses.

Developing a safe yet effective endoscope that includes metalenses requires rigorous design supported by multiscale, multiphysics simulation. The simulation workflow for such a design involves multiple steps. Geometric ray tracing is used to determine the required performance of the metalens inside of the macroscopic imaging system, as characterized by the phase of the light that passes through the metalens. An electromagnetic simulation tool (RCWA or FDTD) is used to characterize the responses of individual meta-atoms. Combining the target phase and the meta-atom response, simulation software creates an arrangement of meta-atoms that forms each metasurface of the metalens and produces a layout suitable for fabrication. The phase profile of the "real" metalens designed with electromagnetic simulation is sent back to ray tracing for validation, to ensure that the lens comprising real meta-atoms still meets system requirements.

Ray tracing analysis is conducted at both the subsystem level, including all the optics that make up the endoscopic imaging system, as well as at the full system level, to include the effect of external factors, such as the light source for the endoscope and the device packaging. Iterations between the ray tracing and electromagnetic simulation tools may be required to achieve optimal performance of the system, especially when considering the effect of fabrication errors or unintended stray light. Once system performance has been validated, a Graphic Design System (GDS) file for the metalens is created to enable the manufacturing of the lens.



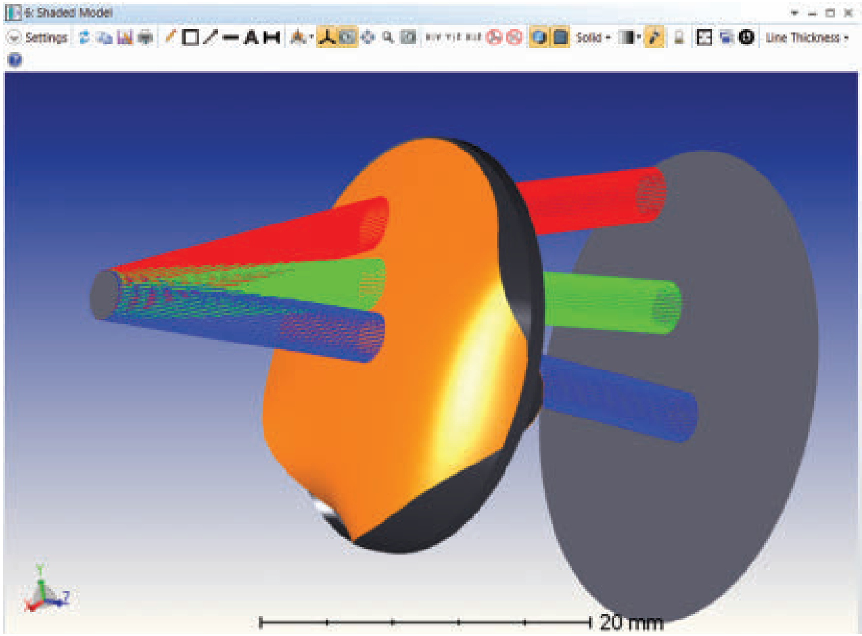
Metalenses, as well as freeform and diffractive elements, present a burgeoning optical technology. To harness their benefits, simulations must consider component and full-system variables.

Design example: aerospace and defense

In addition to the medical sector, multiscale, multiphysics simulation is essential to robust design in aerospace and defense. Systems developed for aerospace and defense are mission-critical: These systems must perform accurately, and for long periods of time under operating conditions that are variable, and sometimes extreme.

Consider a high-speed aircraft used for surveillance or targeting applications. The high rates of speed at which this aircraft must travel will generate turbulence around the craft while atmospheric friction will induce nonuniform heating. This will result in asymmetric loads on the optical sensors that are difficult — if not impossible — to resolve via image processing electronics or software. Instead, the loads must be addressed within the design of the sensor itself.

The simulation workflow for such a design once again involves multiple steps. Geometric ray tracing is used to define the performance of the sensor under nontravel conditions. This analysis includes the effect of fabrication and assembly errors on the optical performance. Computer-aided design (CAD) tools, used to design the optical packaging, are coupled with ray tracing simulations to assess whether the packaging will generate unintended stray light in the combined optomechanical system. Computational fluid dynamics (CFD) simulations are run to calculate the flow fields surrounding



This model, capturing the design and simulation process, demonstrates how simulation is used to design a freeform optic that maximizes uniformity and efficiency across the field of view of an illumination system.

the sensors. These nonhomogeneous flow fields affect the temperature and pressure loads on the optics and the refractive index of the surrounding medium. Further, the 3D refractive index profile of the surrounding medium must be accurately characterized to ensure proper performance of the system. This is especially important for the turbulent near-field region in front of the sensor, where the large variations in refractive index can lead to severe degradation of optical performance.

The optomechanical system, designed with geometric ray tracing and CAD tools, and the temperature and pressure loads, calculated from CFD, are passed on to finite element analysis (FEA) simulation to determine the structural displacements of, and 3D temperature distributions within, the optics. These results from FEA — along with the 3D refractive index profile of medium surrounding the sensor, calculated by CFD — are then brought back to the ray-tracing simulation for a full system-level validation.

It is often the case that the optics must be modified after incorporating the effects of FEA. A simulation framework that supports automated workflows between ray tracing, CAD, CFD, and FEA by leveraging common material libraries and powerful application programming interfaces is essential to enable dynamic optimization of the optics in a streamlined manner.

The future of simulation

In parallel with the development of techniques and algorithms in support of modeling modern optical technologies, advancements in computing technology are expanding the boundaries of what is possible with simulation. The ability to distribute massive computations in the cloud is a powerful means to enable faster simulation. Having real-time feedback on designs provides engineers with deeper insights into their optical designs, leading to the realization of more effective and innovative solutions.

And, as machine learning and artificial intelligence technologies mature, simulation will provide additional resources for engineers to gain added understanding of the systems they are developing and how to improve them. For example, artificial intelligence can be used to define starting points for an optical design that the human designer may have not previously considered. This can in turn generate a new class of optical solutions for use in next-generation devices.

With more powerful and intuitive simulation tools, engineers are empowered to push the limits of optical design and ensure that the next generation of products exceeds the demands of tomorrow. The journey ahead is filled with opportunities to craft optical systems that are more efficient, more precise, and more apt to be integrated into daily life.

Meet the author

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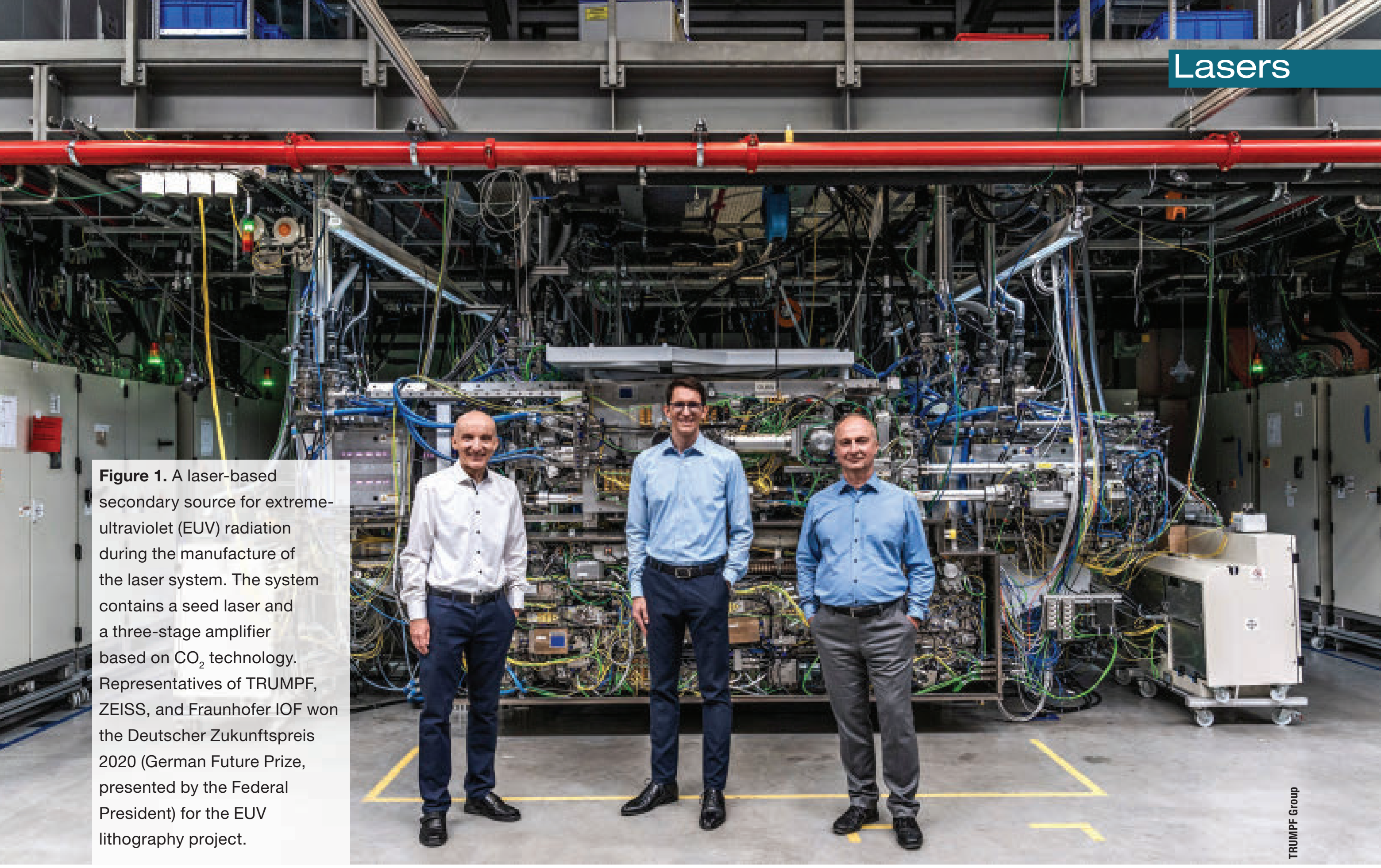

Figure 1. A laser-based secondary source for extreme-ultraviolet (EUV) radiation during the manufacture of the laser system. The system contains a seed laser and a three-stage amplifier based on CO_2 technology. Representatives of TRUMPF, ZEISS, and Fraunhofer IOF won the Deutscher Zukunftspreis 2020 (German Future Prize, presented by the Federal President) for the EUV lithography project.

Lasers Accelerate the Application of Secondary Sources, Among Others

Advancements in ultrashort-pulse laser technology are enabling substantial progress in the field of secondary sources. The application areas that are poised to benefit range from science to biomedical and laser fusion.

BY ANDREAS THOSS
CONTRIBUTING EDITOR

For many years, secondary sources were just a vision held by scientists. Eventually, their progress was driven by the goal to build a particle accelerator, such as the Large Hadron Collider in a laser lab at the European Council for Nuclear Research (CERN).

The physics behind this vision are intriguing: An electron can be accelerated by a light pulse much faster, and much more energy efficient, than by an electromagnetic pulse in a regular particle accelerator.

An urgent need from big business — namely, the semiconductor industry — led to the first industrial-scale solution. The semiconductor industry required a source of extreme-ultraviolet (EUV) radiation with a wavelength of 13.5 nm to meet its manufacturing demands. It took the brilliant ideas of some scientists, plus the bravery of a few business leaders, to develop a secondary source for this purpose. ASML's latest generation of lithography machines is based on this device, which includes the largest laser ever built in serial manufacturing. This was a surprise for many laser experts, because the actual laser inside the system is not a new solid-state laser but the almost-forgotten CO_2 laser (Figure 1).

Chips made with these machines are a must-have in the consumer electronics sector; simply, companies run the risk of being left behind without access to the technology. Industry giant Intel, for example, recently adopted the next generation of EUV lithography machines.

Currently, this secondary source generates approximately $1 billion in annual revenue for its manufacturer, TRUMPF. The formula that describes this technology is simple: one manufacturer, one customer, one big success. The price of ASML stock has increased ~40× since it began promoting EUV nearly 15 years ago in 2010.

The question of whether secondary sources can do more is easily answered: Yes. But answering this question more profoundly requires some background information.

What are secondary sources?

Most often, secondary sources refer to sources of x-ray, electron, or particle beams that are based on lasers as the primary beam source. Secondary sources offer the potential to replace conventional, large particle accelerators with much smaller, laser-based systems. Although laser-based secondary sources are the focus of this article, electron or proton beams can also be used as a driving beam.

Since electrons can be accelerated over a shorter distance with light waves than with microwaves, which have historically been used for accelerator schemes, laser-driven secondary sources hold obvious benefits. These laser accelerators are considerably smaller and require significantly less electrical energy. They promise new opportunities in medicine, particle physics, and other disciplines that require accelerated particles or the

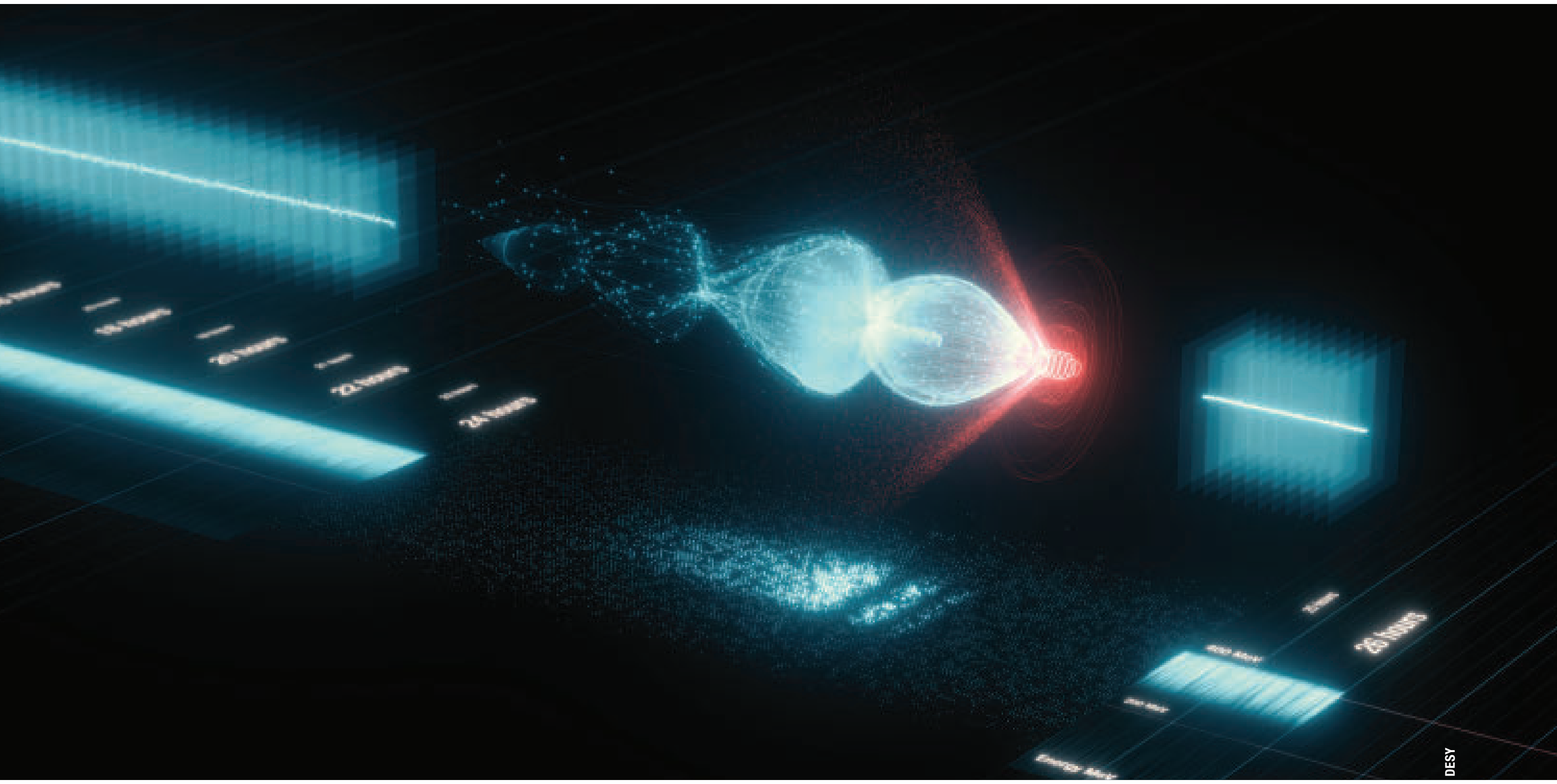

Figure 2. In laser-plasma acceleration, a strong laser pulse **(red)** generates a plasma wave **(blue)** in hydrogen gas by stripping electrons from gas molecules. The electrons "ride" this wave to high energies at extremely high rates of speed.

DESY

Table 1.
Portfolio of Technological Building Blocks at TRUMPF
Orders of Magnitude of Pulse Energies, Pulse Powers, and Intensities

	10 mJ	100 mJ			1 J		10 J
	InnoSlab	InnoSlab	RegAmp	MultiPass	RegAmp	MultiPass	MultiSlab
Chirped-Pulse Amplification (CPA) $\tau<1$ ps	10 GW $>10^{16}$ W/cm^2 ($2\omega_0$ = 10 μm)	100 GW $>10^{17}$ W/cm^2 ($2\omega_0$ = 10 μm)			1 TW $>10^{18}$ W/cm^2 ($2\omega_0$ = 10 μm)		10 TW $>10^{19}$ W/cm^2 ($2\omega_0$ = 10 μm)
Nonlinear Pulse Compression $\tau<50$ ps	200 GW $>10^{17}$ W/cm^2 ($2\omega_0$ = 10 μm)	2 TW $>10^{18}$ W/cm^2 ($2\omega_0$ = 10 μm)			20 TW $>10^{19}$ W/cm^2 ($2\omega_0$ = 10 μm)		200 TW $>10^{20}$ W/cm^2 ($2\omega_0$ = 10 μm)

TRUMPF Group

resulting radiation. This includes industrial process optimization — for example, melt pool videography of copper welding processes for e-mobility[1].

What are the challenges?

Laser-based particle acceleration is not a new field of research, though the advent of laser sources with extremely high peak powers and progress in plasma physics has led to substantial progress in recent years. These factors, paired with the obvious driver — a heightened need from industry — intensified focus and furthered innovation in this technology area.

One system in particular exemplifies many of the challenges that have been overcome with regard to secondary sources. The EUV source that the TRUMPF Group sells to ASML shines a 30-kW CO_2 laser onto tiny droplets of tin that emit EUV (or soft x-rays) at 13.5 nm. This laser is the biggest in serial production. Stability, debris mitigation — all tin droplets are vaporized in a vacuum — plus power scaling and conversion efficiency were among the issues that the developers addressed in this solution[2].

The TRUMPF-built system is obviously one of the most complex laser sources in the world. Yet, it is still a rather simple secondary source. The amplified laser pulse hits a target, and the energy of the main pulse (a pre-pulse shapes the target for increased conversion efficiency) is converted into EUV radiation. This radiation is collected with a huge mirror and sent to the lithography scanner.

Lasers can be used for many more conversion effects, either to generate energetic photons or to accelerate particles. Energetic photons can be generated through nonlinear effects such as high-harmonic generation (HHG). This process demonstrated its utility by enabling the generation of attosecond pulses, for which three acclaimed scientists earned the 2023 Nobel Prize in Physics.

Other processes generate x-rays, too. Inverse Compton scattering, where a low-energy photon scatters with an electron, is one additional example. Further, accelerated electrons hitting a target may create x-rays in a process that is similar to what happens in any x-ray tube.

The laser-based acceleration of electrons is a fascinating aspect of plasma physics: When a laser pulse passes through a plasma, it is a moving electromagnetic field. The field exerts a force on the electrons, pushing them from places with high electric fields to places where the field intensity is low. The light pulse moves through the plasma, as does the electron density wave that it creates. The electrons "surf" on this wave at the speed of light in this medium (Figure 2). This process, laser wakefield acceleration, can accelerate electrons to giga-electronvolts within a few centimeters of the plasma. Such fast electrons can be used to drive protons or other ions. Fast protons can even create neutron beams.

This plasma-physical approach may explain why secondary sources are considered candidates to replace a stage in a particle accelerator, such as those at CERN or SLAC: A laser could accelerate electron bunches to mega-electronvolt or giga-electronvolt energies in comparatively short stages. Such a tabletop setup could replace hundreds of meters of acceleration line and consume ~10× less energy.

While this approach is tempting, it comes with its own challenges. For example, the electron bunch, under this approach, would require beam parameters corresponding to those of the subsequent conventional stages. This interfacing itself poses a challenge. Still, scientists working on the PETRA project at Deutsches Elektronen-Synchrotron (DESY), in Hamburg, Germany, have put the development of such a device on their agenda for the next generation of electron synchrotrons. There, the electron bunches from PETRA are used to create brilliant x-rays.

TRUMPF Scientific Lasers

Figure 3. A Herriott cell used to compress a 200-mJ pulse down to 45 fs.

What are secondary sources good for?

The increasing interest in secondary sources, as well as the dream to replace particle accelerators, owes to a multitude of possible supported applications. These extend well beyond the generation of EUV radiation — a product that already commands a $1 billion market.

One application is related to brilliant x-rays. The term brilliance refers to a combination of intensity and small focus for these x-ray beams. In 2013, scientists at PETRA created a focus of <5 nm in diameter. These beams could "see" the inner structure of biological and technical samples with extreme precision, thereby offering high value to the medical and engineering communities.

As one might expect, beam time at PETRA is always overbooked. Imagine if engineers could bypass moving all their experimental equipment to an accelerator facility for seven days of beam time. Or, consider a quality control system in battery manufacturing that can see each pore in its welds at micron resolution in real time. The list of applications for brilliant, pulsed x-rays is long and apt to grow with the availability of more and cheaper sources.

Another application benefiting the biomedical sector involves the use of a separate secondary source. Fast electrons can be used to accelerate ions, such as protons. A tabletop proton source would be desirable for cancer treatment. Shooting protons or energetic photons into specialty materials, such as beryllium, for example, can trigger the emission of neutrons. A tabletop, turnkey source of neutrons could be used to view the contents of barrels with nuclear waste without the need to open these potentially hazardous vessels. Scanning shipping containers at port to determine the quantity and quality of contents is another possible use case.

Finally, the development of secondary sources is closely connected to nuclear fusion. The successful experiment at the National Ignition Facility (NIF) in 2022 was executed with a system that turned energetic laser beams into x-rays, which started the fusion reaction in a tiny capsule with deuterium and tritium. Meanwhile, other schemes use accelerated ions to ignite fusion.

New systems for secondary sources

The availability of new ultrashort-pulse laser systems has propelled the development of secondary sources in recent years. The reason traces back to its physics: The acceleration of electrons in a laser plasma scales with the intensity of the laser pulses driving the plasma. The laser intensity is expressed as energy per time (equals peak power) and per focal area. Because the focal area cannot be smaller than the wavelength of the laser, the peak power is the way to scale up laser intensity. This can be achieved with both higher pulse energies and shorter pulse length. Terawatt or petawatt lasers, for example, refer to measures of peak power(s).

The biggest scientific lasers in the world currently reach intensities of ~10 PW. Such systems require a hall full of amplifier stages and huge vacuum vessels for the pulse compressors. The source at Extreme Light Infrastructure — Nuclear Physics facility (ELI NP) in Măgurele, Romania, for example, achieves one shot per minute. Currently, the laser with the highest pulse energy stands in California at NIF, where it is managed by Lawrence Livermore National Laboratory. This system delivers slightly >2 MJ/pulse at a rate of about one shot per day.

Obviously, these systems are intended for basic research. So, what lasers would be applied for industrial secondary sources?

"This depends on the desired application," said Tom Metzger, CEO of TRUMPF Scientific Lasers, who supplied the data for Table 1. "There is no single system that could serve them all."

"But these are no fixed values. Most scientists use laser sources they can get for their experiments," Metzger said.

Ti:sapphire vs. neodymium-doped glasses

The choice of laser crystal is a core question for the development of a laser system. So far, most lasers for secondary sources have been scientific systems, for which the characteristics of maximum intensity or energy dominate compared to efficiency and/or repetition rate. Titanium:sapphire (Ti:sapphire) is established as an excellent material for these systems. It offers a broad emission spectrum for the amplification of ultrashort (i.e., broadband) pulses.

Unfortunately, Ti:sapphire must be pumped in the green spectral region, which is usually performed with a frequency-doubled neodymium (Nd)-doped laser. During the past several decades, these have moved from lamp-pumped to diode-pumped, and from 10-Hz repetition rate(s) to multiple kilohertz.

For industrial applications, direct-diode pumping is favored to increase the wall-plug efficiency and to reduce unit price. This provides motivation for TRUMPF Scientific Lasers, for example, to develop lasers based on ytterbium-doped crystals. These lasers can be pumped with diode bars at 9xx nm. Their gain bandwidth is comparably smaller. As a result, the spectrum of amplified pulses must be broadened if ultrashort pulses <500 fs are desired. This is typically completed via Herriott cells, which were initially developed to improve the sensitivity of spectroscopic measurements with a multipass gas cell (Figure 3). Herriott cells can also be used to introduce self-phase modulation, which leads to spectral broadening. Of course, the intensity of the laser pulse must be limited to avoid filamentation or optical damage. Thus, the size of the Herriott cell scales with pulse energy and the desired spectral broadening, which is equal to pulse shortening.

Several methods exist for the generation and amplification of ultrashort pulses. The questions of regenerative or multipass amplification, as well as the geometry of the amplification crystal, each play great roles. The developers at TRUMPF Scientific Lasers use a full range of industrial laser systems from the parent company to build modular systems that can drive secondary sources (Table 1). Fiber lasers deliver the best-quality pulses in oscillators. For amplification, developers may choose between disk, slab, and multislab geometries.

The top row of Table 1 describes how TRUMPF Group developers use a variety

Table 2.
Typical Laser Source Parameters for Specific Secondary Sources

Beam Type	Typical Pulse Length	Typical Pulse Energy
Attosecond Pulse	<30 fs	100 s of microjoules to a few millijoules
High-Harmonic	<30 fs	<1 mJ
Electrons (< megaelectron volts)	<30 to 40 fs	A few millijoules up to 100 mJ
Betatron Radiation (x-rays of <100 keV)	~25 fs (HAPLS: 30 fs; ATLAS 27 fs)	Several joules (HAPLS: 30 J; ATLAS: 70 J)
Hard X-Ray Radiation (several 100 keV from a laser plasma source)	Picoseconds	200 to 500 J
Ion Beams (target normal sheath acceleration)	100 to 1000 fs	>3 to 5 J
Electrons from Laser Wakefield Acceleration (300 MeV to a few gigaelectron volts)	<50 fs	A few to tens of joules
Neutrons (fast, monoenergetic)	30 to 500 fs	A few joules
Neutrons (white, broadband)	<1 ps	100 J

of geometries of ytterbium-doped crystals for the amplification of short pulses. The lower row shows the achieved pulse parameters with additional pulse compression schemes.

Laser fusion and secondary sources

At the recent International Laser Technology Congress AKL'24, Constantin Haefner, Fraunhofer-Gesellschaft's newly appointed executive board member responsible for research and transfer and executive director of the Fraunhofer Institute for Laser Technology ILT, presented a closing lecture on the topic of laser inertial confinement fusion as an opportunity for industry. Haefner also heads the expert committee on inertial confinement fusion of the Federal Ministry of Education and Research BMBF, and he offered a forecast based on results from NIF, which uses an indirect drive method. It is the only method so far that has been used to achieve a burning and ignited plasma regime.

For such a future laser driver, Haefner anticipated parameters of laser pulse energy in the range of 3 to 5 MJ UV radiation; average laser power of ~40 MW and peak power at ~500 TW; and wall-plug efficiency in the range of 10% to 20%.

While NIF was built for one shot per day, the new device should enable 10 shots/s. A major non-laser requirement for this regime is a low price for the almost 900,000 target capsules that the system consumes each day.

Again, these values and figures are based on a method that just started working at NIF. So, any progress with direct drive — as investigated, for example, at the Laboratory for Laser Energetics in Rochester, N.Y. — or the various approaches pursued by laser fusion startups, could change the game.

Steve Patterson, CTO of Leonardo Electronics US, showed at the AKL congress that the efficiency of high-power diode modules is a key parameter for future fusion systems. Leonardo has supplied such modules to former fusion experiments and is engaged in new developments in Germany and the U.S.

This shows an obvious relation to secondary sources: "All secondary sources will benefit from the fusion developments," Metzger said.

"Cheaper and more efficient diode modules will be a key enabler for industrial high-power lasers needed for secondary sources," Metzger said. These lasers will be there long before a fusion power plant goes online. And it is not only about diodes: Beam delivery components, targets, and secondary radiation transport solutions are among the fields poised to benefit from government-supported fusion research. Secondary sources may remain a niche market, but the technological spillover from the development of laser fusion could provide the decisive boost to make these projects economically viable.

For his part, Haefner assumes that several hundred beamline modules are needed for a prospective power station. The development of the technology is already underway. According to a German road map for laser fusion, which Haefner shared at AKL'24, performance scaling of pump diodes is beginning now, with the scaling of pump diode production capacities scheduled to occur in five years. Meanwhile, a first call, the PriFUSIO initiative, has been issued by BMBF and aims to develop key technologies for climate-neutral fusion power plants. Further developments are anticipated to follow.

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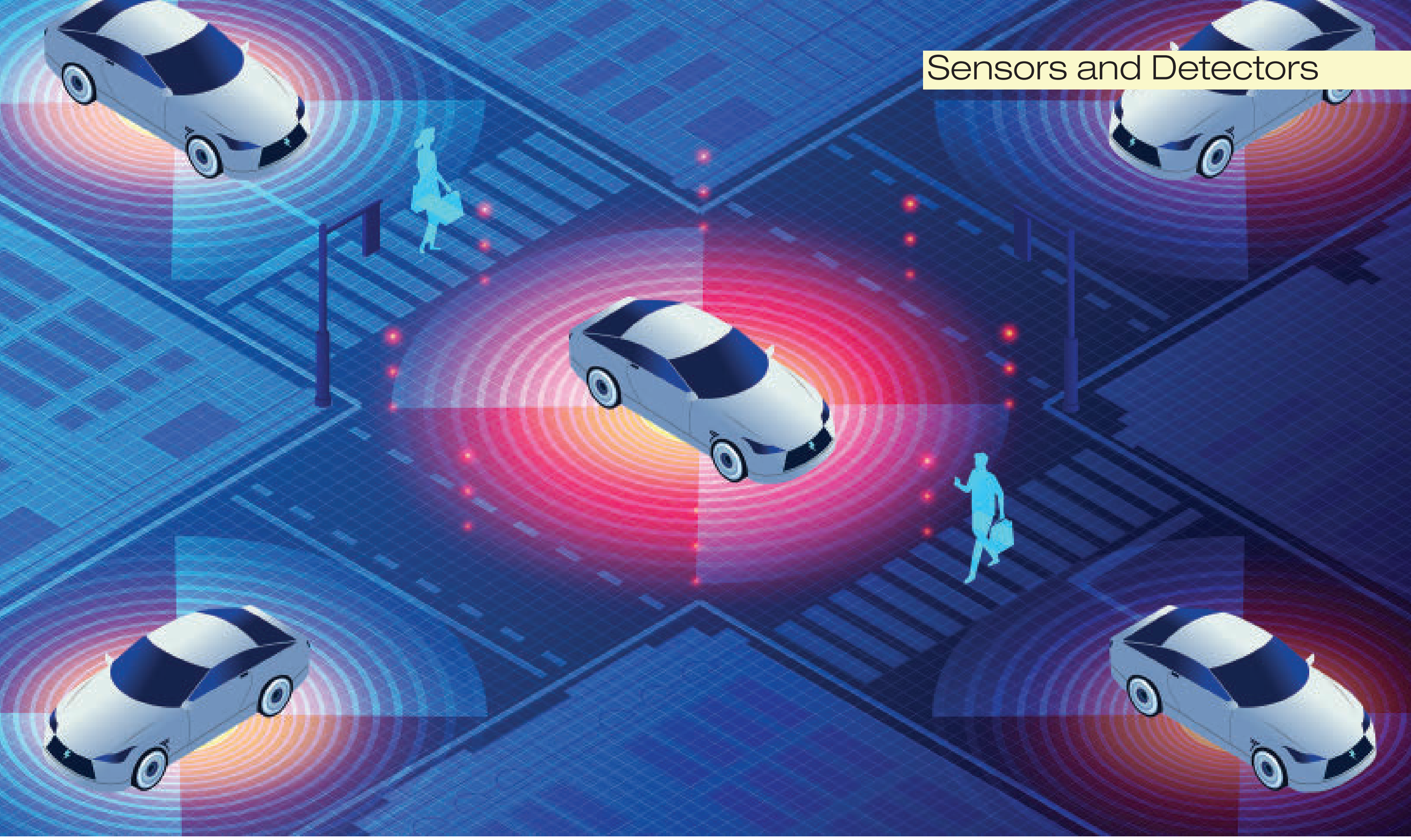


Manufacturers favor the use of vertical-cavity surface-emitting lasers (VCSELs) for their compact size and efficiency. While they have been used in a variety of products and systems during the past 30 years, a preeminent implementation is in automotive lidar to more effectively sense the environment around a vehicle.

Highly Efficient Multijunction VCSELs Advance for Automotive Lidar

The optimization of multijunction VCSEL architectures offers an immediate benefit to automotive lidar and other high-power sensing applications.

Image on this page, courtesy of iStock.com/ArtemisDiane.
All other images courtesy of ams OSRAM.

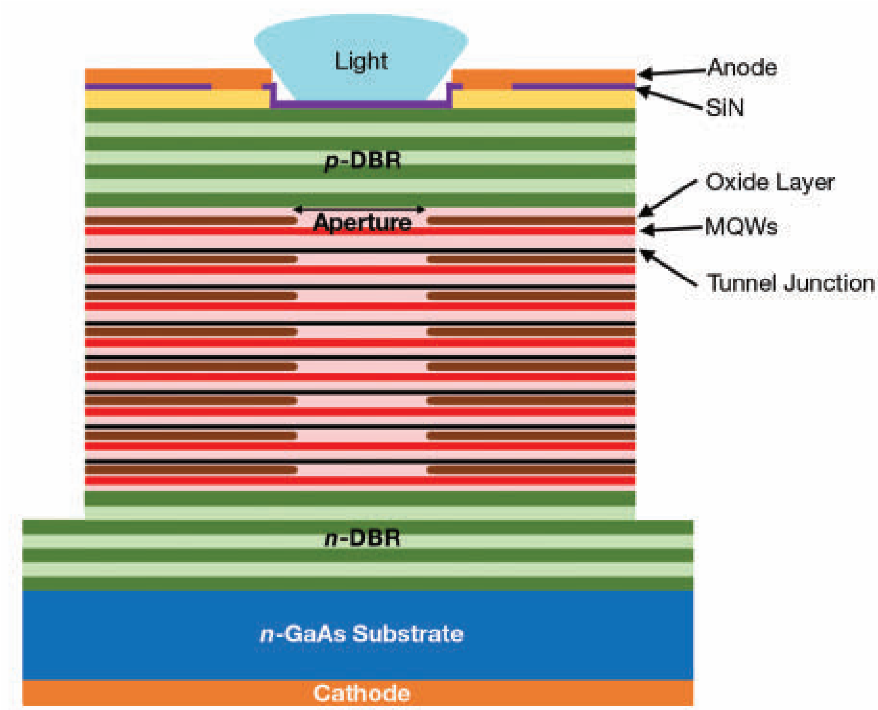
BY AMIRHOSSEIN GHODS
AND KLEIN JOHNSON
AMS OSRAM

Vertical-cavity surface-emitting lasers (VCSELs) have garnered significant attention for various sensing and visualization applications during the past three decades. The sustained progress in their development during this period owes largely to advanced semiconductor growth technology, as well as enhanced expertise in device fabrication processing. Specifically, VCSELs emitting in the near-infrared spectrum, ~800 to 1200 nm, and using the gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) material system, have consistently improved in terms of their performance and range of supported applications.

Short-distance data communication and spectroscopy and biosensing — which require low-to-moderate optical output power(s) — are common applications for VCSELs. These lasers are favored for their compact size and high efficiency. Further, manufacturers can design and develop VCSELs in large arrays.

Such a design makes VCSELs suitable for integration into a wide variety of devices and systems. The introduction of 3D sensing with the iPhone "Face ID" feature in 2017, for example, significantly boosted the use of VCSELs in various consumer electronics, augmented reality/virtual reality devices, drones, automotive in-cabin monitoring and gesture recognition systems, and payment systems. This advancement, targeting the consumer, spurred innovation in system and product development; new applications emerged and existing applications improved and evolved.

More than half a decade later, VCSEL technology is expanding again and penetrating fields such as industrial automation, medical diagnostics, and environmental monitoring. A core application area for the present wave of



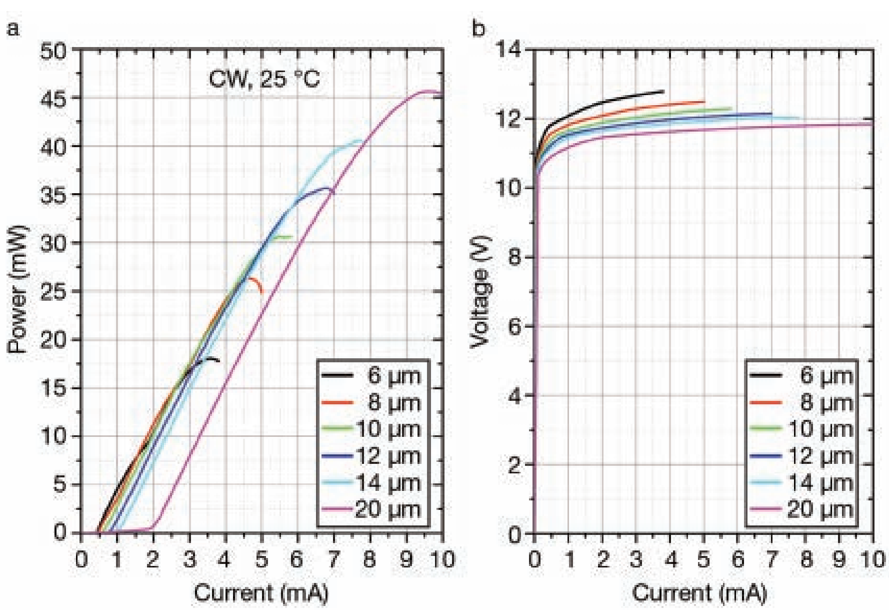
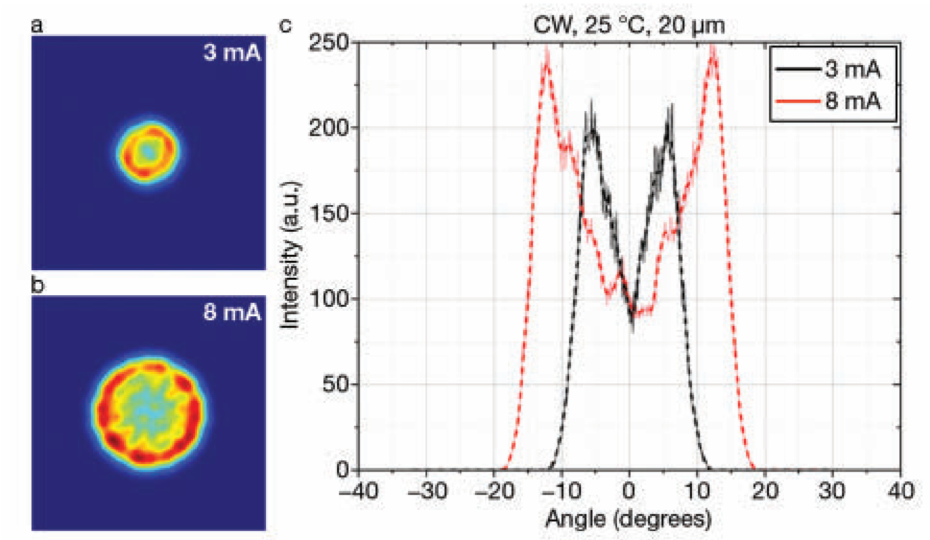


Figure 1. A cross section of the eight-junction (8J) VCSEL epitaxial structure **(above)**. The epitaxial design of multijunction VCSELs enables output power scaling while maintaining die footprint. High-power sensing applications, including automotive lidar, require a high output optical power density. DBR: distributed Bragg reflector; GaAs: gallium arsenide; MQWs: multiple-quantum-wells; SiN: silicon nitride.

Figure 2. The power-current (L-I) characteristics of the single-aperture 905-nm eight-junction (8J) VCSEL die, with varying oxide aperture size, as measured at room temperature **(a) (left)**. The corresponding current-voltage (I-V) characteristics **(b)** show correlation to an increased lasing threshold current and available output power. CW: continuous wave.

Figure 3. Far-field beam characteristics of the 20-μm single-aperture VCSEL die are measured at 3 mA **(a)** and 8 mA **(b)** **(right)**. The cross-section beam profiles **(c)** show an increase in the beam divergence angle, as initiated by increasing bias current: The beam increases by increasing the bias current level from ~15°, which is caused by the increase in the number of higher-order transverse modes that typically emit at wider angles. CW: continuous wave.



VCSEL technology is high-power sensing, which envelops distance lidar applications, such as automotive for advanced driver-assistance systems (ADAS) and self-driving vehicles. Automotive lidar manufacturers use different architectures to create a 3D map of the environment in front of, and sometimes around, the vehicle, actively scanning the surrounding areas. These systems are essential to improve safety and enable autonomous navigation.

To date, edge-emitting lasers (EELs) have dominated regarding the types of laser systems in the lidar market. Systems designers and integrators often select these lasers since they can achieve high output optical power levels.

Recent advancements in the development of high-power multijunction VCSELs capable of producing output power densities well above 1 kW/mm^2 are now positioning VCSELs as a desired substitute. These high-power multijunction sources are a cheaper and more efficient replacement for traditional EELs. Additionally, VCSELs demonstrate better temperature performance than their EEL counterparts, as well as narrower spectral width(s), and a circular beam shape that benefits certain applications, including high-power automotive lidar.

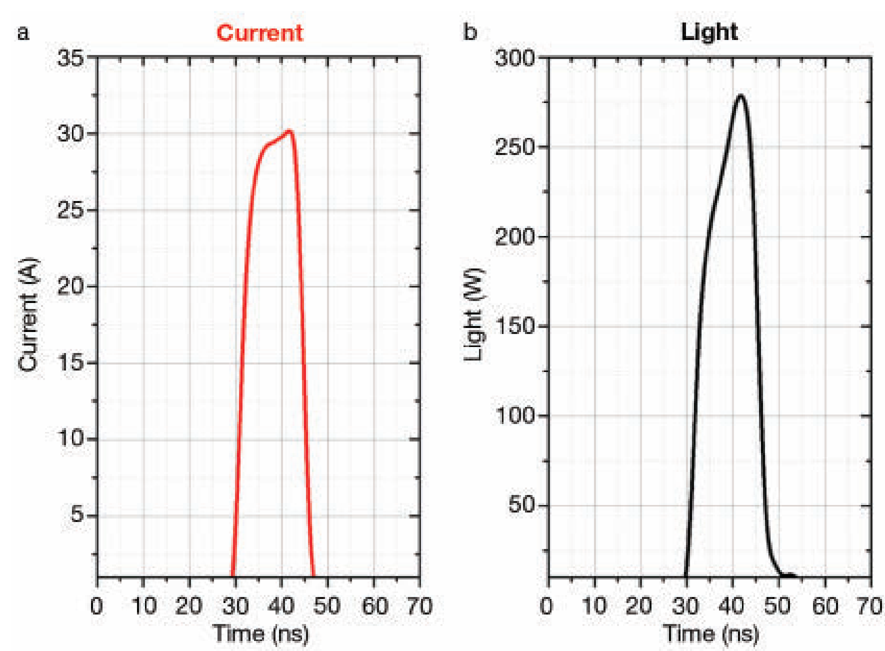
Prefabrication optimizations

Several parameters influencing performance distinguish VCSELs developed for lidar applications from early iteration VCSEL technology as well as from EELs and other laser systems. First, these devices are designed to emit between 900 and 940 nm. This wavelength range minimizes the effect of the background ambient solar spectrum and enables a higher signal-to-noise ratio and detection efficiency. Moreover, silicon (Si) photodetectors, which are typically used in automotive and industrial lidar modules, exhibit peak responsivities around this wavelength range.

Second, the output optical power, especially for long-range lidar >300 m is typically desired to be >1.5 kW/mm^2. Also, a narrow beam divergence angle <25° could help deliver the optical power to a further distance and increase the object detection efficiency of the lidar module.

Increasing the number of active light-emitting junctions is an effective approach to scale the output power — and external quantum efficiency — of VCSELs. In this method, several *pin* junctions are series-connected, and tunnel junctions, placed in between the active junctions, provide the electrical and

Figure 4. A VCSEL die in the form of a linear array of >50 apertures **(below)**. The electro-optical characteristics of this die were measured under short-pulse test conditions. The bias current signal is pulsed into the VCSEL with a peak of ~30 A **(a)**, and the output light pulse is charted **(b)**.



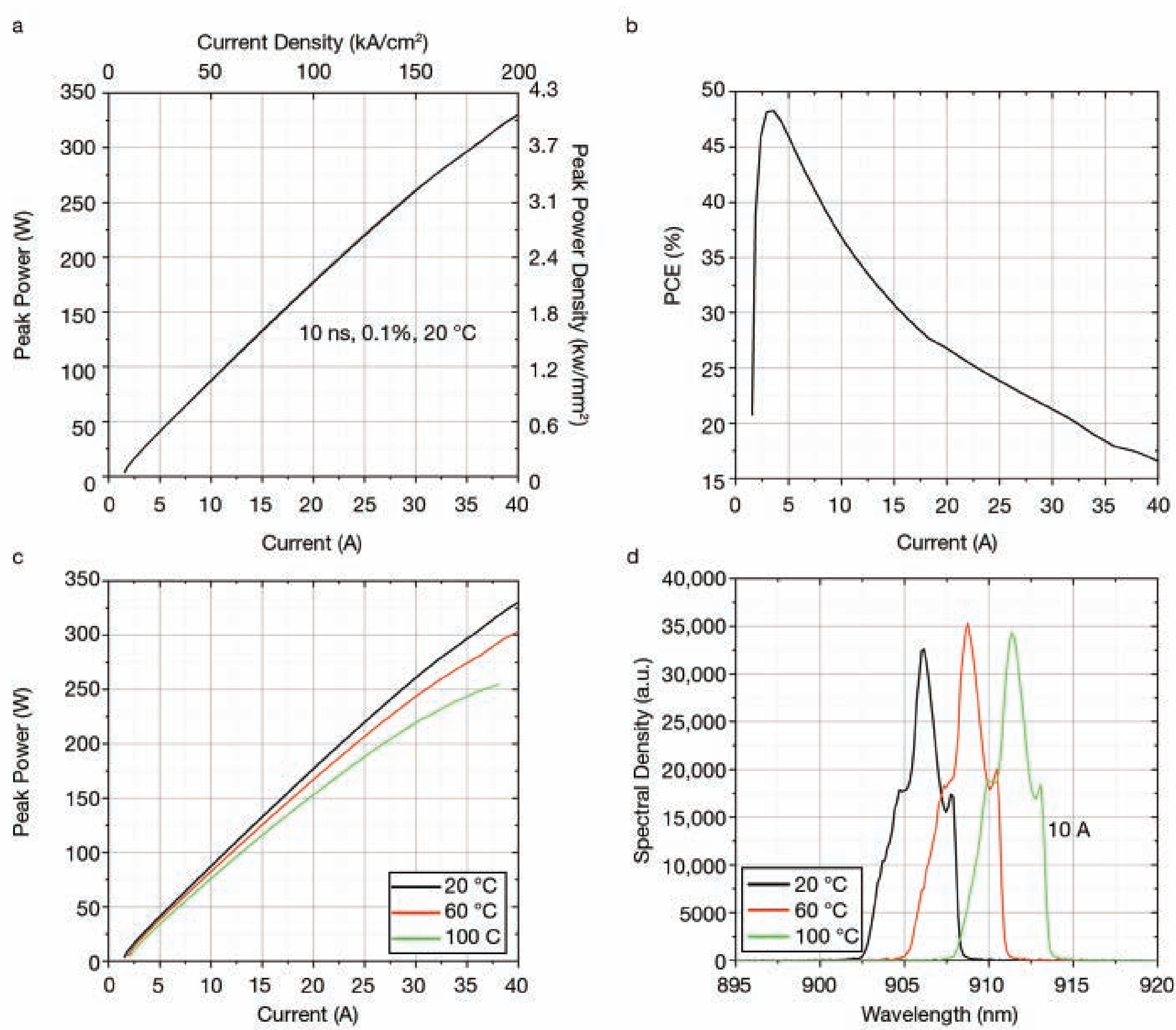


Figure 5. Power-current (L-I) characteristics of the eight-junction (8J) 905-nm VCSEL array die, measured at 20 °C, are charted **(a)**, as well as the calculated power conversion efficiency **(b)**. The L-I characteristics are shown at different substrate temperatures **(c)**; for example, at ~20 A (i.e., 100 kA/cm²), the total measured output power is ~175 W, whereas it decreases by ~15% (to ~150 W) at the substrate temperature of 100 °C. The temperature-dependent spectral response of the VCSEL array die is additionally shown **(d)**. PCE: power conversion efficiency.

optical coupling between the junctions. These tunnel junctions are made of ultrathin layers of highly *p*- and *n*-doped semiconductor materials, which facilitates the process of charge carrier recycling between the neighboring active junctions[1]. In other words, electron-hole pairs injected into bipolar cascade active regions recombine in an active multiple-quantum-wells (MQWs) region and are subsequently regenerated in the adjacent tunnel junction.

In this way, the pairs recombine in the neighboring MQWs stage as well. This process can multiply, as to the number of active MQWs stages, which leads to the possibility of scaling output power while maintaining injected current levels.

Increasing the gain volume in a multijunction VCSEL also makes it possible to reduce the effective reflectivity of the system mirrors without changing the lasing threshold gain. This in turn enables the extraction of more light without increasing the threshold current and lowers the series resistance and voltage, and it increases the power conversion efficiency (PCE) of these devices.

Alternatively, a more complex cavity structure in multijunction VCSELs complicates the design process and overall laser design and may adversely influence electro-optical performance. For example, increasing the number of active junctions can cause a significant increase in the far-field beam divergence[2]. The number of oxide layers in a multijunction structure is likely responsible for this increase, and it also increases the refractive index contrast between the core and the cladding regions of the VCSEL. This may lead to the wider beam divergence angle. The nonuniformity of the oxide fronts in a multijunction VCSEL can further lead to an increase of the "oxide-modes," which is exemplified as higher-order transverse modes in the 2D far-field beam profile or as additional side-peaks in the emission spectrum.

The use of mode filters can suppress the stimulation of these higher-order transverse modes and narrow the divergence angle in multijunction VCSELs. These filters, typically etched at the emitting surface of the device, increase the mirror losses for the higher-order transverse modes, which are emitted at wider angles. At the same time, they ensure that the lasing threshold gain for the transverse modes emitting at narrower angles is unchanged.

Device fabrication and characterization

Especially for use in high-power lidar devices, the characteristic performance of the power sources is a core consideration for the detection mechanism. In recent R&D efforts, ams OSRAM fabricated eight-junction (8J) VCSEL dies, both in the form of a single-aperture die and a densely packed array die. Results from tests performed under varying conditions showed that the multijunction VCSELs produced output power densities >2 kW/mm² with desirable slope and power conversion efficiencies. Both values are favorable in common EEL performance for use in high-power automotive lidar devices.

The multijunction structure of the fabricated devices consisted of eight active light-emitting PIN junctions, in which each junction enclosed MQWs for emission at 905 nm. The epitaxial structure of the 8J VCSEL was grown using metal-organic chemical vapor deposition on an *n*-type GaAs substrate. Two distributed Bragg reflector (DBR) mirrors were positioned to surround the active regions. The mirror pairs for both top and bottom mirrors achieved reflectivities >99%. The reflectivity of the top *p*-DBR mirror was slightly lower than the bottom *n*-DBR mirror, allowing the device to be top-emitting.

Figure 1 shows highly-doped *p*+/*n*+ tunnel junctions providing electrical coupling between the active junctions. An ultrathin, high-aluminum content AlGaAs oxide layer was placed above each active junction to provide lateral electrical and optical confinement. The tunnel junctions and the oxide layers were positioned at the null of the standing electrical field inside the cavity to minimize the internal losses. The MWQs' active stages are placed at the peak of the field to maximize modal gain.

ams OSRAM used UV lithography to fabricate the VCSELs and dry etching and wet oxidation to form circular mesas and the oxide apertures, respectively. Silicon nitride was used as the passivating material for the etched sidewall areas and the antireflective coating layer at the top surface, and top *p*-type and bottom *n*-type ohmic contacts were deposited. The dies were then singulated and packaged onto ceramic substrates for characterization.

The researchers characterized the performance of the VCSEL dies by measuring their power-current-voltage (L-I-V) properties under continuous wave (CW) conditions for single-aperture die, and short-pulse conditions for the VCSEL array die. The researchers also charted spectral response and far-field beam profiles.

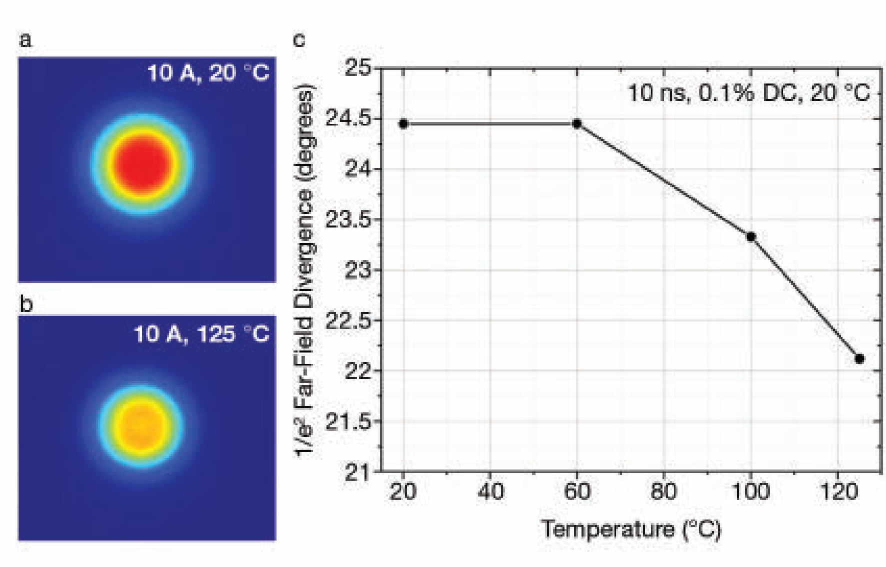


Figure 6. Far-field beam characteristics/profiles **(a-b)** of the eight-junction (8J) 905-nm VCSEL array die. The calculated 1/e² beam divergence angle is shown against substrate temperature **(c)**, where the divergence angle drops from ~24.5° at ~20 °C to ~22.1° at ~125 °C. This reduction in divergence angle could be partly caused by improved lateral current, which is spreading across the oxide aperture at higher temperatures. Overall, the divergence angle is within the range to support automotive lidar applications, in which divergence angles <25° are desired. DC: duty cycle.

Interpreting results

Figure 2 shows the L-I-V characteristics of single-aperture 8J VCSEL dies with varying oxide aperture sizes, between 6 and 20 µm, measured at room temperature. For this design, increasing the aperture size resulted in increases in both the lasing threshold current and available output power. The total voltage mainly consisted of the voltage drop across the eight active junctions, ~1.4 V/junction, in addition to the voltage across each tunnel junction, ~0.1 V/tunnel junction. Figure 2 also reflects the drop caused by the DBR mirrors.

Each of the fabricated VCSEL devices achieved a PCE of >40% and slope efficiency of >7 W/A. Due to a rise in junction temperatures under CW testing conditions, all devices exhibited a thermal rollover at higher injected bias current levels.

Figure 3 shows the far-field beam profiles of the 20-µm aperture VCSEL die at two bias currents as well as the 1D cross section of the far-field beam profiles. Both beam profiles are highly multimode, with several higher-order transverse modes lasing simultaneously, forming a doughnut-shaped beam.

Predicting performance

In subsequent fabrication, ams OSRAM developed a VCSEL die, in the form of a linear array of apertures, which included more than 50 apertures, where each oxide aperture has a diameter of 20 µm. The apertures were hexagonally packed in an emission area of 1500 × 60 µm. The fabricators measured the electro-optical characteristics of this VCSEL die under short-pulse test conditions, with a pulse width of 10 ns and duty-cycle of 0.1%. Figure 4 shows both the injected current signal as well as the output light pulse.

The L-I characteristics of the VCSEL array die measured under short-pulse test conditions is shown in Figure 5a. A peak power as high as ~330 W at the pulsed current of ~40 A, and corresponding to power density of ~4 kW/mm^2 at the current density of ~200 kA/cm^2 was achieved. However, for reliable operation of VCSELs, the bias pulsed current is typically limited to <100 kA/cm^2, where a peak output optical power of 175 W, corresponding to a power density of 2.1 kW/cm^2, is achieved. Figure 5b shows the calculated power conversion efficiency at different current levels, where the PCE reached ~27% at the current density of 100 kA/cm^2. The peak PCE for this device was measured at ~48% at 4 A, corresponding to a current density of ~20 kA/cm^2. The average slope efficiency was ~8.5 W/A.

Figure 5c shows the temperature-dependent L-I characteristics of the VCSEL array die: The total output power decreases by increasing the substrate temperature. Similarly, the temperature-dependent spectral response of the VCSEL array die shows that the device emits at ~905 nm at 20 °C, and subsequently, red-shifts to longer wavelengths by increasing substrate temperature (Figure 5d). The red shift is mainly caused by the shift in the cavity resonance wavelength, in addition to the shift in the bandgap energy of the active gain material. The side-peaks in the emission spectra demonstrate that the fabricate devices are highly multimode.

Figure 6, showing the far-field beam characteristics of the VCSEL array die, details the 2D beam profiles of the VCSEL at the bias current of ~10 A and two different substrate temperatures (Figure 6a,b). A circular flat-top beam profile can be observed under both test conditions, despite the observation of the VCSEL die under CW test conditions where a doughnut-shaped far-field beam pattern is typically observed. Under CW test conditions, the effect of thermal lensing, which is caused by the rise in the junction temperature, could lead to the stimulation of additional higher-order transverse modes that typically emit at wider angles. On the other hand, in the short-pulse test regime, the lack of such a mechanism could contribute to a more evenly distributed beam profile.

Meet the authors

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Klein Johnson has been working in the field of VCSEL technology since the early 1990s, first with Honeywell and later as cofounder of Vixar. He currently leads VCSEL R&D activities at ams OSRAM; email: klein.johnson@ams-osram.com.

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Guzel Musina

Awarded 2024 Teddi C. Laurin Scholarship

Guzel Musina, a Ph.D. student in the University of Houston's Department of Biomedical Engineering, was awarded the 2024 Teddi C. Laurin Scholarship for her contributions to the field of optics and photonics. Musina is pursuing research in the use of optogenetics to explore and treat heart conditions. She is currently performing her Ph.D. project at Baylor College of Medicine under the supervision of Irina Larina.

Musina is the developer of an optogenetic approach to mapping the location of pacemaker cells in the embryonic heart, which is not possible with other methods, according to Larina, a professor of integrative physiology at Baylor. The work detailing the optogenetic approach was presented at Photonics West earlier this year. Musina has authored 26 peer-reviewed articles in journals including *Optica*, *Journal of Biophotonics*, and *Biomedical Optics Express*.

Musina earned her bachelor's and master's degrees at Bauman Moscow State Technical University in Russia, and she completed academic research in the school's Department of Laser and Optical-Electronic Systems. She also served as an undergraduate researcher in the laboratory of Valery Tuchin, with whom she contributed two chapters as a co-author to the *Handbook of Tissue Optical Clearing: New Prospects in Optical Imaging.*

Upon transitioning her studies to the U.S., Musina was elected vice president of the SPIE University of Houston Student Chapter. She is involved in the organization of academic visits to the university and the facilitation of student events to promote exposure and scientific interactions within the student community.

Musina credits her interest in optics and photonics to conversations with her father, a physics teacher, as well as to hands-on activities, such as examining water samples from fishing trips. Musina aims to become an independent principal investigator at a research-intensive university, focusing on the advancement of optogenetics in cardiac biology and disease.


Guzel Musina

Guzel Musina.

Photonics Media partners with SPIE, the international society for optics and photonics, to fund the Teddi C. Laurin Scholarship to raise awareness of optics and photonics, and to foster growth and success in the photonics industry by supporting students involved in photonics. The scholarship is awarded annually in memory of Teddi C. Laurin, the founder of Laurin Publishing and Photonics Media.

Photonics Spectra magazine spoke with Musina about her pursuits in optics and photonics.

What motivated you to pursue research in optogenetics?

The lectures of my father, a high school teacher, kindled a fascination in me for the unseen forces that govern our world. This foundational curiosity evolved into a focused interest in optics and photonics during my college years. I discovered the field of optogenetics under the guidance of Professor Irina Larina. The potential of optogenetics to provide precise control over cellular processes using light captivated me, especially its application in studying congenital heart defects. The promise of using light to revolutionize medical research and therapy is a driving force behind my commitment to this field.

What are the primary areas of focus for your work?

My main goal is to develop an optical tool for manipulating cardiodynamics in mouse embryos. This involves creating and applying advanced optogenetic techniques to study the intricate processes within embryonic cardiac tissues. By focusing on innovative optical imaging, optogenetic control, and novel image processing methods in genetic mouse models, my aim is to improve our understanding of congenital heart defects and potentially contribute to better management of these defects.

How has your educational experience helped guide your career and cultivate success?

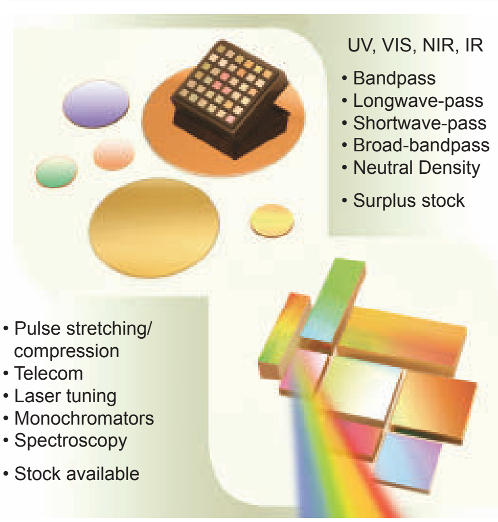
My educational journey, starting at Bauman Moscow State Technical University (BMSTU), in Moscow, and continuing through my Ph.D. studies at the University of Houston, has been pivotal in shaping my career. At BMSTU, I gained a strong foundation in optics and photonics, enhanced by hands-on research in Kirill Zaytsev's lab. These experiences honed my research skills and sparked my interest in biophotonics. I later joined Larina's research group at Baylor College of Medicine. This combination of rigorous academic training and cutting-edge research placed me in the fields of optogenetics, and biophotonics more broadly.

What current trends in optogenetics and biophotonics do you find most inspiring?

One significant trend is the development of advanced light-sensitive proteins that offer greater specificity and control over biological processes. Another exciting area is the integration of optogenetics with other cutting-edge technologies. One example is CRISPR gene editing; such a combination can be used to create more precise light-based therapeutic interventions. In biophotonics, the use of multimodal approaches to study complex biological systems is particularly intriguing. These trends are pushing the boundaries of what is possible in research as well as in clinical applications.

What are your plans for the next stages of your professional journey?

My goal is to become an independent researcher to investigate fundamental biological questions and provide insights into medical processes, ultimately contributing to advancements in health care. Toward this path, my immediate goals include further developing my expertise in optogenetics and biophotonics, with a focus on creating innovative tools for studying mouse embryo cardiodynamics. Through graduate school training, I plan to strengthen key skills such as research project development and critical thinking. I plan to enhance my ability to share research findings through writing and presentations. These skills are essential for a successful scientific career, and I believe that they will enable me to effectively disseminate my research to the broader community of scientists and researchers.

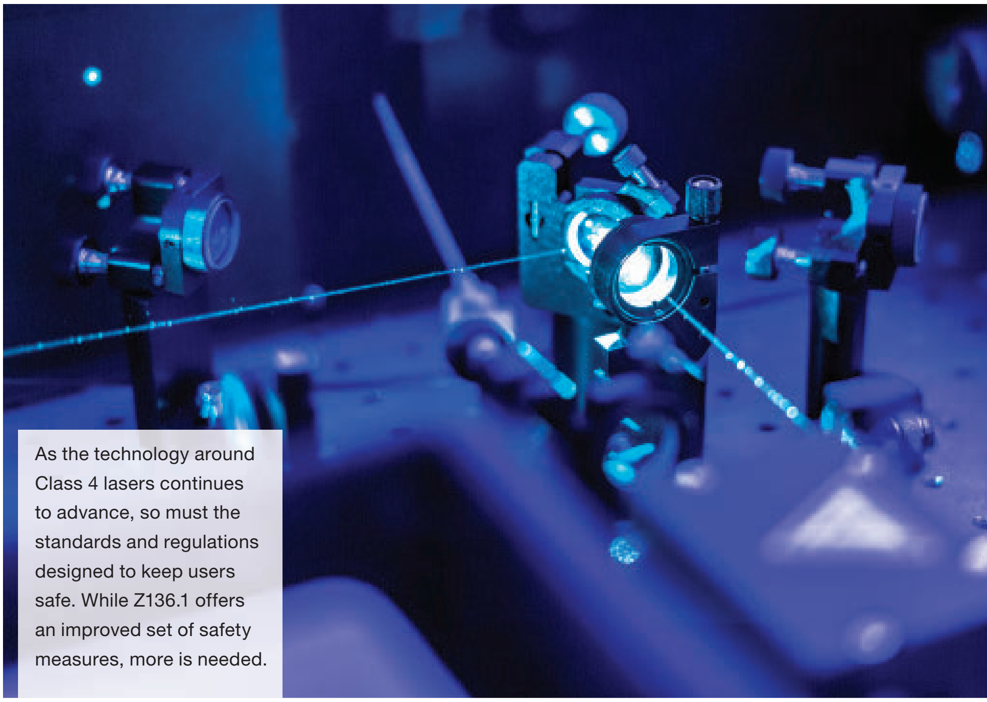


Class 4 Laser Access Faces New Challenges

BY KEN BARAT
LASER SAFETY SOLUTIONS

Among the broad range of technologies that are governed by standards, Class 4 laser systems face a familiar hurdle. While technology standards aim to build parameters for safety, access, and performance, they often struggle to keep pace with the advancements that improve and add value to the technologies that they are ultimately designed to help regulate and streamline for use.

Those who are familiar with the American National Standards Institute (ANSI) Z136 series of laser standards know that the use of Class 4 laser systems requires some level of access control. For those who are unfamiliar, ANSI Z136.1, Safe Use of Lasers, is considered the acceptable road map for laser user safety guidance. The Z136 series has expanded to several application-based vertical standards to address more specific laser safety guidance, such as medical, outdoor, and research.



As the technology around Class 4 lasers continues to advance, so must the standards and regulations designed to keep users safe. While Z136.1 offers an improved set of safety measures, more is needed.

In the past, the effects of standardization (engineering and administrative controls) were considered absolute. Indeed, certain facets of standards — for example, laser safety officer (LSO) appointment, training, and laser controls areas — remain firmly locked in place.

But much like the way that "Star Trek" producers rework the history of their science fiction adventures, standards are also subject to change. Z136 laser use standards are principally geared toward traditional laser systems, and, with new editions of these standards taking nearly seven years to generate, they often lack responsiveness to changes in laser technology and applications. This discrepancy is critical, especially when considering access control, and especially when regulatory bodies, such as OSHA, look to the Z136 standard as their measuring metric for laser safety.

Access control

As the parent document of the Z136 series of laser safety standards, Z136.1, Safe Use of Lasers-2021, gives the Class 4 laser user three broad options for access control: undefeatable, defeatable, and administrative. These standards cover entryway safety controls designed to always allow unobstructed egress by laser personnel and admittance to the laser control area (LCA) under emergency conditions. Z136.1 further states that all Class 4 LCAs shall incorporate one of the following sets of regulations:

a) Undefeatable Area or Entryway Safety Controls

Undefeatable safety latches and area interlocks deactivate the laser or reduce the output to safe levels in the event of unexpected entry into the LCA. Examples include electrical switches, pressure-sensitive floor mats, and infrared and sonic detectors.

b) Defeatable Area or Entryway Safety Controls

Defeatable safety latches and area interlocks shall be used if undefeatable

Image courtesy of iStock.com/Михаил Руденко.

area or entryway safety controls limit the intended use of the laser or laser system. During normal usage requiring operation without interruption, these controls may be used if it is clear that there is no laser radiation hazard at the point of entry. In this case, overriding the safety controls shall be permitted to allow access to authorized personnel if they have been trained and provided with adequate personal protective equipment (PPE). This may be the case for long-term testing or medical procedures.

c) Procedural Area or Entryway Safety Controls

Where safety latches or interlocks are not feasible, for example, during some medical procedures or service procedures, the following shall apply:

1) All authorized personnel shall be adequately trained and provided adequate PPE prior to or upon entry.
2) A door, blocking barrier, screen, or curtains shall be used to block, screen, or attenuate the laser radiation at the entryway. The level of laser radiation at the exterior of these devices shall not exceed dangerous levels, nor shall personnel experience any contact with radiation above the maximum permissible exposure immediately upon entry.

Enduring challenges

Complicating the aforementioned implementations is the expansion of hand-held Class 4 laser systems, which can leave some users of laser welders and/or rust removal systems, for example, in an uncertain position. These hand-held devices can produce hundreds to thousands of watts of open beam paths, establishing themselves as Class 4 lasers, but they often operate with little to no access controls. Rust removal devices can be rolled across floors while some can be carried on the back of a user. Laser welders, while having very limited beam paths, also fall under these laser standards and require access controls in their work area.

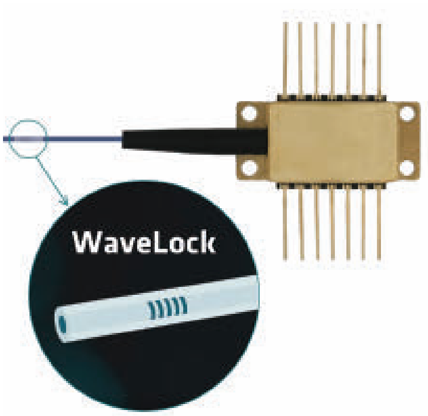
Further, laser fingerprint detectors, such as those used by forensics teams at crime scenes, also fall under these standards, but challenge the ability to establish required controls governing user access. These examples demonstrate the expanded application of Class 3B and Class 4 laser systems beyond their original applications and their envisioned environments, presenting challenges to meeting safety standards.

In addition, a new type of access control must now be considered, as many groups operate Class 4 lasers from offsite locations. Many — including myself — define these operations as those occurring in which users can make changes to systems remotely. These changes may include opening or closing shutters or inserting optics with motorized mounts from a distant location. While this is a great convenience to those users, it presents new challenges and potential dangers. A core challenge that I have observed, and one that faces many facilities, is the failure to address occupancy in LCAs when a remote user accesses the system. Offsite use inherently complicates the job of the LSO, who must evaluate risk to anyone in the LCA. The possibility that remote workers could inadvertently expose others to open beams, or that users in the LCA could open an enclosure without knowing that a beam is accessible, must be kept top of mind.

To keep up with evolving technology, laser standards and safety officers must consider how to protect all parties when a facility uses remote access. They must also consider what type of access control, if any, is needed for those mobile Class 4 laser products.

As the LSO looks to provide laser safety through access control, several options should be considered, and interlocks are a common solution. From an administrative perspective, barriers, key cards, and electronic locks that control access but do not disturb laser operations could be a solution. For open use applications, a safety watch, barriers, and awareness training for general staff can all contribute to laser safety. As for remote users, indicator lights displaying remote access status and other procedures to confirm remote operation or room occupancy must be developed. Technology will keep advancing and standards and LSOs must be aware of new challenges and controls to keep workers safe.

lasersafetysolutions@gmail.com



FBG Wavelength Locker

The WaveLock Series from **TeraXion** comprises fiber Bragg grating lockers for laser diode stabilization and control. The lockers feature high wavelength accuracy, low temperature dependence, a high side mode suppression ratio, and low insertion loss. The product can be used in applications such as laser pumping, sensing, and spectroscopy.
info@teraxion.com

Smart Mid-Infrared Laser

The TOPO smart from **TOPTICA Photonics AG** is a smart continuous wave mid-infrared laser for sensing and spectroscopy applications. The laser uses a pumping scheme to boost performance, and it includes a touchscreen and multiple connectivity options for integration into existing setups. The TOPO smart features a tuning range of 3100 to 3500 nm, a mode hop free tuning range of >15 GHz, a <500-kHz linewidth, an output power of >30 mW, and a beam quality factor <2.
sales@toptica.com

Nanoscale Imager

The IR-neaSCOPE from **attocube** is designed for nanoscale analysis that requires measurements only of IR absorption, including IR imaging and spectroscopy. The imager detects laser-induced photothermal expansion in the sample without the need of an IR detector or interferometry. The IR-neaSCOPE is suitable for samples with large thermal expansion coefficients, such as polymers and biomaterials, among others.
info@attocube.com

Laser Sensor

The Coherent PM10K+ from **Coherent** is a laser power sensor for measuring the power output of CO_2, fiber, diode, and continuous wave lasers. In <3 s, the calorimeter-based sensor can measure the output of lasers up to 10 kW and 12 kW intermittent and is available in both USB and DB25 cable compatible interface formats. The Coherent PM10K+ features a 65- × 65-mm active area to prevent clipping of large beam sizes and includes a laser interlock function that terminates the laser during measurement to protect the sensor from damage.
info@coherent.com

RGB-IR Stereo Camera

The EAGLE 2 LI-VB1940-GM2A-119H from **Leopard Imaging** is an RGB-IR high-resolution stereo camera for autonomous vehicles, robotics, AI-Internet of Things, and 3D reconstruction applications. Incorporating two automotive-grade 5.1-MP global shutter RGB-IR image sensors, the dual-sensor configuration enables depth perception and spatial accuracy while decreasing motion artifacts. The EAGLE 2 LI-VB1940-GM2A-119H features an IP6X rating, night vision capabilities, and two wide- and narrow-angle IR dot pattern projectors for depth perception and object detection capabilities.
sales@leopardimaging.com

3D Lidar Sensor

The YLM-10LX from **Lumotive** and **Hokuyo Automatic** is a 3D lidar sensor for industrial

automation and service robotics applications. Built with Lumotive's light control metasurface optical beamforming technology and Hokuyo's lidar systems, the sensor has a long range and wide field of view with software-defined scanning capabilities. The YLM-10LX allows for the adjustment of performance parameters, such as the sensor's resolution, detection range, and frame rate with the ability to have multiple fields of view programmed and used simultaneously.
info@lumotive.com

UVA LED Emitter

The SST-08H-UV from **Luminus Devices** is a high-power UV-A LED for applications such as horticulture, curing inks, medical instrumentation, fluorescence imaging, and disinfection, among others. Able to be driven at a single amp, the product is available in peak wavelength options, including 365 nm, 385 nm, 395 nm, and 405 nm. The SST-08H-UV uses a robust, sulfur, and corrosion-resistant package and features a 3.5- × 3.5-mm form factor as well as a wide viewing angle of 130° to provide uniform illumination.
sales@luminus.com

DBR Laser Cores

The ML6600 from **Modulight** is a distributed Bragg reflector laser core for quantum spectroscopy applications with high levels of mechanical, optical, and acoustical isolation. Coming in wavelengths of 650 nm, 760 nm, 780 nm, 785 nm, 795 nm, and 935 nm, the core exhibits a linewidth as low as below 500 kHz and is paired with low-noise current drivers and temperature controllers. The ML6600 can use

both free-space output and single-mode polarization maintaining fiber for light delivery and also includes cloud connectivity and predictive maintenance features.
sales@modulight.com

Benchtop Microscopes

The BC43 WF and SR from **Oxford Instruments Andor** are wide-field and superresolution, respectively, benchtop microscopes for studying single-cell and multicellular organoids, tissue sections, and large-model organisms. The BC43 WF can be used for automated and fluorescence imaging and allows researchers to extend into confocal and superresolution microscopy, while the BC43 SR can resolve samples down to 140 nm. Both microscopes use the company's installation qualification/operational qualification quality control program, making them operate within controlled parameters.
info@andor.com

MIR Imaging Module

The Neutrino SX8-ISR 35-700 from **Teledyne FLIR** is an AI-enabled MIR imaging module for integrators developing intelligence, surveillance, and reconnaissance systems. Using Teledyne FLIR's Prism AI, the imaging module provides detection, classification, and target tracking at a resolution of 1280×1024 pixels. The Neutrino SX8-ISR 35-700 uses a long-life linear Stirling cooler that provides a mean time to failure of $>$27,000 h and fully integrated continuous zoom optics and comes with Gigabit Ethernet, Camera Link, and RS232/422.
flir@flir.com

CO_2 Laser Source

The OEM 45iE from **Luxinar** is a 450-W sealed CO_2 laser source for industrial processing applications. The laser source provides a separate radio frequency module, allowing for remote mounting of the radio frequency unit and for the laser source to have a smaller form factor. The OEM 45iE features a short optical pulse length with high peak power, a minimum shipment power of 540 W, and a typical power stability of $\pm$1% using optional power feedback control and a narrow wavelength band.
info@luxinar.com

MIR Detector

The Mini Blackbird 1280 HFM from **Semi-Conductor Devices** is a MIR high-definition detector for applications in aerial defense and surveillance. The sensor's accompanying proximity electronic board supports video engine capabilities with low power consumption and provides capabilities in radiometric operations for accurate data collection for thermal imaging, target detection, environmental monitoring, persistent surveillance, and threat detection. The Mini Blackbird 1280 HFM features a linear cooler for use in harsh environments and as payloads for UAVs.
marketing@scd.co.il

Pockels Cell

The Pegasus Pockels Cell solution from **G&H** is a lithium niobate Pockels cell design that can be used as an alternative to rubidium titanyl phosphate for near- and mid-IR applications. To address the wavelength range between 700 and 3500 nm, the cells were built for fast rise-time and high repetition-rate operations with aperture sizes of up to 9 mm. The Pegasus Pockels Cell

solution's electro-optic figure of merit indicates a larger change of refractive index, which makes the crystal highly responsive to applied electric fields, and also work well with mid-infrared lasers, such as Er:YAG 2.94 µm, Er,Cr:YSGG 2.79 µm, Ho:YAG 2.10 µm, and Tm:YAG 2.01 µm.
info@gandh.com

Low-Profile Mirror Mount

Optical Surfaces Ltd.'s low profile mirror mount provides a secure platform for large and heavy high-precision flat, spherical, on-axis, and off-axis mirrors. Designed in black anodized aluminum, the mount can match the size and shape of the mirror in use in a compact low-profile envelope to enable optimization of alignment. In addition, angular alignment (tip and tilt) of mounted mirrors is achieved about the vertical and horizontal axes using dual-action adjusters with fine-screw and ultrafine differential micrometer action. The low-profile mirror mount also allows for rapid alignment of large mirrors and comes with a baseplate for mounting on optical tables.
sales@optisurf.com

Elevator Rotary Stages

The ATR-V-60-60 Series from **Optimal Engineering Systems** are compact elevator-rotary stages that can be used in laser drilling, machining, inspection, metrology, mirror and camera positioning, and photonics applications. Using a scissor lift design, the stages use roller bearings and slide rails to create a smooth motion and parallelism throughout the travel of the table. The ATR-V-60-60 Series stages are capable of continuous rotation due to their bearings and 90:1 worm gear and feature 120- $\times$ 80-mm tables, 60 mm +/− 2 mm of vertical travel, 60-mm diameter rotary stages, and a 5-kg load capacity.
sales@oesincorp.com

Laser Cleaning System

The CleanTech CR-3030 from **Laser Photonics Corporation** is a small form factor Class 4 dual-axis roughening laser for cleaning, roughening, and surface preparation. Supplied with an air-cooling system, the laser is 85% smaller than Laser Photonics' CleanTech 1500-CTHD and weighs ~70% less. The CleanTech CR-3030 features laser head overheat protection that displays the current temperature on the system monitor and halts operation if it surpasses 50 °C, and it has a smartphone app that allows mode changing via the mobile application.
fiberlaser@laserphotonics.com

UV Spectroradiometers

The CSS-45-UV and BTS256-LED-UV from **Gigahertz-Optik** are UV spectroradiometers for industrial, medical, and research applications. The CSS-45-UV detects UV LED irradiance from 200 to 400 nm and includes plug and play via USB with supplied software and the option to use it as a stand-alone remote detector head or with Gigahertz-Optik's CSS-D hand-held meter. The BTS256-LED-UV features a built-in 50-mm diameter integrating sphere for direct LED power measurements, the measurement of spectral UV measurements from 200 to 550 nm, and plug and play via USB with supplied software.
info-us@gigahertz-optik.com

PID Controller

The MLC Series from **Bristol Instruments** is a proportional-integral-derivative (PID) controller that can electronically control the frequency output of multiple lasers. The controller can work with laser wavelength meters and fiber-optic switches to provide a complete laser frequency stabilization system and can be used in experiments that require active regulation of laser frequency, such as laser cooling and trapping. The MLC Series features a frequency resolution of 200 kHz as well as the ability to detect and stabilize small frequency deviations of up to eight lasers.
info@bristol-inst.com

4-Axis Receiver

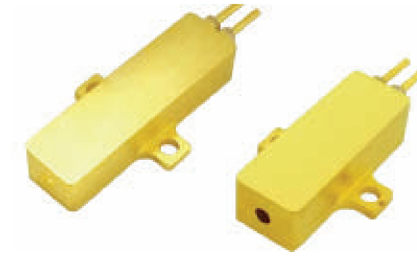
The Microgage Cylindrical 4-Axis Receiver from **Pinpoint Laser Systems** is suitable for industrial machinery alignment applications. The receiver measures two linear axes, x and y, and their two angular components, pitch and yaw, showing how well the machinery is aligned along a common centerline, and the angular readouts show whether parallelism problems are present. The Microgage Cylindrical 4-Axis Receiver uses a narrow laser as a reference line and operates over distances of 100 ft with a precision of 0.0005 in. and 0.005°.
info@pinpointlaser.com

Compact Oscilloscope

The MXO 5C series from **Rohde & Schwarz** is a compact oscilloscope for addressing rack mount and automated test system applications where users are confronted with space limitations. Doubling as a stand-alone bench oscilloscope, it comes in both four and eight channel models in bandwidth ranges with 100 MHz, 200 MHz, 350 MHz, 500 MHz, 1 GHz, and 2 GHz models. The MXO 5C series has a capture rate of up to 4.5 million acquisitions per second and features a vertical height of 8.9 cm, a channel density of 1500 cubed cm per channel, and an energy cost of 23 W per channel.
info@rohde-schwarz.com

Static Target Projector

The LWIR STP from **Optikos** is a longwave infrared fixed-focus static target projector for testing automotive thermal cameras and LWIR cameras. The projector projects a virtual object from a fixed distance using a remotely controllable illuminator and provides an onboard interface that allows users to set the source temperature locally, eliminating the need for a remote computer. The LWIR STP also features interchangeable collimator barrels and target assemblies, which enable users to customize the projector according to the camera under test.
sales@optikos.com



Eye Safe Laser Modules

The Eye Safe laser modules from **Electro Optical Components** is a family of compact laser modules for meteorological radar and laser range finding in drones or in military helmets. The modules produce lasers at 1535-nm wavelengths at a power of up to 1000 µJ, making them eye safe. The Eye Safe modules feature a 5- × 8- × 40-mm form factor, wide temperature range, and repetition rate of between 1 and 10 Hz.
info@eoc-inc.com

Dual Extended-Head Camera

The Phoenix Dual Extended-Head camera from **LUCID Vision Labs** is a gigabit Ethernet vision 2.0 camera for applications that require a wider field of view, including stereo vision systems, autonomous mobile robots, UAVs, and intelligent transportation systems. Using dual 5.0-MP sensors, the camera is equipped with two Sony IMX264 global shutter image sensors, each with a resolution of 2448 × 2048 pixels. The Phoenix Dual Extended-Head camera has a lightweight and compact 28- × 28-mm design that allows for integration into space-constrained setups.
sales@thinklucid.com

Granite-Based Wafer Stages

Physik Instrumente's (**PI**'s) granite-based multi-axis motion systems can be used for the automation of wafer metrology, glass substrate inspection, and lithography applications. Based on modular concepts, the stages are customizable with technologies including air bearings, rails-on-granite, direct drive motors, nanometer resolution encoders, and piezo drive systems. The granite-based systems can travel at ranges including a meter or more, depending on the configuration.
info@pi-usa.us

Industry Events

AUGUST

SPIE Optics + Photonics
(Aug. 18-22) San Diego.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/optics-and-photonics?SSO=1.

The 10th International Conference on Machine Vision and Machine Learning 2024 (MVML)
(Aug. 19-21) Barcelona, Spain.
Contact International ASET Inc., +1 613-834-9999, **info@mvml.org**; www.mvml.org.

SEPTEMBER

SEMICON Taiwan 2024
(Sept. 4-6) Taipei, Taiwan.
Contact SEMI Taiwan, +886 3-560-1777, **semicontaiwan@semi.org**; www.semicontaiwan.org/en.

European Optical Society Annual Meeting (EOSAM) 2024
(Sept. 9-13) Naples, Italy.
Contact Boglárka Selényi, **eosam@europeanoptics.org**; www.europeanoptics.org/events/eos/eosam2024.html.

World Molecular Imaging Conference
(Sept. 9-13) Montréal.
Contact World Molecular Imaging Society, +1 310-215-9730, **wmis@wmis.org**; www.wmis.org/wmic-2024-about.

CIOE
(Sept. 11-13) Shenzhen, China.
Contact China International Optoelectronic Exposition, +86 755-8629-0901, **cioe@cioe.cn**; www.cioe.cn/en.

SEMICON India 2024
(Sept. 11-13) Greater Noida, Delhi, India.
Contact SEMI India, **semiconindia@semi.org**; www.semi.org/en/connect/events/semicon-india-2024.

ECOC 2024
(Sept. 22-26) Frankfurt, Germany.
Contact VDE, +49 69-63080, **ecoc2024@vde.com**; www.ecoc2024.org.

Frontiers in Optics + Laser Science
(Sept. 23-26) Denver.
Contact Optica, +1 202-223-8130, **custserv@optica.org**; www.frontiersinoptics.com/home/.

MEDevice
(Sept. 25-26) Boston.
Contact Informa, +1 310-445-4273, **registration.ime@informa.com**; www.biomedboston.com/en/home.html.

W3+ Fair Jena
(Sept. 25-26) Jena, Germany.
Contact Antje Fuhr, +49 040-66-906-928, **antje.fuhr@fleet-events.de**; www.w3-fair.com/en/jena/.

OCTOBER

Neuroscience
(Oct. 5-9) Chicago.
Contact the Society for Neuroscience, +1 202-962-4000, **meetings@sfn.org**; www.sfn.org/meetings/neuroscience-2024.

SEMI MEMS & Sensors Executive Congress (MSEC)
(Oct. 7-9) Québec City.
Contact SEMI, **mfabiano@semi.org**; www.semi.org/en/connect/events/mems-sensors-executive-congress-msec.

AutoSens Europe
(Oct. 8-10) Barcelona, Spain.
Contact Sense Media, +44 (0)208-133-5116, **info@sense-media.com**; www.auto-sens.com/europe/.

VISION
(Oct. 8-10) Stuttgart, Germany.
Contact Landesmesse Stuttgart GmbH, +49 711-18560-0, **info@messe-stuttgart.de**; www.messe-stuttgart.de/vision/en/.

BioPhotonics Conference 2024
(Oct. 15-17) Virtual.
Contact Photonics Media, +1 413-499-0514, **conference@photonics.com**; www.photonics.com/bpc2024.

FABTECH
(Oct. 15-17) Orlando, Fla.
Contact SME, +1 313-425-3000, **information@fabtechexpo.com**; www.fabtechexpo.com.

Optica Laser Congress and Exhibition
(Oct. 20-24) Osaka, Japan.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/laser_congress.

SCIX
(Oct. 20-25) Raleigh, N.C.
Contact FACSS, +1 856-224-4266; www.scix-conference.org/.

Single-Molecule Sensors and Nanosystems International Conference — S3IC 2024
(Oct. 28-30) Paris.
Contact S3IC 2024 Organizing Committee, +33 1-46-60-89-40, **s3ic2024@premc.org**; www.premc.org/conferences/s3ic-single-molecule-sensors-nanosystems/registration.

SPIE PHOTONEX
(Oct. 30-31) Manchester, England.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/photonex.

PAPERS

Cell Bio
(Dec. 14-18) San Diego.
Deadline: Abstracts, Aug. 6
Contact ASCB, +1 301-347-9300, **info@ascb.org**; www.ascb.org/cellbio2024/.

SPIE Medical Imaging
(Feb. 16-20) San Diego.
Deadline: Abstracts, Aug. 7
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/medical-imaging.

SPIE Smart Structures + Nondestructive Evaluation
(March 17-20) Vancouver, British Columbia.
Deadline: Abstracts, Sept. 11
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/smart-structures-nde.

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

NOVEMBER

ICALEO
(Nov. 4-7) Hollywood, Calif.
Contact the Laser Institute of America, +1 407-380-1553; www.icaleo.org/.

EMVA Machine Vision Forum
(Nov. 7-8) Mulhouse, France.
Contact European Machine Vision Association, +34 931-80-70-60, **info@emva.org**; www.emva.org/events/more/european-machine-vision-forum-2024/.

SEMICON Europa 2024
(Nov. 12-15) Munich.
Contact SEMI Europe, +49 30-3030-8077-0, **semiconeuropa@semi.org**; www.semiconeuropa.org.

DECEMBER

SEMICON Japan 2024
(Dec. 11-13) Tokyo.
Contact SEMI, +81 3-3222-5755, **semijapan@semi.org**; www.semiconjapan.org/en.

Cell Bio
(Dec. 14-18) San Diego.
Contact ASCB, +1 301-347-9300, **info@ascb.org**; www.ascb.org/cellbio2024/.

JANUARY

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

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, Korea.
Contact SEMI, +82 2-531-7800, **semiconkorea@semi.org**; www.semiconkorea.org/en.

MARCH

Pittcon 2025
(March 1-5) Boston.
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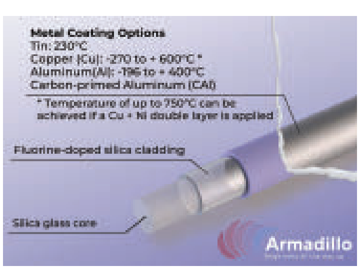

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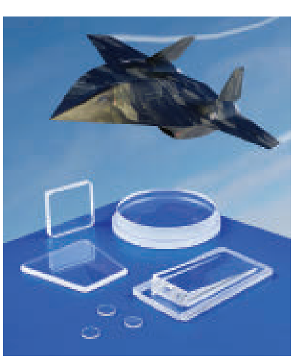

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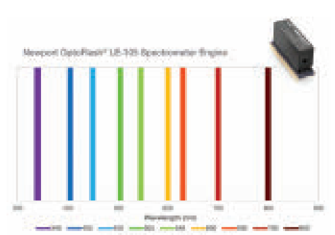

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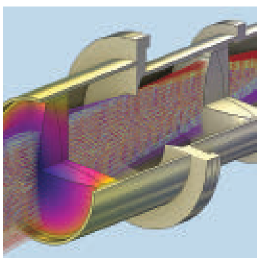

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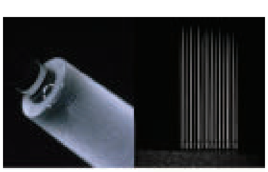
The NYFORS SMARTSPLICER



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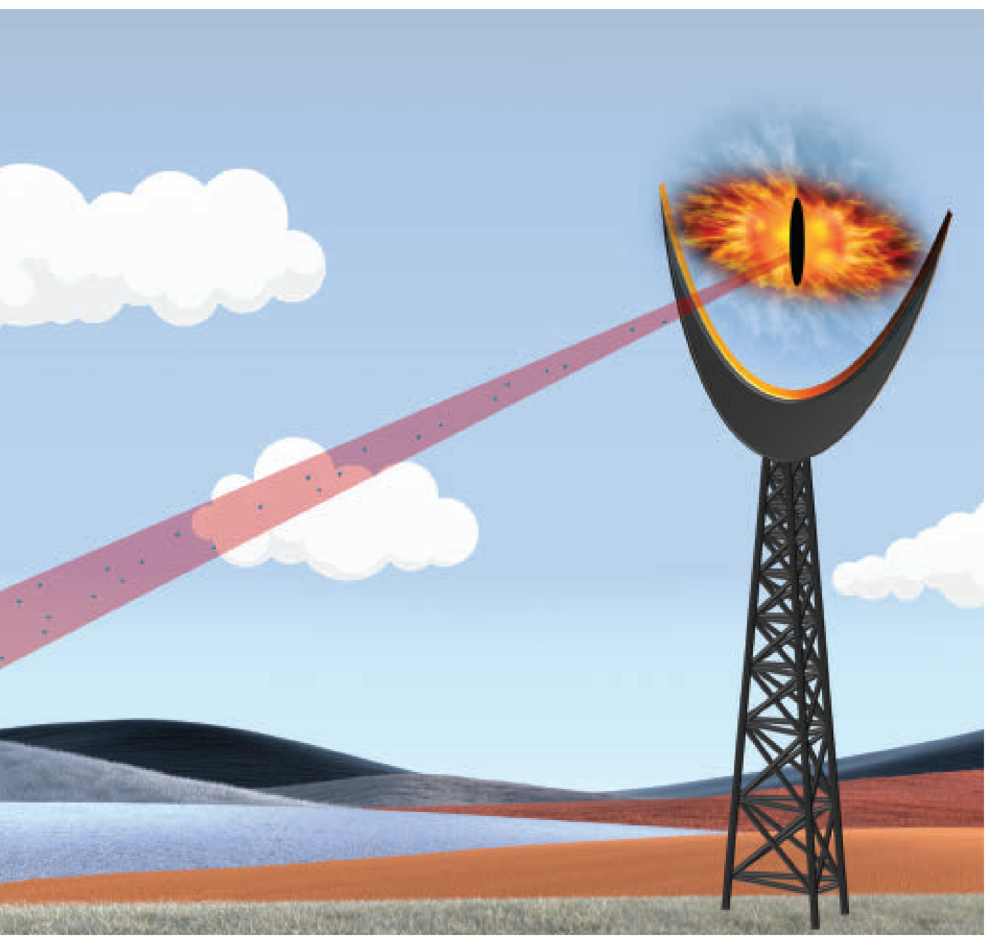
You … shall not … pass inspection!

The Lord of the Rings shares a precious few commonalities with the contemporary workforce. The journey that Frodo, Gandalf, and the rest of the fellowship undertook to the fiery mouth of Mount Doom to cast the one ring into the flames and rid Middle-Earth of an ancient evil, for example, may well extend beyond the rigors of your nine-to-five and day-to-day.

At the same time, invisible — though less overt — threats to our industrial workforce loom large. No one wants to find a leaky pipe in a worksite or manufacturing plant releasing dangerous chemicals in the form of aerosolized clouds into the surrounding air. Such a situation poses a health risk to everyone in the area.

But what if there were a device, perhaps one oddly reminiscent of the "dark lord," that could detect the noxious fumes before the emergence of a threat? What if such a high-fantasy mechanism could alert the appropriate response teams?

Funny you should ask.



A fellowship of engineers and chemists from the University of Colorado Boulder (CU Boulder), Caltech, University of California, Santa Barbara, and a trio of companies have come together to create a laser-based device the size of a small suitcase to analyze potential gas clouds before they can become dangerous. The ironically named SAURON, which stands for Standoff Aerosol measUrement Remote Optical Network, would be placed on top of towers in reminiscence of the iconic flaming eye.

Instead of serving as a hindrance to advancing hobbits, the network aims to deliver life-saving capabilities. The system uses frequency comb lasers, which parse through aerosol clouds, finding trace amounts of particles and detecting chemicals that pose health risks, such as polycyclic aromatic hydrocarbons, ammonium nitrate, and fentanyl. The effort is funded by a multimillion-dollar contract from the federal office of the director of national intelligence.

According to principal investigator and professor of mechanical engineering at CU Boulder Greg Rieker, the SAURON system contrasts other devices of the same name, in that it runs on batteries rather than a dark, arcane power. This means that the engineered system will be able to be integrated in well-trod and infrastructure-crowded areas, such as airports, city blocks, and industrial sites.

Embarking on their own great journey, the researchers hope to make their lasers even more sensitive and compact through the development of integrated photonic chips, in collaboration with companies Nexus Photonics and hQphotonics.

In the meantime, perhaps it wouldn't hurt to see whether the system could be fine-tuned to find physical objects such as, maybe, a gold ring of power or other items that people might find, in a word, *precious* …

Image courtesy of Greg Rieker.

Precision *Laser Diode Controller*

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