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September 2024

PHOTONICS spectra®

THE Optics Issue

PHOTONICS MEDIA
LAURIN PUBLISHING

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Helios Y Imaging Colorimeter NEW

Highlights

- Supports several EF mount lenses
- Optional OD filter
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- Dark current compensated

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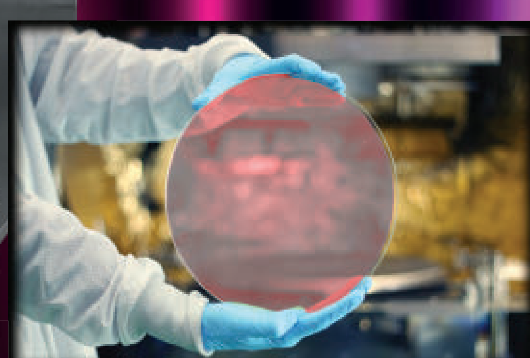

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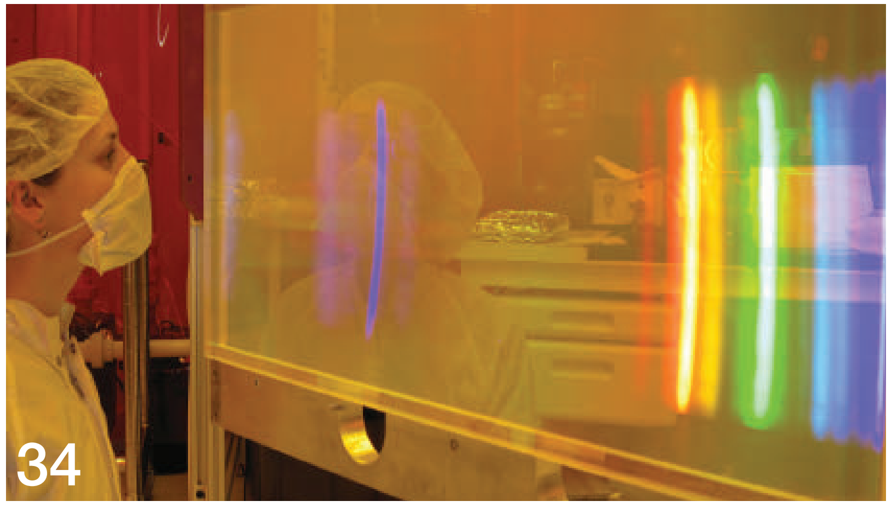
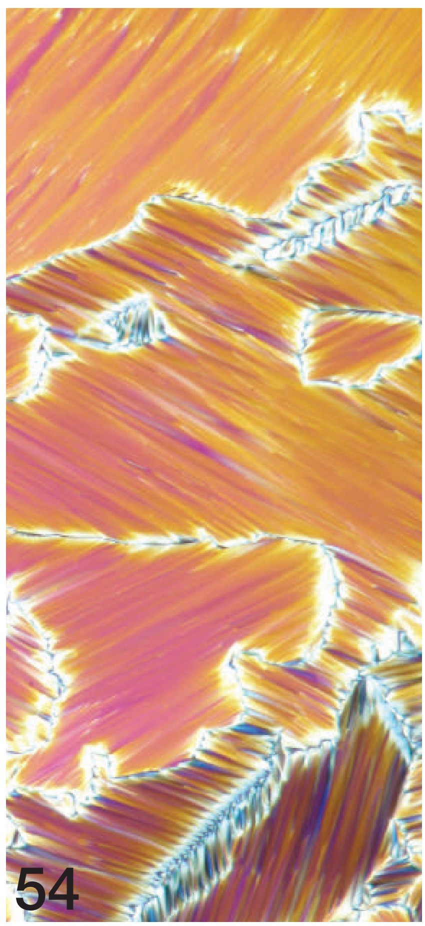
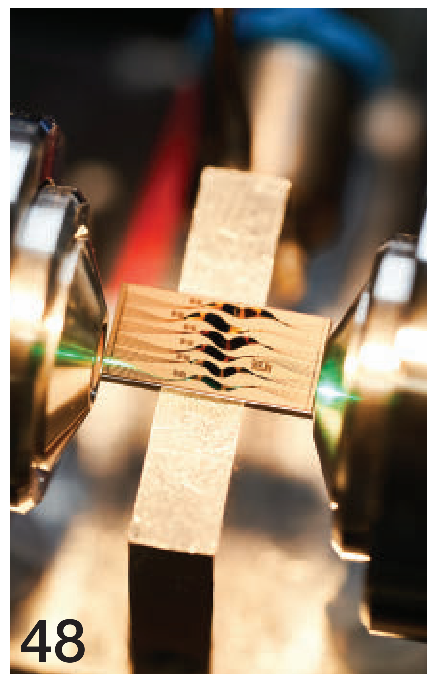
September 2024 volume 58 issue 9

Features







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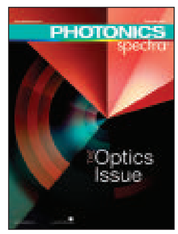
Departments

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

Columns



The Cover

Optical component and instrument designs are fueling progress in industry, aerospace and defense, and the life sciences, with many sophisticated designs enabling improved test and measurement protocols. At the same time, these optics require new characterization schemes. Image courtesy of iStock.com/Goettingen. Cover design by Senior Art Director Lisa N. Comstock.

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Editor's Note

New wisdom abounds

Since its first issue in 1967, *Photonics Spectra* has been proud to champion advancements in optics and photonics. Today, more than half a century later, this undertaking still serves as this magazine's goal as well as its mission.

The *Photonics Spectra* Editorial Advisory Board is integral to this goal and central to this mission. As a collective body, and through its individual members, it is a dynamic resource for the editors of this publication.

And this month, after many weeks of anticipation, the board is set to expand. We are pleased to welcome four distinguished industry professionals to our Editorial Advisory Board: Joseph Spilman; Bruno Gross; Robert Bourdelais; and Scott Bass.

These appointments mark an exciting time and signal a momentous rise in emergent technologies — quantum, integrated photonics, and automation, to name a few — that are poised to feature prominently in the years to come. Broadening our expertise will greatly enhance our ability to cover photonics as an industry, field, and community in a way that draws on lessons from the past and present to anticipate and inform the future.

Our ability to do so is paramount to promote robust, meaningful dialogue among photonics engineers, scientists, and system end users.

An announcement and introduction to *Photonics Spectra*'s new Editorial Advisory Board members can be found on page 10, and a complete list of board members can be found on this page.

September also marks our annual Optics Issue. In this year's edition, industry contributors Flemming Tinker (Aperture Optical Sciences) and Tom Baur and Michael Kraemer (Meadowlark Optics) discuss large-format optics and optical materials, respectively. Along with contributing editor Marie Freebody, Tinker, Baur, and Kraemer present three different inroads to consider the indelible relationship that exists between optics and metrology.

Luceda Photonics' Chiara Alessandri, JFS Laboratory's Beibei Wu, Cailabs' Jean-François Morizur, and Power Technology's William Burgess also feature in this issue.

The additions of Joseph Spilman, Bruno Gross, Robert Bourdelais, and Scott Bass to the Editorial Advisory Board could not have come at a better time. While it is their profound industry knowledge that brings them to the board this September, it is their shared passion for optics that further aligns this issue with the announcement.

jake.saltzman@photonics.com

Editorial Advisory Board

Robert R. Alfano, Ph.D
City College of New York

Joel Bagwell
Elbit Systems of America LLC

Scott Bass
Edmund Optics

Robert Bourdelais
MKS/Newport Corp.

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Crocombe Spectroscopic Consulting

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WTP Optics

Ryszard S. Romaniuk, Ph.D.
Warsaw University of Technology, Poland

Joseph Spilman
Optimax Systems Inc.

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Contributors

Chiara Alessandri
Chiara Alessandri is product marketing and technical sales manager at Luceda Photonics. She oversees market research, positioning, and messaging efforts, and works with ecosystem partners and in customer collaboration for the design software and services provider. Page 48.

Michael Kraemer
Michael Kraemer holds a master's degree in mathematics and doctorates in both physics and mathematics. He has worked as a software engineer for 24 years. His research interests include tunable filters, ellipsometry, and achromatic polarization devices. Page 54.

Tom Baur
Tom Baur is the founder and board chairman of Meadowlark Optics. He focuses on product development, bringing new materials to the photonics community for polarization control and improving metrology for polarization components. Page 54.

Jean-François Morizur
Jean-François Morizur is cofounder and CEO of Cailabs. He holds a Ph.D. in quantum optics from the Australian National University and the Université Pierre et Marie Curie and is co-inventor of Cailabs' multiplane light conversion (MPLC) technology. Page 63.

William Burgess
William Burgess is co-CEO of Power Technology Inc., a member of the Laser Institute of America (LIA), and an SPIE senior member. He is also a member of the ANSI Z136.1 committee responsible for writing and maintaining the "Safe Use of Lasers" standards. Page 60.

Flemming Tinker
Flemming Tinker is the founder and president of Aperture Optical Sciences Inc. He has been a developer of large optics and imaging technologies for more than 35 years and has advised optics companies worldwide. Page 34.

Marie Freebody
Contributing editor Marie Freebody is a freelance science and technology journalist with a master's degree in physics from the University of Surrey in England. Page 42.

Beibei Wu
Beibei Wu is a senior engineer of silicon photonics at JFS Laboratory. She worked in silicon photonics/lidar R&D at Chongqing United Micro-Electronics Center. She received her doctorate in optical engineering from Huazhong University of Science and Technology. Page 48.

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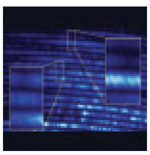
Measuring Starlight with an Ultrafast Laser: Astrocomb Development for the Extremely Large Telescope



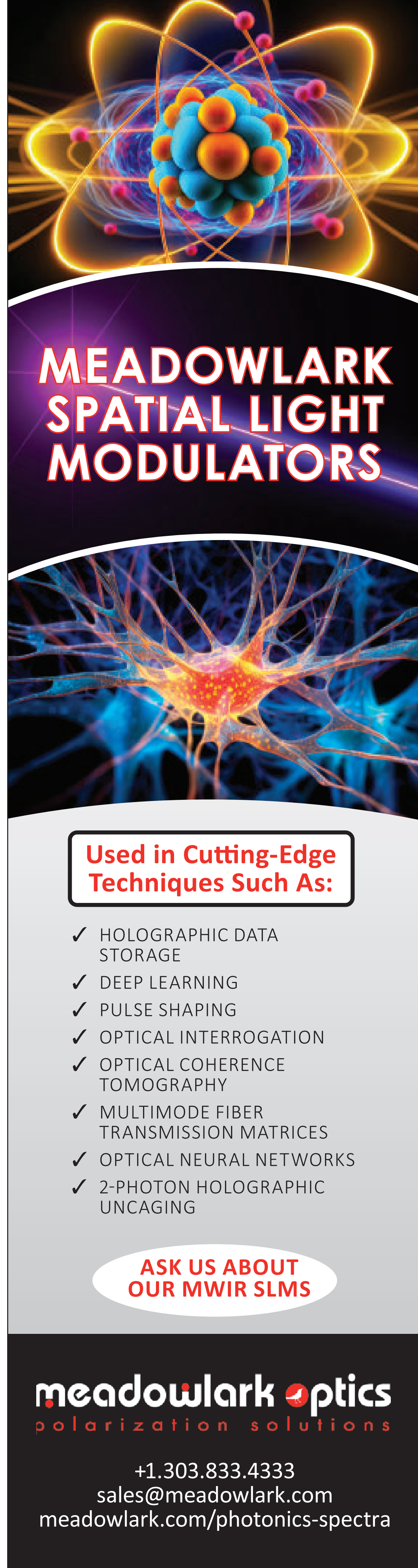
Heriot-Watt's Yuk Shan Cheng explores the role of the Extremely Large Telescope's ANDES spectrograph and its need for a high precision frequency calibrator. She focuses on the development of astrocombs, which, despite their demonstrated success, pose integration challenges in modern telescope facilities. This presentation includes approaches to these challenges, recent implementation at the Southern African Large Telescope, and advancements in astrocomb technology at Heriot-Watt, including the development of a continuous UV-blue/green astrocomb.
To view, visit **www.photonics.com/w997**.

Industry Innovations in Fiber-Based Frequency Combs: Ultrabroadband Comb with Sub-3-kHz Free-Running Linewidths

Femtosecond frequency combs represent unparalleled measurement tools with applications in spectroscopy, metrology, and quantum physics. This discussion delves into the critical aspects of maximizing the passive stability of these instruments. Researchers have identified distinct minima where the carrier-envelope offset frequency (fCEO) drops below 1 kHz. Details on individual comb lines unveil the contributions to phase noise and their interplay. This presentation showcases the development of frequency combs with sharp teeth at designated positions throughout the spectrum from fCEO to 300 THz.
Sponsored by Toptica.
To view, visit **www.photonics.com/w1005**.

Reflective Optics for Multispectral EO Systems

Large reflective optics are essential for high-performance multispectral electro-optics imaging systems. These systems capture wavelengths to improve target identification and offer a comprehensive environmental view. They excel in adverse conditions by penetrating smoke and challenging weather. Using advanced data fusion, these systems enhance target recognition, adapt to surveillance and disaster response, and minimize necessary maneuvers. Join MKS Ophir for an insightful webinar on the advancements in reflective optics for multispectral systems.
Presented by MKS Ophir IR Optics.
To view, visit **www.photonics.com/w1043**.



Photonics Spectra Magazine Adds Four Industry Leaders to Editorial Advisory Board

Edmund Optics

Scott Bass.

MKS/Newport Corp.

Robert Bourdelais.

Thorlabs

Bruno Gross.

Optimax

Joseph Spilman.

Photonics Spectra is pleased to announce the appointment of four distinguished professionals to its Editorial Advisory Board. These appointments reflect the magazine's commitment to maintaining the highest standards of expertise and insight in the field of photonics.

The appointments, effective immediately, increase the number of *Photonics Spectra* Editorial Advisory Board members to 15 optics and photonics luminaries.

The new Editorial Advisory Board members:

Scott Bass, Edmund Optics

Scott Bass is vice president, global marketing and corporate communications at Edmund Optics, a leading optical solutions provider with product and manufacturing solutions supporting the industrial inspection, semiconductor, and life sciences/biomedical sectors. An SPIE board advisor, Bass chairs the SPIE Corporate & Exhibitor Committee and is a member of the SPIE Board Artificial Intelligence (AI) Presidential Task Force. Bass leads programming and development efforts for Edmund's Innovation Summit Series.

Robert Bourdelais, MKS/Newport Corp.

Robert Bourdelais is senior global business development manager at MKS/Newport. In more than three decades in the photonics industry, Bourdelais has held leadership positions in engineering, R&D, operations management, and product management. He is the author of more than 200 issued patents and a past recipient of the Eastman Innovator award. His technical areas of expertise include LCDs & OLED displays, medical devices, microelectronics, digital imaging, polymer chemistry, and optics.

Bruno Gross, Thorlabs Inc.

Bruno Gross is vice president of Thorlabs, Europe and an expert in laser technologies and photonics applications. Gross has served in a variety of director and senior management roles within the photonics industry, including as managing director of Menlo Systems; managing director of ZETT OPTICS; and general manager of Thorlabs GmbH. He also served as a consultant with McKinsey and Company prior to joining Menlo Systems upon its entry into a long-term collaboration with Thorlabs in 2002.

Joseph Spilman, Optimax Systems Inc.

Joseph Spilman is president of Optimax, a global optics manufacturer and solutions provider in Ontario, N.Y. Under Spilman's leadership, Optimax has advanced in its role as a leading market provider of precision and laser-grade optics and optical components, and stands as a pillar of the Rochester, N.Y., precision optics ecosystem. The company recently launched Starris: Optimax Space Systems, a business focused on the development of space-qualified optical payloads.

Photonics Spectra looks forward to the contributions of its new board members, who will help shape the future direction of the magazine and ensure that it remains an essential resource for professionals in the photonics community.

A complete listing of the advisory board can be found on page 7.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BioPhotonics Conference
Showcases Advancements in High-Speed Imaging and Tissue Analysis

During the *BioPhotonics* Conference, innovators and leading practitioners across the spectrum of the biophotonics landscape will spotlight advancements in system design and biomedical and life sciences application. The online event takes place October 15 to 17 and features sessions from technology developers and scientists from the optics and photonics industry and academic sectors.

Luminary figures as well as startup companies and established players feature in this year's program. Sessions will focus on trends in microscopy, imaging, and spectroscopy in specific program tracks. Selected topics include STED microscopy, compact microscopes, tunable femtosecond lasers, broadband spectroscopy, clinical imaging, linear optics, and nonlinear optics.

Keynote speakers discuss methods, assessment in imaging

Three technology tracks, one on each day of the conference, kick off on October 15. Advancements in live-cell imaging and interactions will take center stage.

Afrouz Anderson, a program director at the National Institute of Biomedical Imaging and Bioengineering (NIBIB), begins the conference with her keynote session during the Microscopy track. The talk, titled "Optical Imaging and Spectroscopy at the National Institute of Biomedical Imaging and Bioengineering," highlights NIBIB's partnerships and programs. These initiatives include rapid acceleration of diagnostics (RADx), NIBIB-supported phantom libraries, development of optical imaging phantoms, quantum sensing in biomedical applications, and various training opportunities.


Afrouz Anderson.


Christian Huck.


Stephen Boppart.

The Spectroscopy track will be keynoted by Christian Huck, professor of analytical chemistry at the University of Innsbruck. Huck will discuss the usefulness of vibrational spectroscopy in bioanalysis due to its tested short analysis times, noninvasiveness, and potential

Biophotonics luminaries Afrouz Anderson, Christian Huck, and Stephen Boppart discuss insights into brain functioning and origins of disease in their keynote programs.

for screening chemical and physical properties simultaneously. This is supported by the popularization of the miniaturization of spectrometers in research and industry.

Closing out the online conference, the Imaging track will feature a keynote presentation from Stephen Boppart, professor and chair in engineering at the University of Illinois Urbana-Champaign, focusing on multimodal imaging in tumor margin assessment. For many surgical oncology procedures, exceedingly high positive margin rates indicate that tumor cells are often left behind in the patient. Boppart and his team are developing a multimodal multiscale approach that uses optical coherence tomography (OCT) imaging of the large-area tumor cavity with switchable high-resolution subcellular nonlinear optical imaging (NLOI) for generating real-time digital histopathology images. AI algorithms have been developed to screen incoming OCT images to alert the surgeon to suspicious areas.

Influential names

Returning and first-time presenters will provide the latest updates on existing technologies and introductions to trends in devices and techniques that have been incorporated into ongoing life sciences and clinical research. Aydogan Ozcan will return to present on feature analysis using programmable diffraction with digital neural networks along with Ocean Optics senior product scientist, Derek Guenther, who will speak on using broadband spectroscopy in the detection of per- and polyfluoroalkyl substances in water. They will be joined by Juliet Gopinath (University of Colorado Boulder) and Charles Lin (Harvard Medical School) in the Microscopy track; Alexis Weber (University at Albany, State University of New York) and Fay Nicolson (Dana-Farber Cancer Institute) in the Spectroscopy track; and Mihaela Balu (University of California, Irvine) and Francesco Saverio Pavone (University of Florence) in the Imaging track.

In addition to prominent names in research, representatives from companies such as Hamamatsu Corporation, Ocean Optics, Evident Scientific, Zaber Technologies, Teledyne Princeton Instruments, and MKS Ophir will discuss topics in all three trends.

Register now

Registration for the 2024 *BioPhotonics* Conference is open now. To reserve your spot and find updates and information, visit **www.photonics.com/bpc2024**. The webcast will be recorded and available on demand.

BioPhotonics
Bringing Light to the Life Sciences
CONFERENCE
October 15-17, 2024

MICROSCOPY

KEYNOTE:
Optical Imaging and Spectroscopy at the National Institute of Biomedical Imaging and Bioengineering
Afrouz Anderson, National Institute of Biomedical Imaging and Bioengineering

Advancements in STED Microscopy Provide a Window into the Brain
Juliet Gopinath, University of Colorado Boulder

Compact Microscope System Design: Symmetry Principles, Modalities, and Applications
Ronian Siew, Venture Biotech Modules Business and Rebecca Charboneau, Edmund Optics

Designing a Custom Fluorescence Illumination System
TBA, CoolLED

Imaging the Hematopoietic System: From Mice to Humans
Charles Lin, Harvard Medical School

Integration of Programmable Diffraction with Digital Neural Networks Supports Feature Analysis
Aydogan Ozcan, UCLA

Live-Cell Imaging Applications Drive Component and Wavelength Selection for Hyperspectral Microscopy
Mike Fussell, Zaber Technologies

Microscope Objective Design Considerations for Spatial Biology and Digital Pathology
Steve Briggs, Evident Scientific

Sub-Nanometer Resolution of Protein-DNA Interactions Enabled by pMINFLUX and Graphene
Philip Tinnefeld, The Ludwig Maximilian University of Munich

Tunable Femtosecond Lasers for Bioimaging: Balancing Energy and Power
Dariusz Świerad, Fluence.technology

SPECTROSCOPY

KEYNOTE:
The Use of Vibrational Spectroscopy in Natural Product and Bioanalysis
Christian Huck, University of Innsbruck

In Situ Detection of Gold Colloid Aggregates in Alzheimer's Disease
Kazushige Yokoyama, State University of New York at Geneseo

Raman Spectroscopy and Self-Referencing Algorithm Differentiate Human and Nonhuman Blood
Alexis Weber, University at Albany, State University of New York

Swept-Source Raman Provides Large-Scale Real-Time Monitoring
Nili Persits, MIT

TD-NIRS Produces Quantitative and Reliable Tissue Oximetry
Michele Lacerenza, PIONIRS

Unveiling Deep-Seated Tumors with SESORRS
Fay Nicolson, Dana-Farber Cancer Institute

Using Broadband Spectroscopy to Detect PFAS in Drinking Water and Biological Samples
Derek Guenther, Ocean Optics

Wide-Field Superresolution Photothermal Infrared Spectroscopy and Imaging of Biological Materials
Mustafa Kansiz, Photothermal Spectroscopy Corporation

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Environmental Sensing,
Lidar, Metrology

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IMAGING

KEYNOTE:
Intraoperative Multimodal Imaging Provides Multiscale Tumor Margin Assessment
Stephen Boppart, University of Illinois Urbana-Champaign

2D & Time-Gated Imaging with SPAD Arrays
Slawomir Piatek, Hamamatsu Corporation

Advanced Clinical Skin Imaging with Label-Free Multiphoton Microscopy
Mihaela Balu, University of California, Irvine

All-Optical Electrophysiology in the Brains of Behaving Animals
Adam Cohen, Harvard University

Large Sensors and High-Speed sCMOS Cameras Enable Discovery
Joseph Deasy, Teledyne Princeton Instruments

Lasers in Health and Medicine
Nathan Brouwer, MKS Ophir

Lighting up the Brain: From Qualitative to Quantitative Methods to Guide Brain Tumor Surgery
Pablo Valdes Quevedo, University of Texas at Austin

Linear and Nonlinear Optical Imaging Enable Large-Area Brain Morpho-Functional Imaging
Francesco Saverio Pavone, University of Florence

Canon to produce coating materials for perovskite solar cells

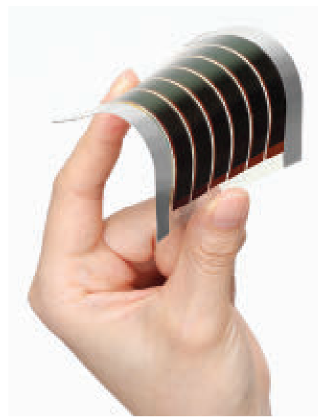
Canon developed a functional high-performance semiconductor material that it expects will improve the durability and mass-production stability of perovskite solar cells, the company said. Canon began shipping samples in June and expects to begin mass production next year.

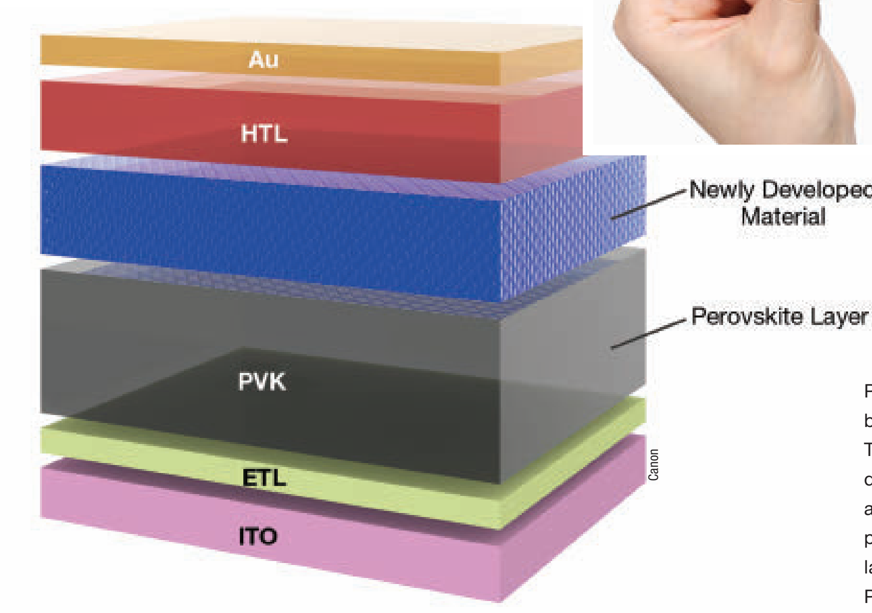
While perovskite solar cells offer advantages compared with silicon-based cells in terms of weight, flexibility, and the ability to generate electricity from indoor lighting, their commercialization has been hindered by issues with stability as well as challenges in manufacturing cells with a large surface area. The crystal structure of the perovskite layer, which facilitates photoelectric conversion, is susceptible to damage by water, heat, oxygen, and other atmospheric factors, which leads to low durability.

The functional material developed by Canon provides a thick coating over the perovskite layer while maintaining a high rate of photoelectric conversion efficiency, which has been difficult to achieve with conventional materials, Canon said. The material can be coated at a thickness of 100 to 200 nm, compared with conventional coating layers, which provide a thickness of just tens of nanometers.

Following initial development, Canon said that it plans to collaborate with companies engaged in mass production of perovskite solar cells.

A paper co-authored by researchers at Toin University of Yokohama and Canon was published in the *Journal of Materials Chemistry A* (www.doi.org/10.1039/D4TA02491E).





Perovskite solar cells could achieve mass production by adding a coating developed by Canon to their structure. The coating is expected to provide protection against degradation due to environmental factors, such as water and heat, which have historically hindered the adoption of perovskite-based solar cells. ETL: electron transport layer; HTL: hole transport layer; ITO: indium tin oxide; PVK: polyvinylcarbazole.

PhotonDelta expands to U.S. with California office

Netherlands-based photonic chip accelerator PhotonDelta opened an office in California, supporting its growth of the photonic chip industry by facilitating collaboration between European and North American organizations. Backed by $1.2 billion to run R&D programs, international road mapping activities, and investment activities in startup companies, PhotonDelta's new office seeks to bridge complementary technologies — namely, silicon photonics in North America, with European expertise in materials such as indium phosphide.

PhotonDelta considers this combination to be critical for the creation of active components and silicon nitride to make sensors and quantum processors. The Netherlands is a leader in integrated photonics technology, with the highest concentration of photonic chip technology organizations in the world and considerable expertise in indium phosphide and silicon nitride-based chips. The U.S. and

North America have complementary expertise in silicon photonics and benefit from extensive manufacturing experience and infrastructure for CMOS processes.

"The integrated photonics industry is not a national industry, it's a global industry," said Jorn Smeets, PhotonDelta's North American managing director. "We need to make sure that we connect to the organizations that are good at things that are relevant or necessary to bring the industry forward and work together."

In the U.S. and North America, Smeets said, there are many organizations working in integrated photonics, and silicon photonics in particular. Due to geographic reasons, collaboration with these organizations is difficult.

"You need to have someone on the ground that is in the same time zone that can meet on shorter notice and attend networking events," Smeets said.

Helping to solve North American challenges in integrated photonics through collaboration and investment is something that will be broadly beneficial, both in North America and in the Netherlands, Smeets said. To that end, PhotonDelta is working to establish partnerships with prominent American industry organizations and businesses, not only for technological collaboration, but also for promoting a general awareness of the technology.

One major impetus behind this is to bolster the workforce, for which the organization has set aside considerable funds. According to Smeets, these efforts may include university exchange programs. "That's going to be a win-win, if we can overcome these challenges and make technology for multiple markets, create new applications, and produce efficiently in high volumes to make the technology affordable," Smeets said.

The PhotonDelta ecosystem comprises 70 organizations that form a complete value chain, including design services, foundries for photonic chip fabrication, packaging, test, and assembly as well as several fabless companies that use PIC technology for solutions.

During the past five years, PhotonDelta has raised more than $500 million within the country's burgeoning startup scene.

Joel Williams, News Editor
joel.williams@photonics.com

This month in history

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

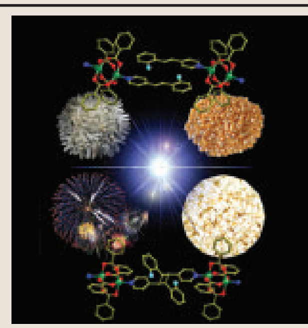
1994

A robotic device from Lawrence Livermore National Laboratory was created to provide the Lick Observatory with the ability to capture up to 100 images at once. The device, called the automated multi-object spectrometer (AMOS), placed up to 100 fiber optic computer program-controlled leads on the focal plane of the telescope to track celestial bodies.

2004

Scientists at the University of Applied Sciences Münster tried to generate up to 7 W of single-frequency power by diffusion-bonding a thin Nd:YAG disk to an undoped YAG nonplanar ring oscillator (NPRO). In later experiments, the scientists planned to adjust the NPRO geometry while replacing the implemented Gaussian pump beam with a flat top profile.

2014



A team led by researchers at the National University of Singapore suggests the microscopic phenomenon could find macroscopic applications turning sunlight into mechanical energy. The research showed that UV light sources, such as the sun, could be used to trigger chemical reactions that drive practical mechanical motions.

2019

Researchers at Okinawa Institute of Science and Technology discovered that adding a protective layer of epoxy resin to the top of a perovskite solar cell can significantly reduce the amount of lead that the cell discharges into the environment. They also found that the epoxy could partially return the cell to its original shape under direct sunlight if the cell was damaged.

DigiLens to develop reality solutions for U.S. government

Y-12 National Security Complex

Ashley Stowe **(left)**, director of the Oak Ridge Enhanced Technology and Training Center (ORETTC) for Consolidated Nuclear Security at the Y-12 National Security Complex, and Chris Pickett, CEO of DigiLens.

DigiLens, a developer of optical technologies for VR and AR applications, signed a memorandum of understanding with federal contractor Consolidated Nuclear Security, operator of the Y-12 National Security Complex, to collaborate on extended reality (XR) technologies, including in VR, AR, and mixed reality waveguides and head-up displays. DigiLens will collaborate with the Oak Ridge Enhanced Technology and Training Center (ORETTC) to develop technologies in support of U.S. government missions, including the integration of wearable computers and smart glasses to enhance immersion. ORETTC is leading Y-12's efforts in XR.

"The Y-12 partnership will focus on advancing sensor integrations and developing a total solutions package … tailored to support advanced maintenance repair and operations, and situational awareness for first responders, maintainers, and operators," said Brian Hamilton, DigiLens vice president of sales and marketing.

According to Y-12, DigiLens' ARGO AR/XR smart glasses device adheres to many of the requirements for U.S. government AR solutions, such as modularity for future products, high display transparency for improved situational awareness, and low eye glow. The glasses are built to military specifications and compliance-based ruggedization.

"We believe the lightweight size and functionality compared to the bulkier headsets will help adoption of AR within manufacturing where extended use is required," said Ashley Stowe, director of ORETTC.

Briefs

ZEISS opened an R&D and manufacturing site at the Suzhou Industrial Park in Suzhou, China. The 13,000-sq-m site will be used to produce industrial quality solutions, research microscopes, surgical microscopes, and ophthalmic equipment. This opening marks the group's first land purchase for its self-built project in China.

MKS Instruments unveiled its plans to build a super center factory in Penang, Malaysia, to support the production of wafer fabrication equipment in the region and globally. According to MKS CEO John T.C. Lee, the planned facility's location provides proximity to customers and suppliers, and benefits from a strong semiconductor ecosystem. MKS expects to construct the new facility in three phases beginning in early 2025.

Wave Photonics, a developer of technologies for the adoption of integrated photonics, secured a £4.5 million ($5.7 million) investment led by the U.K. Innovation & Science Seed Fund and Cambridge Enterprise, taking the company's total funding to date to £5.4 million. The money will be used for the development of on-chip photonics designs for quantum technologies, sensors, biosensing, and data center applications.

Goodfellow, a supplier of metals and materials, acquired microfabrication company **Potomac Photonics**. According to Goodfellow, the acquisition strengthens its presence in the medical device and microfluidics sectors and provides an immediate manufacturing footprint in the U.S. Potomac Photonics, based in Baltimore, holds capabilities in the micromachining of materials, including polymers, metals, ceramics, and glass with micron-scale features.

Thermo Fisher Scientific Inc., a medical technologies company, completed its acquisition of **Olink Holding AB**, a provider of proteomics solutions. The transaction values Olink at approximately $3.1 billion with a net of $96 million of acquired cash. Olink will become part of Thermo Fisher's Life Sciences Solutions segment.

Nikon Corporation, a developer of optoelectronics-based technologies, plans to relaunch subsidiary **Morf3D** as **Nikon AM Synergy Inc.** The rebranding includes new leadership and a shift from the former general-purpose contract manufacturing service bureau business, leading to the closure of the El Segundo, Calif., location and the divestment of nonessential equipment. The subsidiary will instead operate from Nikon's advanced manufacturing business unit facility in Long Beach, Calif. Simultaneously, Nikon is planning the relocation of its global corporate headquarters within Tokyo.

NY CREATES, a nonprofit focused on semiconductor-based R&D, and South Korea's **National Nanofab Center**, a public organization for providing semiconductor technology services, entered into a partnership that aims to develop a shared hub for enabling joint research, aligned technology services, testbed support, and the creation of an engineer exchange program to bolster chips-centered R&D and workforce development.

The Economic Development Administration, a part of the U.S. Department of Commerce, awarded a $41 million federal grant to Montana's **Headwaters Regional Technology and Innovation**

Nokia strikes deal to acquire optical networking leader Infinera

Nokia reached an agreement to acquire Infinera in a deal worth $2.3 billion, valuing the optical networking solutions provider at $6.65 per share. The transaction will boost Nokia's position in optical technologies and increase its exposure to webscale customers, both of which have been strategically targeted by Nokia.

The deal comes amid the forecasted and ongoing AI boom, necessitating optical network scale-up and the sustained development of optical communications technology. The combination is expected to increase the scale of Nokia's Optical Networks business by 75% and will allow it to accelerate its product road map timeline and breadth, the company said.

Specifically, the acquisition expands Nokia's expertise in digital signal processor development, silicon photonics, and indium phosphide semiconductor materials sciences, and provides deeper competency in photonic integrated circuit technology.

Internet content providers make up >30% of Infinera's sales, and its presence in the North American optical market represents ~60% of its sales, which improves Nokia's optical scale in the region, and complements Nokia's positions in Europe, Asia-Pacific (excluding China), and other regions. Infinera's recent achievements in in-line systems and pluggables, as well as in the development of high-speed, low-power optical components for intra-data center applications suited for AI workloads, provide the combined business with a strong position in burgeoning market areas, according to the companies.

Nokia aims to achieve €200 million (approximately $214 million) of net comparable operating profit synergies by 2027, and the transaction, along with the recently announced sale of Submarine Networks, will create a reshaped network infrastructure to meet these goals, according to the company. This infrastructure, the company said, is to be built on fixed networks, IP networks, and optical networks.

The transaction will be split between at least 70% cash and up to 30% stock. The deal has been approved by the boards of both Nokia and Infinera and is slated to close during the first half of 2025.

$11.2B

— the estimated value of the global thin-film photovoltaics market by 2028, according to MarketsandMarkets

Hub. The hub is a consortium of organizations, including Montana State University, with the goal of developing smart photonic sensing systems that can be deployed in autonomous systems and applied to critical defense, resource management, and disaster prevention applications. The grant is part of a collection of 12 investments that are being awarded by the Economic Development Administration to technology hubs across the U.S., totaling $504 million.

The **University of Colorado Boulder** (**CU Boulder**) received a $20 million grant from the U.S. National Science Foundation to launch the **National Quantum Nanofab**, a facility for researchers and quantum specialists to design and fabricate quantum devices. The facility will take an estimated five years to be completed.

Semiconductor facilitator and accelerator **CMC Microsystems** and **Innovation, Science, and Economic Development Canada** (**ISED**) launched FABrIC, an initiative meant to provide financial and technical resources, mentorship, and training for semiconductor businesses, engineers, and scientists in Canada. Powered by a 120 million CAD ($88 million) investment from ISED's Strategic Innovation Fund, FABrIC will enable the training of 25,000 students and 1000 professors over five years and will provide Canadian universities and colleges with technical resources for students and researchers to design and manufacture advanced semiconductor devices during their studies.

Thermal imaging and sensors developer **InfraTec GmbH Infrarotsensorik und Messetechnik** finished the construction of an extension building in Dresden, Germany. In addition to new offices, the extension includes production and development areas for thermography cameras and infrared detectors over a total area of 2700 sq m. The construction was backed by a €20 million ($21.4 million) investment by the Development Bank of Saxony.

Full-stack photonic quantum computing systems provider **ORCA Computing** is leading a collaborative R&D consortium, including members **Toshiba Europe Ltd.**, **Bay Photonics Ltd.**, **Imperial College London**, and **University College London**, to develop multiplexing technologies to advance quantum networking for use in quantum computing and data centers. The consortium plans to create a suite of technologies, such as quantum memories, frequency shifters, and spatial switches, to be operated in tandem. According to the consortium members, this will allow networking to take place within and between quantum computers to exponentially scale to performance levels necessary for industrial scale quantum computing and networking.

Photonic smart coatings company **SunDensity Inc.** established a wholly owned subsidiary, **SunDensity Canada**, through the acquisition of solar materials startup **QD Solar Inc.** The asset acquisition agreement allows the organizations to explore a wider range of materials and processes for solar applications and will accelerate technology development, SunDensity said. QD Solar CEO Dan Shea, CTO Sjoerd Hoogland, and COO and lead chemist Armin Fischer will transition to COO and general manager, CSO, and CIO and chief chemist, respectively. The terms of the acquisition were not disclosed.

Upgraded Advanced Photon Source delivers first light

Argonne National Laboratory/Jason Creps

Mohan Ramanathan, associate project manager of the APS Upgrade, opens the shutter at the 27-ID beamline, letting in light for the first time since the facility paused its operations in April 2023.

The Advanced Photon Source (APS) delivered its first x-ray beams to a scientific beamline following completion of a planned upgrade. Operations were suspended during the past year while the original electron storage ring, responsible for producing x-ray beams, was removed to make way for a new one.

The new storage ring is made up of 1321 powerful electromagnets, thousands of power supply units, and a thin, but lengthy, vacuum system through which it all connects. It runs on 32 miles of power cable, eight miles of diagnostic cable, and 20 miles of optical fiber.

The storage ring pioneers the use of multi-bunch swap-out injection, a method of periodically replenishing electrons in the beam as it circulates. Previously, the APS used a technique developed in the 1990s, called top-up injection, which provides nearly constant stored beam currents to x-ray experiments by "topping up" electron bunches that have lost electrons.

Because of the strong nonlinear focusing fields in the recently upgraded APS, top-up injection is no longer possible. Instead, bunches of electrons will be injected directly onto the nominal stored-beam trajectory, completely replacing the stored bunches. This swap-out method uses fast kicker magnets to extract and dump the stored bunch while moving the beam from injectors and placing it in the stored bunch's place, all in a span of a few nanoseconds. The process will repeat every few dozens of seconds to keep the beam current constant.

According to Argonne National Laboratory, the APS is the first modern synchrotron x-ray source to use this technique.

After more than a month of commissioning the new storage ring, the APS team has begun the process of bringing each of the 71 beamlines into operation.

The first scientific beamline to receive x-rays was 27-ID, home of the resonant inelastic x-ray scattering program at the APS. Researchers will be able to use the line to study complex materials that could be used to power future technologies.

During the next year, all APS beamlines will return to operation.

Spectris acquires SciAps

Precision measurement company Spectris entered into an agreement to acquire SciAps for consideration of up to $260 million, comprising an up-front consideration of $200 million, plus a deferred element of up to $60 million. SciAps will be integrated into Malvern Panalytical in the Spectris Scientific business upon the completion of the deal.

According to Spectris, in addition to expanding Malvern Panalytical's footprint in North America, the acquisition gives the company access to highly complementary technology and expands Malvern's portfolio beyond laboratory and benchtop equipment into hand-held instruments.

SciAps is a developer of portable and hand-held analytical instruments based on laser-induced breakdown spectroscopy (LIBS), as well as x-ray fluorescence. The acquisition adds these capabilities and provides access to the adjacent hand-held x-ray fluorescence market. SciAps' solutions are used to identify compounds, minerals, and elements in materials in major industries including mining, metal recycling, battery materials, rare-earth metals, manufacturing, and agriculture.

$1.4T — the expected value of the global liquid crystal display market by 2029, according to Data Bridge Market Research

Additive Manufacturing Materials Consortium targets standards

The Additive Manufacturing Materials Consortium selected MIMO Technik and ASTRO Mechanical Testing Laboratory to help develop open laser powder bed fusion parameter sets for consortium member materials in the U.S. MIMO Technik and ASTRO Mechanical Testing Laboratory will serve as lead fabrication and testing partners on the effort. The consortium plans to use ASTRO and MIMO Technik's proprietary MASTRO method alongside software from founding consortium member Dyndrite to speed the development and delivery of materials.

Developed during the last two years, the MASTRO AM-MCQP-2024: Additive Material Characterization and Qualification Protocol for Production Readiness is a hyperfast qualification process that involves iterative experiments to determine values for all variables that influence the metal printing process. The parameters are then stored in Dyndrite Build Recipes for usage.

The platform consists of standardized and shareable MASTRO Dyndrite build recipes, which are used for parameter development and the ASTRO testing process. MASTRO-qualified materials are now in production for fracture-critical hardware, including landing gear, propulsion systems, payload structures, and defense applications.

Space Force issues four contracts for optical communications

The U.S. Space Force's Space Systems Command (SSC) awarded four contracts for the development of laser communications terminal prototypes. The contracts, awarded to Blue Origin, CACI International Inc., General Atomics, and Viasat, serve to commence the first of three phases under the $100 million Enterprise Space Terminal (EST) program.

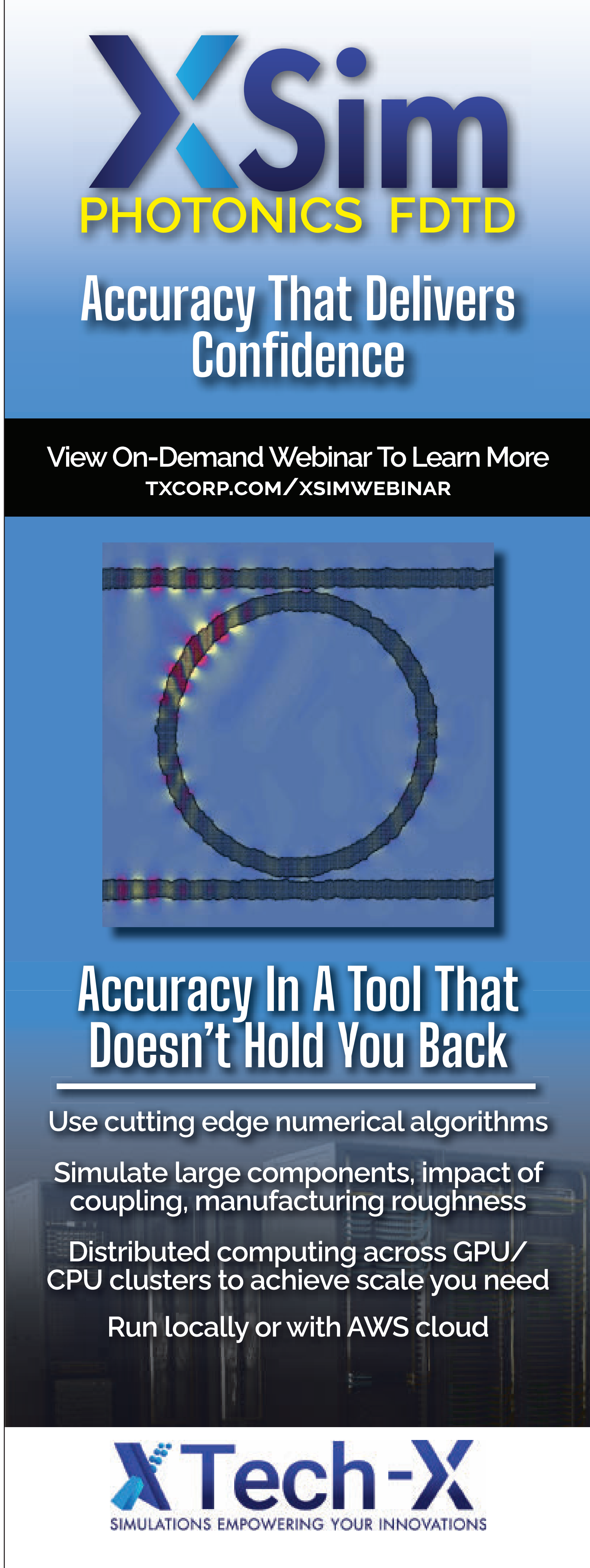
The EST program aims to enable on-orbit crosslink compatibility among future space systems via the use of a standardized enterprise waveform. This waveform will be implemented in a long-range and low size, weight, power, and cost space optical communications terminal.

According to SSC, ESTs are a key building block of the broader Space Data Network, which will build a space mesh network for resiliency and information path diversity.

Further, the program leverages prior investment by the Department of Defense and commercial developers to operationalize an enterprise waveform designed to communicate in the Beyond Low Earth Orbit regimes.

"The EST prototypes will be a huge step forward for a future space mesh network across different orbital regimes ranging from low Earth orbit to past the geosynchronous orbit regime," said John Kirkemo, senior materiel leader of SSC's Advanced Communications Acquisition Delta.

The contracts were awarded through SSC's Space Enterprise Consortium. The consortium provides rapid space technology innovations through its academic and commercial industry members.



onsemi acquires SWIR Vision Systems

Image sensor company onsemi acquired SWIR Vision Systems, a provider of colloidal quantum dot (CQD)-based SWIR technology. SWIR Vision Systems became a wholly owned subsidiary of onsemi following the deal. The company was integrated into onsemi's Intelligent Sensing Group and continues to operate in North Carolina.

SWIR Vision Systems' CQD technology extends the visibility and detection of systems beyond the range of standard CMOS sensors into SWIR wavelengths. To date, the adoption of SWIR technology has been limited due to the high cost and manufacturing complexity of the traditional indium gallium arsenide process.

onsemi will combine its silicon-based CMOS sensors and manufacturing expertise with SWIR Vision's CQD technology to deliver integrated SWIR sensors at a lower cost and higher volume, according to onsemi. This combination will result in more compact, cost-effective imaging systems that offer extended spectra and can be used in commercial, industrial, and defense applications.

In enhancing its intelligent sensing product portfolio, onsemi expects that the integration of SWIR Vision Systems' technology will lead to growth in the industrial, automotive, and defense markets.

Quantum startup planqc raises $54M

Quantum computing firm planqc secured €50 million (approximately $54 million) in series A financing. The startup plans to establish a quantum computing cloud service and to develop quantum software for applications in industries including health care, climate tech, automotive, and finance.

Founded in 2022 and based in Germany's Munich Quantum Valley, the company is developing neutral atom-based quantum computing built on a foundation of research conducted at the Max Planck Institute of Quantum Optics. Quantum information is processed by arranging neutral atom qubits trapped in optical lattices and manipulating them with precisely controlled laser pulses.

In its collaboration with the Max Planck Institute for Quantum Optics, planqc previously showcased the scaling of the number of neutral atoms used as qubits to 1200. According to the company, the milestone can pave the way for fault-tolerant quantum computers. More broadly, the power of quantum computers is poised to fuel the discovery of new materials and pharmaceuticals; address optimization challenges in fields such as climate research, industry, and transpor-

People in the News

Radiant Vision Systems, a provider of imaging systems for scientific evaluation of light sources and displays, appointed **Stone Jiang** CEO, succeeding **Doug Kreysar**, who has retired. During his 12 years with Radiant, Jiang's responsibilities have consisted of strategic planning, business development, sales, and support for Radiant's customers worldwide. He most recently served as Radiant's executive vice president and general manager of China and has previous experience as general manager of Orbis and Keithley Instruments Inc. Kreysar will continue to serve the company in a senior advisor role.


Radiant Vision Systems

Jiang.

Elke Arenholz was named director of the National Synchrotron Light Source II, a U.S. Department of Energy (DOE) Office of Science user facility at DOE's Brookhaven National Laboratory. Arenholz has held senior leadership positions at the DOE's Pacific Northwest Laboratory, Oak Ridge National Laboratory, Cornell High Energy Synchrotron Source, and the Advanced Light Source at Lawrence Berkeley National Laboratory.


Brookhaven National Laboratory

Arenholz.

Fraunhofer-Gesellschaft appointed **Constantin Häfner** executive board member responsible for research and transfer. Häfner currently serves as executive director of the Fraunhofer Institute for Laser Technology ILT (Fraunhofer ILT) in Aachen, Germany. Häfner previously led the Advanced Photon Technologies program at Lawrence Livermore National Laboratory, where he worked on the development of next-generation, high-average power petawatt laser systems.


Fraunhofer-Gesellschaft

Häfner.

Photonic supercomputing company Lightmatter named **Simona Jankowski** CFO. Jankowski joins Lightmatter from NVIDIA, where she was vice president of investor relations and strategic finance. The company also appointed **Richard Beyer** and **Robin Washington** to its board of directors. Beyer previously served as CEO of Freescale Semiconductor Inc. and is a member of the board of directors of Micron Technology Inc. Washington is a board member of Alphabet, Honeywell International, and Salesforce.

Precision Optics Corporation Inc. named **Clay Schwabe** vice president of sales and marketing. Schwabe has more than 15 years of experience in sales and marketing and has held leadership roles at Veranex, PRIA Healthcare, Vertiflex, and Medtronic.

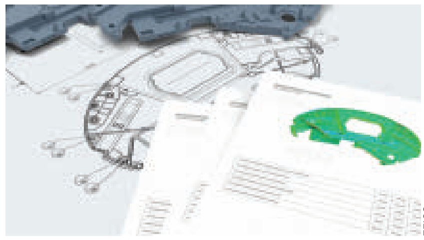
Quantifi Photonics, a photonics test and measurement company, appointed cofounder and former CTO **Iannick Monfils** CEO following the departure of fellow cofounder **Andy Stevens**. Since cofounding Quantifi Photonics in 2012, Monfils has led the company's engineering team as well as the company's development of its product portfolio to include test solutions for coherent optical modulation, high-volume manufacturing of photonic tation planning; and usher in a new era of cryptography.

planqc was commissioned last May to develop a quantum computer for the German Aerospace Center. According to the company, it was also recently contracted by the German government to build a 1000-qubit quantum computer at the Leibniz Supercomputing Centre.

ZEISS partners with Artec 3D for software sales

ZEISS established a partnership with Artec 3D, a Luxembourg-based developer and provider of portable 3D scanners. Per the agreement, Artec 3D will offer ZEISS' inspection software as an extension to their range of 3D-scanning hardware.

According to Artec, the partnership will start by focusing on ZEISS INSPECT Optical 3D and ZEISS REVERSE ENGINEERING. The software platforms allow 3D measurement data to be analyzed and converted into comprehensive reports and provide scan-to-CAD (computer-aided design) capabilities.


ZEISS

ZEISS' metrology software will be available through Artec 3D to enable users to create comprehensive reports by analyzing 3D measurement data acquired by Artec's scanners.

Artec said that the pairing of ZEISS software and Artec Studio software will enhance capabilities in speed and automation and provide greater options for advanced users working on complex 3D measurment tasks.

integrated circuits and pluggable optical transceivers, and general-purpose photonics. He has more than 23 years of experience in the photonics and telecommunications industry. Stevens will continue to advise the executive team and remains a shareholder in the company.

TiniFiber, a manufacturer of optical cabling solutions, named **Alain de Wolff** managing director for global sales and business development. Prior to joining TiniFiber, de Wolff served in senior roles at Gilat Satellite Networks, AMOS-Spacecom, and Mer Telecom.


TiniFiber

de Wolff.

VIGO Photonics, a developer of edge IR detectors, added to its VIGO Photonics USA team. The company named **Daniel Hirsh** and **Merry Ann Libonate** directors of sales for industrial gas sensing, and security and defense, respectively. Hirsh previously served as a regional sales manager for Teledyne Gas and Flame Detection, and Libonate joined from JENOPTIK, where she served as sales director, industrial solution. VIGO also named **Robert Myers** senior applications engineer. Prior to joining VIGO, Myers served as product manager for LightPath Technologies.

Ayar Labs, an optical interconnect solutions company, named **Pooya Tadayon** vice president of packaging and test. Tadayon was formerly a fellow and director of assembly and test pathfinding within Intel's Assembly and Test Technology Development group. He holds more than 47 patents in areas including test interconnect technology, thermal technology, and package/product architecture. At Ayar Labs, he will be tasked with creating an outsourced semiconductor assembly and test process to support volume production of optical input/output solutions for next-generation AI applications.


Ayar Labs

Tadayon.

NAVITAR
AMETEK
HIGH PERFORMANCE IMAGING SOLUTIONS
LENSES and CAMERAS
Modular SYSTEMS
Precision ALIGNMENT
CUSTOM SOLUTIONS
Designed for Manufacturability

Delivering Quality Imaging Solutions for Industrial & Life Science Applications for Over 50 Years
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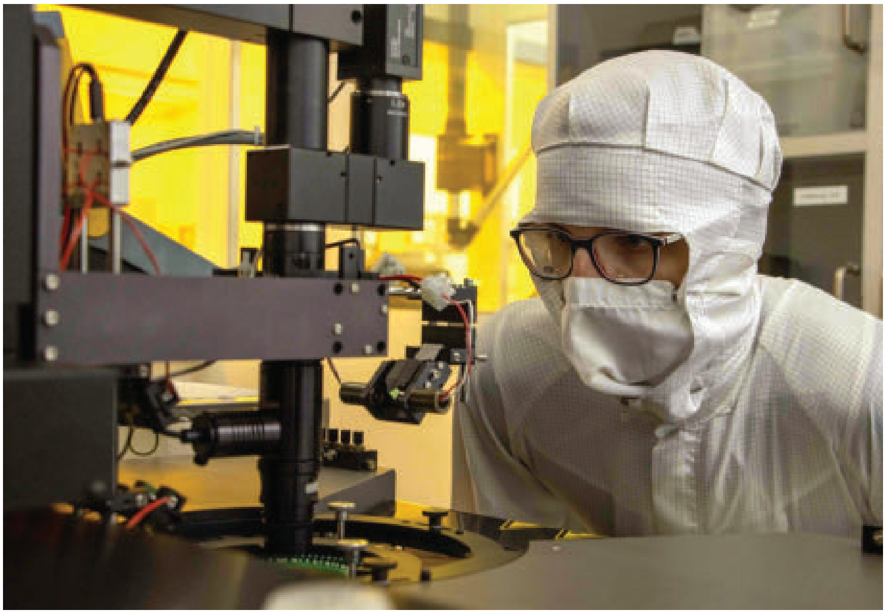
Silicon-based NIR photodiodes signal an imaging breakthrough



Fraunhofer IPMS

Researchers at Fraunhofer Institute for Photonic Microsystems IPMS (Fraunhofer IPMS) are developing silicon photodiodes, sensitive in the NIR range, for more cost-effective manufacturing of image sensors. The effort supports applications including autonomous driving, security, medical and chemical imaging, and spectroscopy, among others.

DRESDEN, Germany — As the core component of image sensors, photodiodes are indispensable in many applications. While silicon is a favored material for crafting these components for use in the visible range, silicon's low sensitivity in the NIR has necessitated developers' use of other materials as substitutes. These alternate materials, including indium gallium arsenide (InGaAs), can be expensive and harmful to the environment.

In response, researchers on a project led by the Fraunhofer Institute for Photonic Microsystems IPMS (Fraunhofer IPMS) are developing sensitive silicon-based photodiodes that, according to the researchers, will enable silicon to function for use in NIR image sensors. The effort, the researchers said, addresses the demand for lower production costs and more manageable environmental effects, both of which are poised to result from silicon photodiodes that are more sensitive to the NIR.

According to Michael Müller, project coordinator from Fraunhofer IPMS, the researchers' advancement is based on implementing a structure in the photodiode. "Instead of the usual planar device topography, we use novel pyramidal and ring structures that function like a light collecting basin," Müller said.

In addition, using a very thin metal layer in the Schottky barrier, the researchers demonstrated an increase in the photodiode's internal quantum efficiency, meaning the number of charge carriers that light generates in the semiconductor.

Müller and his team believe that these two innovations will combine to significantly increase sensitivity and ultimately enable silicon's use for NIR applications. If successful, the project is expected to enable a range of applications, particularly in price-sensitive, high-volume markets such as autonomous driving. This application requires new lidar sensors and fog cameras for environmental monitoring. The initiative also targets areas including security technology, chemical and medical imaging, hyperspectral imaging, and spectroscopy.

Funded by Germany's Federal Ministry of Education and Research, the three-year MesSi project will draw on €566,000 (about $614,300) in funding.

Spectral purity measurement method supports photonic quantum computing

CANBERRA, Australia — Exciton-polariton lasers offer low-power operation, making them a promising source of coherent light for various low-energy applications. Until now, however, measurement of the spectral purity, or linewidth, of this type of laser has largely remained elusive.

Using a commercial scanning Fabry-Pérot interferometer, researchers at FLEET, the Australian Research Council's Center of Excellence in Future Low-Energy Electronics Technologies, investigated the energy and linewidth of exciton-polariton lasers in the single-mode regime. The researchers demonstrated that, contrary to previous assumptions, the exciton-polariton laser can maintain an ultra-narrow linewidth of 56 MHz, or 0.24 μeV (microelectron volts) — 10× smaller than those in previously published results.

Moreover, the measured linewidth of the laser corresponds to a coherence time of 5.7 ns. The long coherence time suggests that the macroscopic quantum state of the laser could be manipulated for quantum computing.

Exciton-polariton lasers are coherent light sources generated by the decay of bosonic condensates of exciton-polaritons — hybrid particles arising from the coupling of photons and excitons. These devices achieve lasing without population inversion and at a threshold much lower than that of an equivalent conventional photon laser.

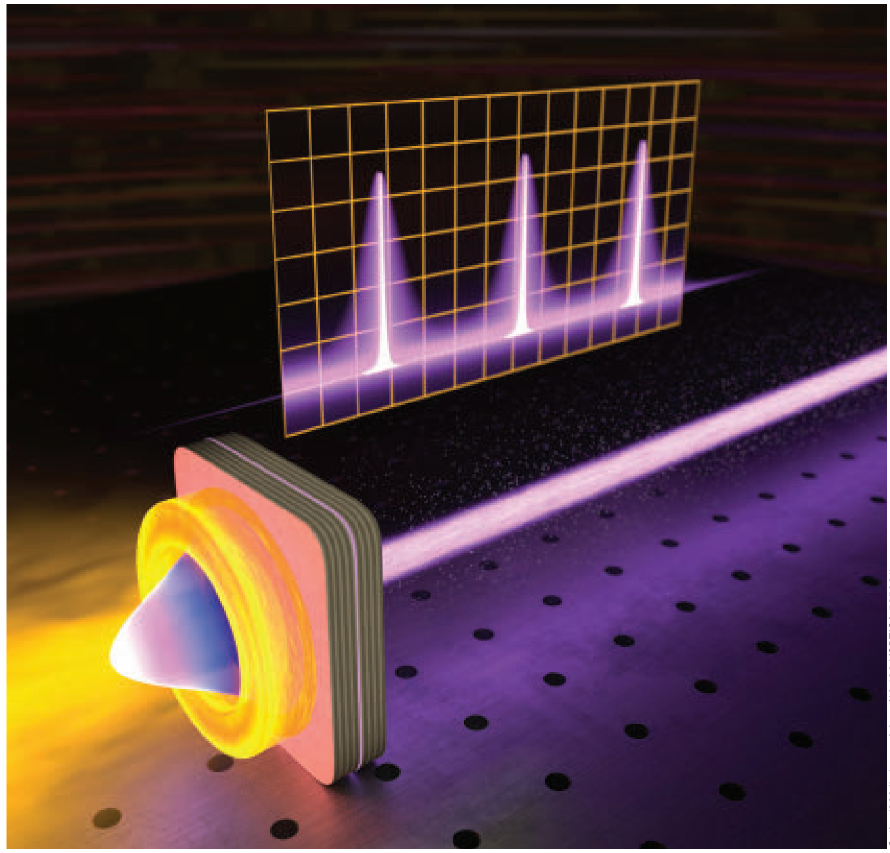
Previous attempts to measure exciton-polariton laser linewidth required multiple experimental iterations and averaging over timescales that were orders of magnitude longer than the polariton lifetime and the coherence time. This affected the measurement of fluctuations in energy and linewidth.

Using the Fabry-Pérot interferometer, the FLEET team directly measured the linewidth and small energy shifts of chopped, continuous-wave (CW) polariton condensates (quasi-CW pulses). "The interferometer enabled unprecedented levels of detail that were obscured in previous measurements using conventional techniques," FLEET researcher Bianca Rae Fabricante said.

The researchers investigated the influence of optical trapping on the linewidth of the laser, showing that, contrary to previous studies, the excitonic reservoir responsible for creating the trap does not strongly affect the emission linewidth, provided the condensate is trapped and the pump power is well above the condensation (i.e., lasing) threshold.

The excitonic reservoir was previously thought to introduce significant noise into the exciton-polariton laser. The researchers showed that, as long as the polaritons are trapped, the effect of the reservoir remains weak.

Despite its strong nonlinearity, the exciton-polariton laser has a linewidth that is comparable to that of VCSELs, which are used in facial recognition and augmented reality. The current leading technology, single-mode VCSELs, demonstrates a linewidth of 50 MHz.



Optica (2024), (www.doi.org/10.1364/OPTICA.525961)

An illustration of a trapped polariton condensate giving rise to the laser emission with an ultra-narrow spectral peak detected by a scanning Fabry-Pérot interferometer. Researchers in Australia used an interferometric method to demonstrate that the exciton-polariton laser can maintain an ultra-narrow linewidth that is 10× smaller than those in previously published results.

"Polariton lasers are potentially better than VCSELs for low-energy applications since they can operate at lower powers," researcher Mateusz Król said. The laser's long coherence time of at least 5.7 ns theoretically makes it possible to perform thousands of successive operations on the exciton-polariton laser source, to form a macroscopic quantum state of condensed exciton-polaritons for quantum information processing.

"Our work not only pushes the boundaries of exciton-polariton laser technology, but also opens up new avenues for utilizing exciton-polaritons for classical and quantum computing," researcher Eliezer Estrecho said.

Further, the exciton-polariton laser's low-threshold operation, nonlinearity, and solid-state platform are promising for numerous low-power applications. These applications include ultrafast optical polarization switches, modulation applications, compact sources of terahertz radiation, and logic elements.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.525961).

Topological platform boosts comb efficiency, end use potential

COLLEGE PARK, Md. — On-chip optical frequency combs enable numerous applications, but the predominant use of single-ring microresonators in on-chip combs can limit the combs' frequency range and optical power. A path to generating optical frequency combs, developed by a team from the University of Maryland (UMD), yielded a nested "comb-within-a-comb" that, according to UMD researchers, could lead to smaller, more efficient frequency combs for atomic clocks, rangefinders, quantum sensors, and other applications that require the precise measurement of light.

A topological platform with a 2D array of coupled microresonator rings (i.e., micro-rings) serves as the base of the nested frequency comb. The light from the comb is confined to the edges of the array. The array accommodates fabrication-robust topological edge states with linear dispersion.

The researchers designed a chip with hundreds of micro-rings arranged in a 2D grid. They engineered a complex pattern of interference that takes input laser light and circulates it around the edge of the chip while the material of the chip itself splits the light into many frequencies.

Because continuous wave lasers delivered too much heat to the chip, the researchers used a custom-built pulsed laser to deliver light to the comb. They found that pulses from off-the-shelf pulsed lasers were too short and contained too many frequencies to provide the edge-constrained light that was needed to support the design of the topological frequency comb. The researchers also went through multiple chip iterations before it arrived at a chip design that could support the topological frequency comb.

The individual micro-rings form cells that allow the light to jump from ring to ring — that is, from one pathway to another. The micro-rings are designed to create specific forms of interference between the paths. Collectively, the rings disperse the input light into the many teeth of the comb and guide the light along the edge of the grid.

Together, the micro-rings form a super-ring. The presence of both individual micro-rings and a super-ring causes the comb to have two different time and length scales, because it takes longer for light to travel around the super-ring than the micro-rings.

This phenomenon is what leads to the generation of two nested frequency combs. The micro-rings produce a coarse comb, with frequency spikes spaced widely apart. Within each coarsely spaced spike, a finer comb is nested, produced by the super-ring.

This nested, comb-within-a-comb structure could be useful in applications that require precise measurements of two different frequencies that are separated by a wide gap.

The team placed an infrared camera above the chip to capture images of the light circulating around the edge of the chip. By pumping the edge states, the researchers generated a nested frequency comb that showed oscillation of multiple edge state resonances across approximately 40 longitudinal modes, while being spatially confined at the 2D lattice edge.

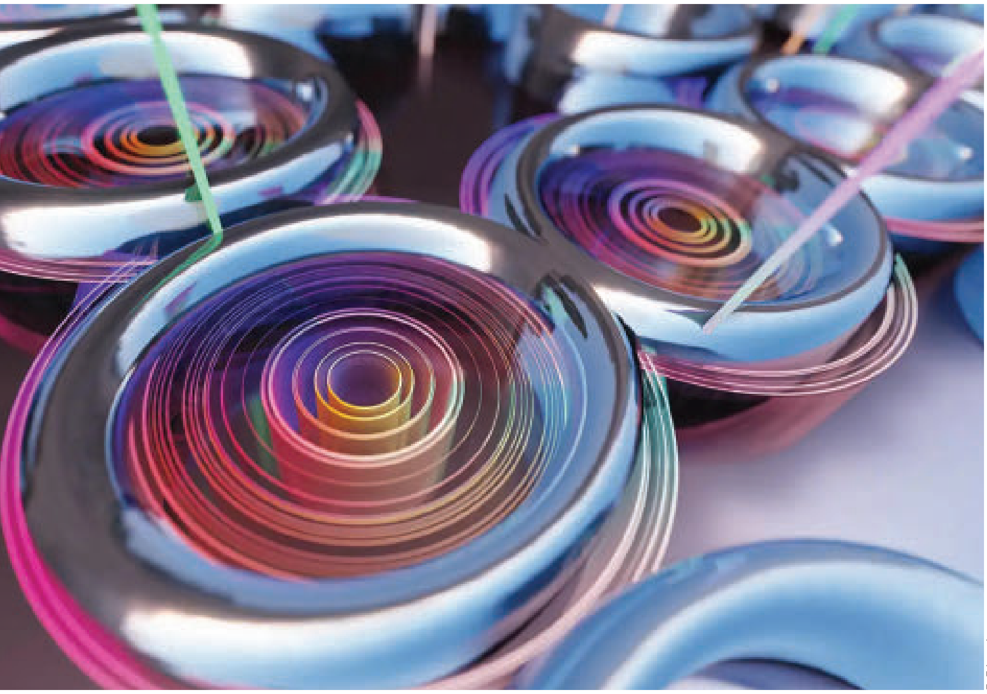
High-resolution analysis of the light frequencies from the comb, using a spectrum analyzer, enabled the researchers to detect one comb with relatively broad teeth and, nestled within each tooth, a hidden, smaller comb.

Although the nested comb developed by the UMD team is only a proof of concept, the developed device could ultimately lead to more efficient frequency combs for quantum sensing, ranging, and metrology.

The experiment with nested optical frequency combs was performed on a chip made from silicon nitride, though according to the researchers, the design could easily be translated to other photonic materials to create combs in different frequency bands.

The team believes that the on-chip topological frequency comb could serve as a platform for the study of topological photonics, especially in applications where a threshold exists between relatively predictable behavior and more complex effects — such as the generation of a frequency comb.

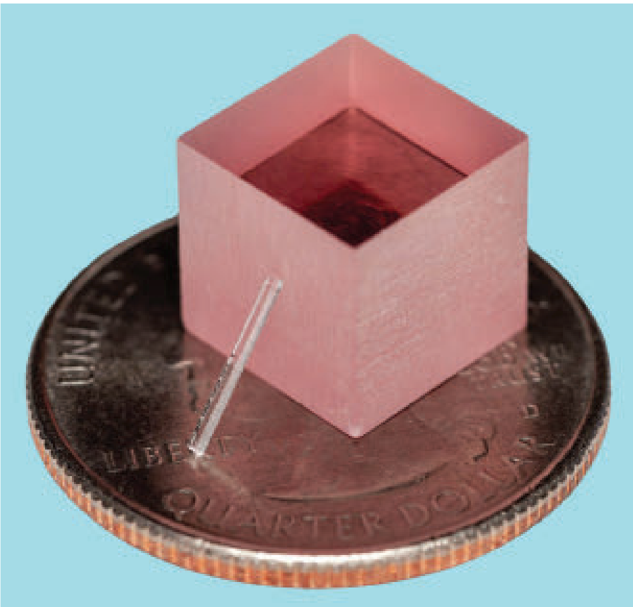
The research was published in *Science* (www.doi.org/10.1126/science.ado0053).



E. Edwards

Researchers at the University of Maryland (UMD) developed a silicon nitride-based chip with hundreds of microscopic rings that target improvements to both frequency range and optical power.

Researchers shrink titanium-sapphire laser to chip scale



Yang et al., *Nature*

The titanium-sapphire (Ti:sapphire) laser is four orders of magnitude smaller (10,000×) and three orders less expensive (1000×) than other Ti:sapphire lasers. The laser is depicted leaning against a block of Ti:sapphire while sitting on a quarter.

STANFORD, Calif. — Lasers based on titanium-sapphire (Ti:sapphire) provide top performance in fields such as quantum optics, spectroscopy, and neuroscience. But this performance comes at a steep cost. Along with costing thousands of dollars, these devices require a lot of space and power. Ti:sapphire lasers take up several cubic feet and require other high-powered lasers to supply them with enough energy to function.

Making a jump from tabletop to the microscale, engineers at Stanford University developed a Ti:sapphire laser on a chip. According to the researchers, the prototype is four orders of magnitude smaller (10,000×) and three orders less expensive (1000×) than any previous Ti:sapphire laser.

“Instead of one large and expensive laser, any lab might soon have hundreds of these valuable lasers on a single chip,” said Jelena Vučković, Stanford’s Jensen Huang Professor in Global Leadership and senior author of the research.

Further, Vučković said, the laser can be fueled simply with a green laser pointer.

To fashion the on-chip laser, the researchers began with a bulk layer of Ti:sapphire on a platform of silicon dioxide (SiO_2), all riding atop true sapphire crystal. Then, they ground, etched, and polished the Ti:sapphire to an extremely thin layer, just a few hundred nanometers thick. They then patterned a waveguide into the layer.

“Mathematically speaking, intensity is power divided by area. So, if you maintain the same power as the large-scale laser, but reduce the area in which it is concentrated, the intensity goes through the roof,” said Joshua Yang, a doctoral candidate in

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Vučković's lab and co-first author on the research.

"The small scale of our laser actually helps us make it more efficient."

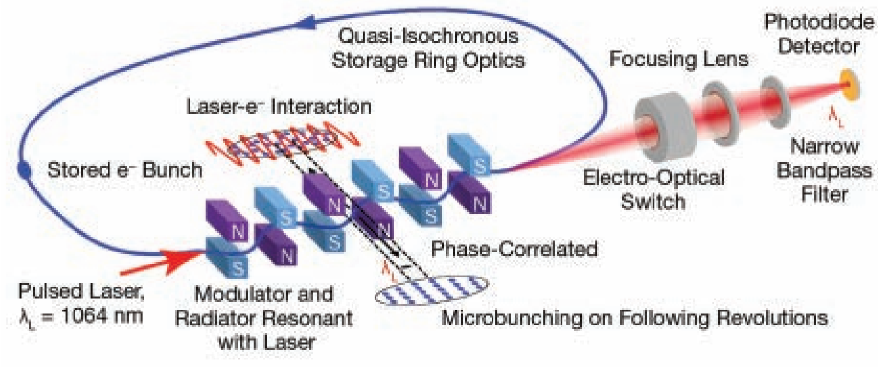
A microscale heater that warms the light traveling through the waveguides was added, allowing the researchers to change the wavelength of the emitted light to tune the color of the light anywhere between the 700-nm (visible) and 1000-nm (IR) ranges.

The on-chip laser supports applications in quantum physics, for example, where the laser could provide an inexpensive and practical solution to scale down state-of-the-art quantum computers. Medical fields could benefit from the Ti:sapphire laser, too, where the laser could find use for optogenetics or in compact OCT technologies for ophthalmology.

Curently, the researchers are working to develop ways to mass-produce the chip-scale Ti:sapphire lasers on wafers, with the goal of bringing them to market.

The research was published in *Nature* (www.doi.org/10.1038/s41586-024-07457-2).

Lithography-supporting source outpowers established accelerators



HZB/Nature Communications Physics

To keep up with the demand for shorter wavelengths to support the development of semiconductor technology, researchers are developing sources of coherent ultraviolet radiation. A new technique could provide a way to generate coherent synchrotron radiation at an electron storage ring to supply kilowatt-level average power radiation in the extreme-ultraviolet (EUV) range.

BERLIN — Scientists from Helmholtz-Zentrum Berlin (HZB), Tsinghua University, and Germany's national metrology institute Physikalisch-Technische Bundesanstalt (PTB) are building the foundation for a future source for coherent ultraviolet radiation, known as steady-state microbunching (SSMB). According to the researchers, SSMB could provide a way to generate coherent synchrotron radiation at an electron storage ring to supply kilowatt-level average power radiation in the extreme-ultraviolet (EUV) regime.

The effort ultimately supports the development of an EUV radiation source with a power level suitable for lithography — at a time when semiconductor manufacturers are actively seeking shorter wavelengths to etch structures of a smaller scale. According to the researchers, SSMB could meet the power level demands for lithography applications that cannot be met by established accelerator technologies, and also provide applications in various fields of science and industry with ultrahigh-brilliance x-ray radiation at high repetition rates.

When ultrafast electrons are deflected, they emit synchrotron radiation that can be used in storage rings where the particles are magnetically forced onto a closed path. This longitudinally incoherent light consists of a broad spectrum of wavelengths and its high degree of brilliance makes it an excellent tool for materials research. Monochromators can be used to select individual wavelengths from the spectrum, though this reduces the radiant power by many orders of magnitude.

In 2010, physicist Alexander Chao, a member of the current research team, showed that if the electron bunches orbiting in a storage ring become shorter than the wavelength of the light they emit, the emitted radiation becomes coherent and more powerful. Then, researcher Xiujie Deng, also a member of the current team, defined settings for the SSMB for a specific type of circular accelerator with low-alpha rings. These rings create short particle bunches that are only 1-µm long after they interact with a laser.

"You need to know that the electrons in a storage ring are not homogeneously distributed," researcher Arnold Kruschinski said. "They move in bunches with a typical length of about a centimeter and a distance around 60 cm." This is six orders of magnitude greater than the microbunches proposed in the 2010 research, Kruschinski said.

In 2021, the researchers validated the settings created by Deng, using what they believed to be the first storage ring designed for low-alpha operation. Through extensive experiments, the team has now fully validated Deng's theory for generating microbunches.

The team's studies are performed in an ongoing proof-of-principle experiment, where microbunching is generated from an energy modulation imposed by a 1064-nm laser. The results so far confirm the dependence of the microbunching process on laser modulation amplitude, and the accuracy of the theoretical description of the microbunching mechanism. They further show that the influence of transverse-longitudinal coupling dynamics corresponds to the team's theoretical expectations, and can be manipulated with a high degree of accuracy. The SSMB scheme with the most potential for high-power EUV radiation is based on using transverse-longitudinal coupling dynamics to generate efficient microbunching.

Starting from an electron storage ring with a high repetition rate in the megahertz, SSMB could potentially use an optical laser modulator to replace the radio frequency cavity as the main longitudinal focusing element, creating persistent microbunches in the circular accelerator. High average power coherent radiation could be produced in this way. With a suitable higher-harmonic generation scheme, the wavelengths of the radiation could reach the EUV. SSMB could also serve as a source of high-brightness, narrow-bandwidth UV radiation for angle-resolved photoemission spectroscopy.

To date, efforts have been made to improve the capability of free electron lasers (FELs) to generate ultrashort, high peak-power radiation pulses up to the hard x-ray regime. Currently, however, FELs are unable to supply high average power radiation at the kilowatt level at short wavelengths, according to the researchers.

Preparations for the next phase of the SSMB experiment are ongoing, though HZB project manager Jörg Feikes believes that it will take some time before SSMB is introduced as an actual radiation source for EUV.

The research was published in *Nature Communications Physics* (www.doi.org/10.1038/s42005-024-01657-y).

Timekeeping breakthrough offers to rewrite nature's constants

LOS ANGELES — Researchers have long dreamed of the secrets they could unlock by raising the energy state of an atom's nucleus using a laser. Accomplishing this would allow the atomic clocks of today to be replaced with a nuclear clock with far greater accuracy. But doing so is not an easy task, as electrons surrounding the nucleus react easily with light. A great deal of light is needed to reach the nucleus and increase its energy state.

By raising the energy state of an atomic nucleus, researchers at UCLA are paving the way for advancements in a broad range of topics, from deep space navigation to understanding longstanding questions in physics. By embedding a thorium atom within a highly transparent crystal and bombarding it with lasers, the researchers succeeded in making the nucleus of the thorium atom absorb and emit photons in a manner similar to how electrons perform the same function in an atom. The researchers embedded thorium-229 with a transparent crystal rich in fluorine, which can form especially strong bonds with other atoms, suspending the atoms and exposing the nucleus like a fly in a spider web.

Because the electrons bind so tightly with fluorine, the amount of energy it takes to excite them is very high. This allows the lower-energy light to reach the nucleus.

The thorium nuclei could then absorb these photons and re-emit them, allowing the excitation of the nuclei to be detected and measured. By changing the energy of the photons and monitoring the rate at

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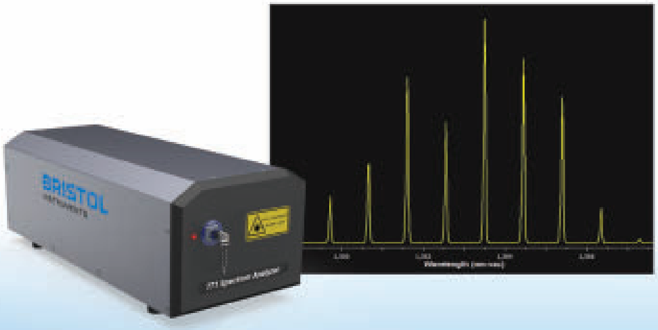

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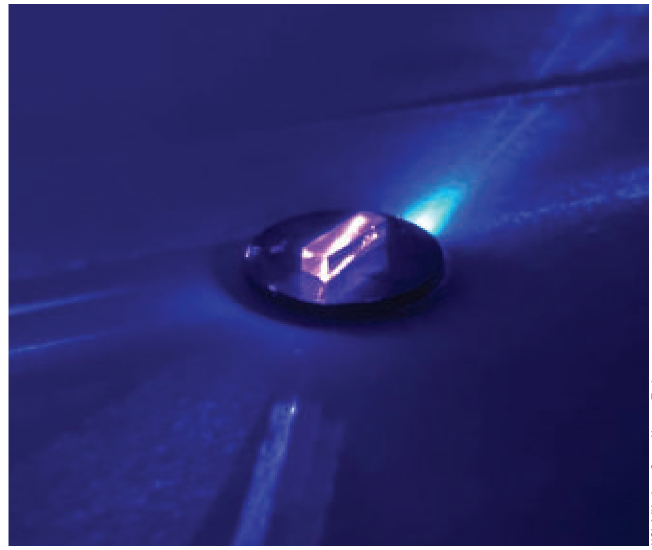

UCLA/Hudson Group/James Terhune

An advancement that targets precision timekeeping and, specifically, the portability and accuracy of clocking devices, relies on the use of lasers to excite the nucleus of a thorium-229 atom.

which the nuclei are excited, the team was able to measure the energy of the nuclear excited state.

"We have never been able to drive nuclear transitions like this with a laser before," lead researcher Eric Hudson said. "If you hold the thorium in place with a transparent crystal, you can talk to it with light."

With the technology, the measurement of time, gravity, and other fields that are currently performed using atomic electrons can be made with orders of magnitude higher accuracy. This is because atomic electrons are influenced by many factors in their environment, which affects how they absorb and emit photons and limits their accuracy. Neutrons and protons, on the other hand, are bound and highly concentrated within the nucleus and experience less environmental disturbance.

Once the technology is deployed in a nuclear clock, scientists may be able to determine whether fundamental constants vary, such as the fine-structure constant, which sets the strength of the force that holds atoms together. Hints from astronomy suggest that the fine-structure constant might not be the same everywhere in the universe or at all points in time. Precise measurement using the nuclear clock of the fine-structure constant could completely rewrite some of these most basic laws of nature.

"Using a nuclear clock for these measurements will provide the most sensitive test of 'constant variation' to date and it is likely no experiment for the next 100 years will rival it," Hudson said. He said that the technology could find use wherever extreme precision in timekeeping is required in sensing, communications, and navigation.

In addition, a thorium-based nuclear clock would be much smaller and more robust, portable, and accurate than existing atomic clocks, according to the researchers.

The research was published in *Physical Review Letters* (www.doi.org/10.1103/PhysRevLett.133.013201).

Production process lowers quantum dot laser manufacturing costs

ETRI

A process developed by researchers at South Korea's Electronics and Telecommunications Research Institute (ETRI) uses metal-organic chemical vapor deposition (MOCVD) systems to manufacture quantum dot lasers at a lower cost and with favorable results compared with molecular beam epitaxy-manufactured comparable devices **(shown)**.

DAEJEON, South Korea — Researchers from South Korea's Electronics and Telecommunications Research Institute (ETRI) developed a technology to mass-produce quantum dot lasers using metal-organic chemical vapor deposition (MOCVD) systems. The work could help to lower production costs of semiconductor lasers, according to the developers.

The researchers developed indium arsenide/gallium arsenide (InAs/GaAs) quantum dot laser diodes on gallium arsenic (GaAs) substrates, which are suitable for the 1.3-µm wavelength band used in optical communications. "The mass production technology for quantum dots can significantly lower the production costs of high-priced optical communication devices, enhancing the competitiveness of the national optical communication component industry and contributing substantially to basic science research," said professor Dae-Myeong Geum of Chungbuk National University, and a participant on the research.

Quantum dot lasers are known for their excellent temperature characteristics and strong tolerance to substrate defects, allowing for larger substrate areas and consequently lower power consumption and production costs. Traditionally, quantum dot laser diodes have been produced using molecular beam epitaxy. This method suffers inefficiencies due to slow growth speed, which poses challenges for mass production.

The developed method, the researchers said, provides high density and good uniformity. The produced quantum dot semiconductor lasers demonstrated continuous operation at temperatures up to 75 °C, which, according to the researchers, represents a world-leading result in yield quality obtained via MOCVD.

Previous optical telecommunication devices used expensive 2-in. indium phosphide (InP) substrates, resulting in high manufacturing costs. The new technology uses GaAs substrates, which are less than one-third the cost of InP substrates.

The research team plans to enhance the reliability of the technique and transfer it to domestic optical communication companies. These companies will receive key technology and infrastructure support through ETRI's semiconductor foundry, accelerating the commercialization timeline.

The research was published in the *Journal of Alloys and Compounds* (www.doi.org/10.1016/j.jallcom.2024.173823).

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New and improved skipper CCDs count photons from distant galaxies

BATAVIA, Ill. — Using an instrument on the 4.1-m Southern Astrophysical Research (SOAR) Telescope, researchers obtained the first astronomical spectrum using skipper charge-coupled devices (CCDs). Originally envisioned for this purpose, the technology had been largely limited to the study of charged particles since its introduction in 1990.

CCDs are 2D arrays of light-sensitive pixels that convert incoming photons into electrons. Conventional CCDs were the first image sensors used in digital cameras. While CMOS sensors have largely replaced them in consumer cameras, CCDs remain a staple in many scientific imaging applications. Their precision, however, is limited by electronic noise.

“If you have one electron in a pixel, sometimes you’ll measure three electrons,” said Alex Drlica-Wagner, a cosmologist at the U.S. Department of Energy (DOE)’s Fermi National Accelerator Laboratory (Fermilab), who led the project. “Because of the noise, you can’t make a precise measurement.”

Skipper CCDs were imagined to address this limitation. Instead of taking a measurement of that one electron just one time, a skipper CCD will measure it multiple times, taking an average of the randomized readout noise for a more precise measurement.

This method was expected to provide much greater accuracy. However, the technological limitations in both the readout electronics and in the detector fabrication process at the time prevented the improvements from matching with the theoretical value.

“[Users] ended up still being able to reduce the readout noise through this multiple measurement process, but [they] couldn’t do it quite as well as the theoretical prediction,” Drlica-Wagner said. In theory, measuring the charge four times would reduce the noise by a factor two. Measuring it 16 times would reduce noise by a factor of four. The results were still an improvement, but the technique increased the readout time.

“For astronomy, that’s time that could be spent collecting more photons,” Drlica-Wagner said.

The skipper CCD was largely shelved until 2017, finding use in rare particle detection.

It has only recently been used for astronomical observation. A collaboration between physicists, astronomers, and engineers at Fermilab, the University of Chicago, the National Science Foundation’s NOIRLab, Lawrence Berkeley National Laboratory, and the National Astrophysical Laboratory of Brazil sought to combine the incremental improvements to advance the technology to its initially predicted potential and beyond. The work is a culmination of improvements in CCDs that has enabled smaller structures on the detectors, higher production yield and consistency, improved readout electronics, advancements in the silicon used to produce the sensors, and improvements in packaging, among other factors.

“All of this allows us to now achieve the theoretical noise performance,” Drlica-Wagner said. The current measurement uncertainty stands at 0.039 electrons of noise, Drlica-Wagner said.

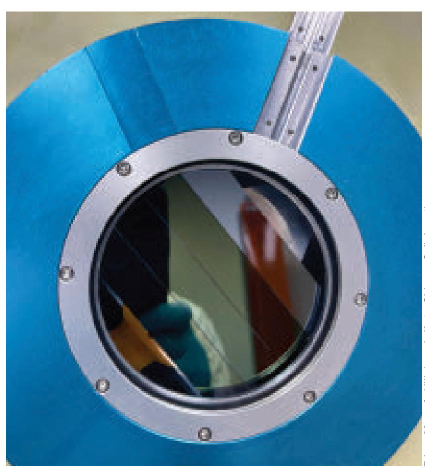
Twice this spring, researchers used skipper CCDs in the SOAR Integral Field Spectrograph to collect astronomical spectra from a galaxy cluster, two distant quasars, a galaxy with bright emission lines, and a star that is potentially associated with a dark matter-dominated ultra-faint galaxy.

“What’s incredible is that these photons traveled to our detectors from objects billions of light-years away, and we could measure each one individually,” said Fermilab researcher Marrufo Villalpando.

Although the project to improve skipper CCDs yielded results that enabled its use in astrophysical study, researchers are still working to push the technology forward. The next generation of skipper CCDs, developed by Fermilab and Lawrence Berkeley National Laboratory, is 16× faster than current devices. These devices are poised for inclusion in upcoming cosmology projects from the DOE, such as the spectroscopic experiments DESI-II and Stage-5 Spectroscopic Survey. Another is NASA’s Habitable Worlds Observatory, which seeks to directly image and take spectra of exoplanets in the habitable zones of sun-like stars.

“The rate at which photons would arrive is so low that you really need very low noise detectors to be able to measure them,” Drlica-Wagner said.

Joel Williams, News Editor
joel.williams@photonics.com



Edgar Marrufo Villalpando/AstroSkipper Collaboration

Four skipper charge-coupled devices (CCDs) mounted inside a cryogenic vacuum vessel in preparation for on-sky observations are shown **(above)**.

NOIRLab

After bringing skipper charge-coupled devices (CCDs) up to par with their theorized accuracy for photon detection, researchers deployed the technology at the Southern Astrophysical Research (SOAR) Telescope in Chile **(left)** to collect astronomical spectra from a variety of sources.

Spectroscopic method measures soil contaminants with ease, accuracy

TOKYO — Researchers at Waseda University and the National Institute of Advanced Industrial Science and Technology (AIST, Japan) developed a method that provides a simple route to accurately assess the concentration of nano- and microplastics (N/MPs) in different soil types. Current methods for this application require the separation of soil organic matter content through chemical and physical processes. The isolated plastics are then analyzed using a microscope, Fourier-transform infrared spectroscopy, pyrolysis-gas chromatography/mass spectrometry, or Raman spectroscopy. These methods require advanced skills and are limited in their ability to measure N/MPs that are <1 µm. And, some of the N/MPs in the soil are lost in the separation process. The newly developed method allows accurate measurement of N/MP concentration regardless of their size, and without separation from organic matter.

To spectroscopically clarify the optimal conditions and wavelength combinations required to measure N/MP concentrations in soil, the researchers prepared six types of soil containing N/MPs from samples where characteristics, such as particle size distribution and organic content, differed. They mixed the soil types with 203-nm polystyrene nanoparticles to create six different simulated N/MP-contaminated soil suspensions. N/MP concentration was maintained at 5 mg/L.

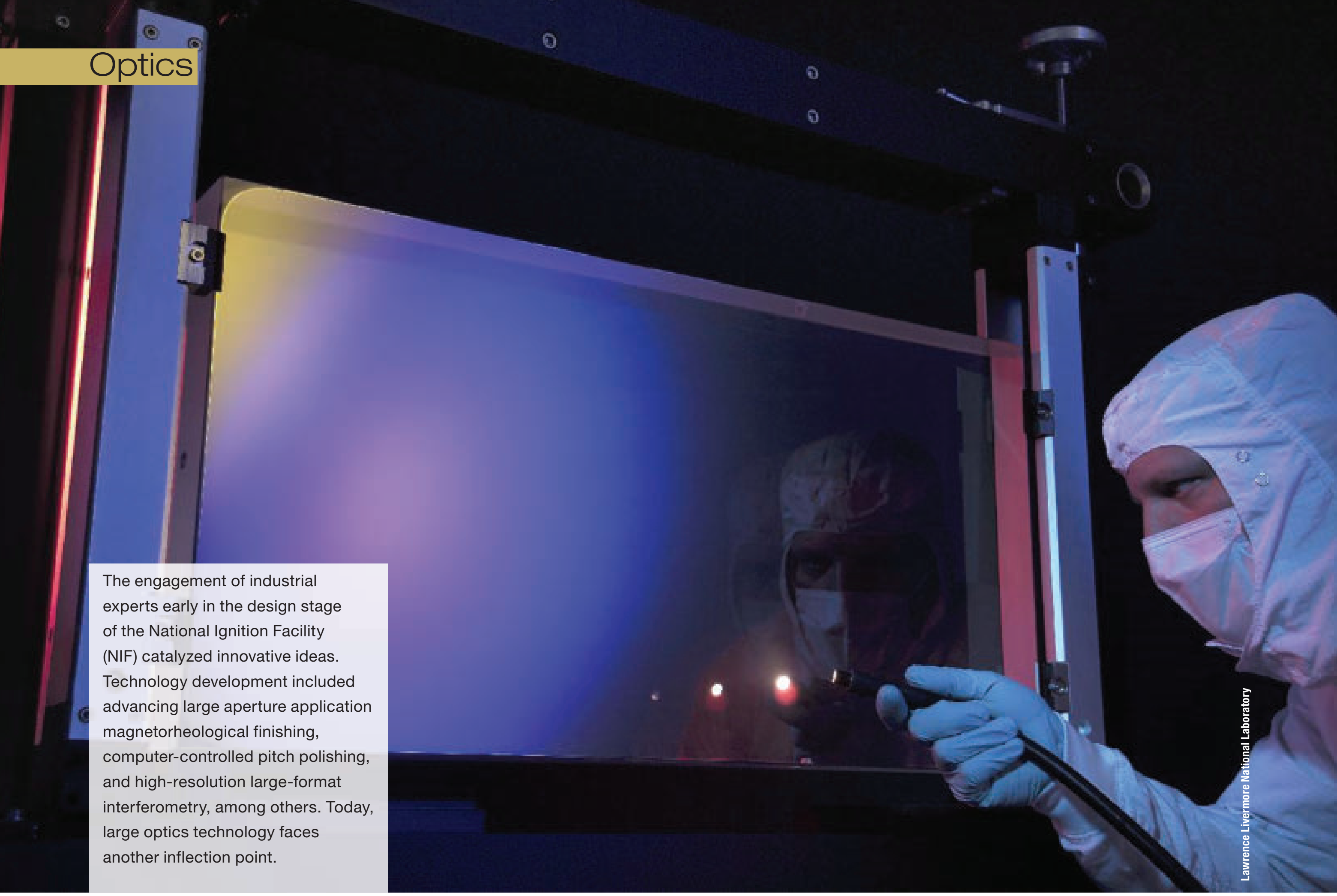
"We measured the absorbance of these soil suspensions at various wavelengths ranging from 200 to 500 nm using a spectrophotometer and, based on this, determined the N/MP concentrations in the soil," researcher Kyouhei Tsuchida said. "Then, the best combination of two wavelengths was identified for measuring N/MPs, which helped negate the interference from soil particles and leached components in the suspension."

A wavelength combination of 220 to 260 nm, and 280 to 340 nm had the lowest error level for the samples, making this wavelength combination the most suitable for measuring N/MP concentrations in different soil types.

Since the adsorption potential of N/MPs in the soil varies depending on soil characteristics, the researchers created a calibration curve between the concentration of N/MPs in the soil suspensions and the N/MP content added to the dry samples. The curve showed a linear relationship between the two variables and allowed for the adsorption of N/MPs on soil particles.

"Our novel measurement approach can quantify different N/MPs, including polyethylene and polyethylene terephthalate, in a variety of soils and can easily be used as an initial assessment tool. Moreover, it can help further our understanding of the distribution and migration behavior of N/MPs in the geosphere environment," Tsuchida said.

The research was published in *Ecotoxicology and Environmental Safety* (www.doi.org/10.1016/j.ecoenv.2024.116366).



The engagement of industrial experts early in the design stage of the National Ignition Facility (NIF) catalyzed innovative ideas. Technology development included advancing large aperture application magnetorheological finishing, computer-controlled pitch polishing, and high-resolution large-format interferometry, among others. Today, large optics technology faces another inflection point.

Lessons from the Past Shape the Future of Large Optics

Specifications for large-format optics have changed. The next wave of commercial large optics must adapt.

BY FLEMMING TINKER
APERTURE OPTICAL SCIENCES INC.

In the 1990s, several daunting technological challenges converged, redefining both the perception and parameters of large optics. With the unprecedented demands of initiatives, such as the Lawrence Livermore National Laboratory's (LLNL's) National Ignition Facility (NIF), the James Webb Space Telescope, the Extremely Large Telescope (ELT), and numerous other large telescope projects on the drawing board, the optics industry required a scale-up and new levels of performance. In the electronics sector, meanwhile, new-to-emerge classes of consumer and industrial devices demanded large-format, defect-free glass panels, which further influenced the upward growth trajectory of large optics.

Now, another inflection point has emerged to facilitate the future of large optics, motivated this time by the expansion of laser fusion technology and the strategic demand for directed energy defense systems.

From historic scale-up projects in astronomy and high-energy laser systems, leaders in the optics industry have learned valuable lessons that will guide the field forward. With new growth drivers creating a set of challenges, which are still evolving, it has never been more critical to understand and consider the perspectives of leading professionals. As industry broadly readies to adjust, a look to the past provides valuable insights to chart the course ahead.

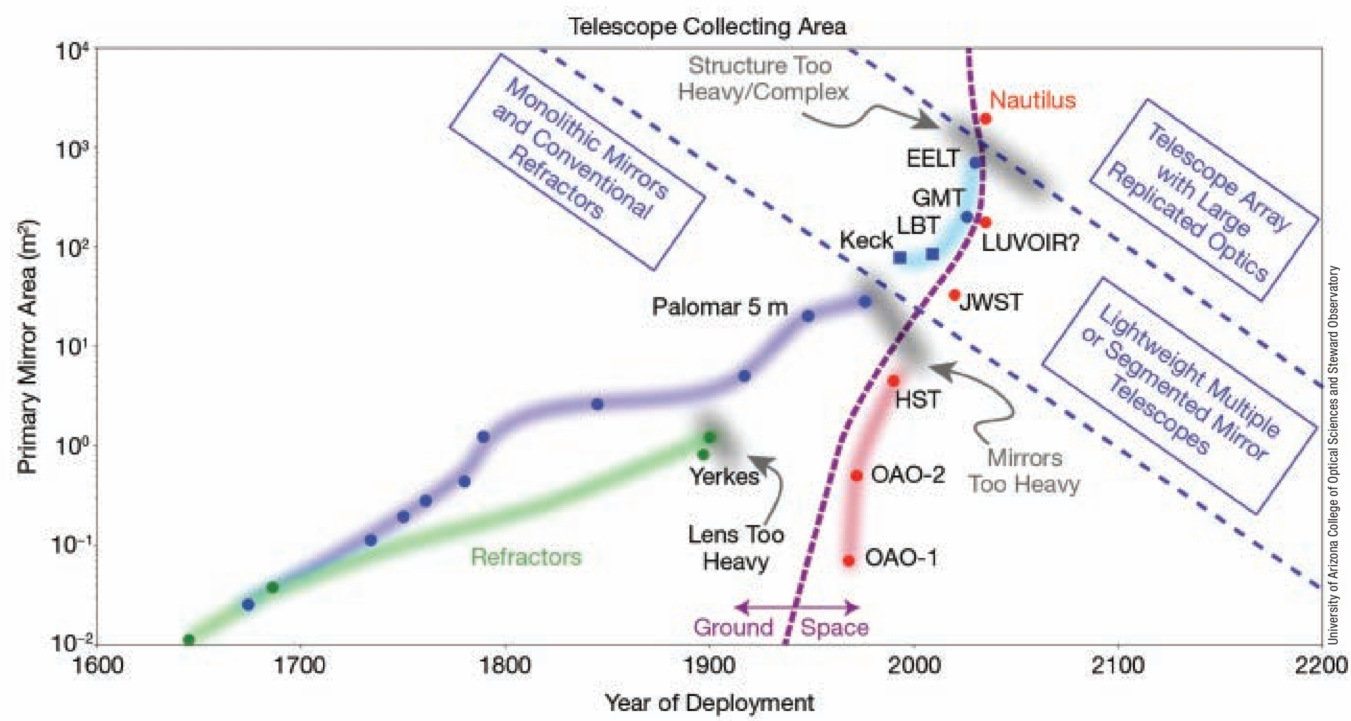
How large is large?

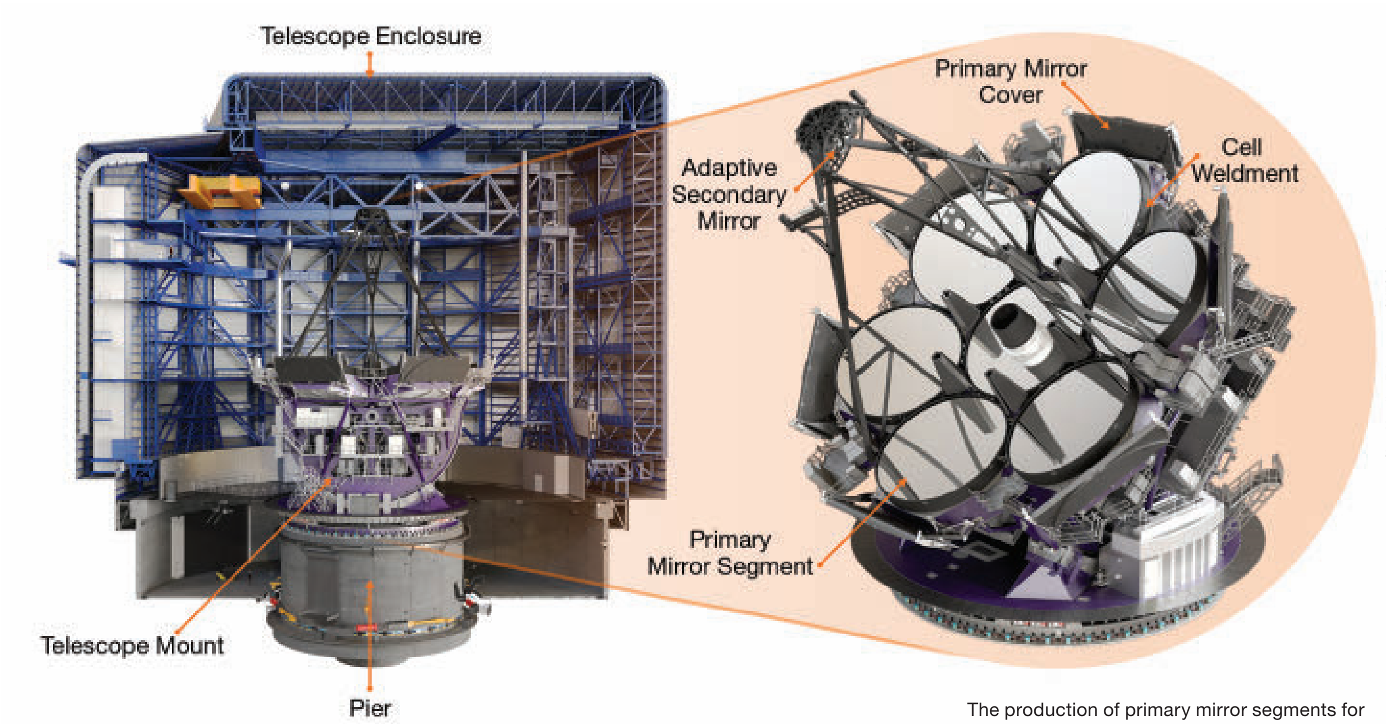
In the 1980s, "large optics" generally enveloped any class of optics having an aperture >4 in. Even today, the majority of optics produced are this size or smaller, though the technology and global capability for optics of up to 300 mm is not uncommon. Surface finishing and metrology and coating technology have matured in response to 300-mm-class semiconductor wafers and requisite lithography technology. In many circles, large optics begins with elements or components of 0.5 m and describes any optic greater than this size.

This is not to say that large optics is a nascent concept. Since Lord Rayleigh described the inverse relationship between aperture and resolution, scientists have pushed designers and manufacturers to develop larger telescopes to improve the detail of images. Increased aperture also provides for larger light collection as well as improved signal strength to more deeply penetrate the heavens and reveal new exoplanets and the presence of life.

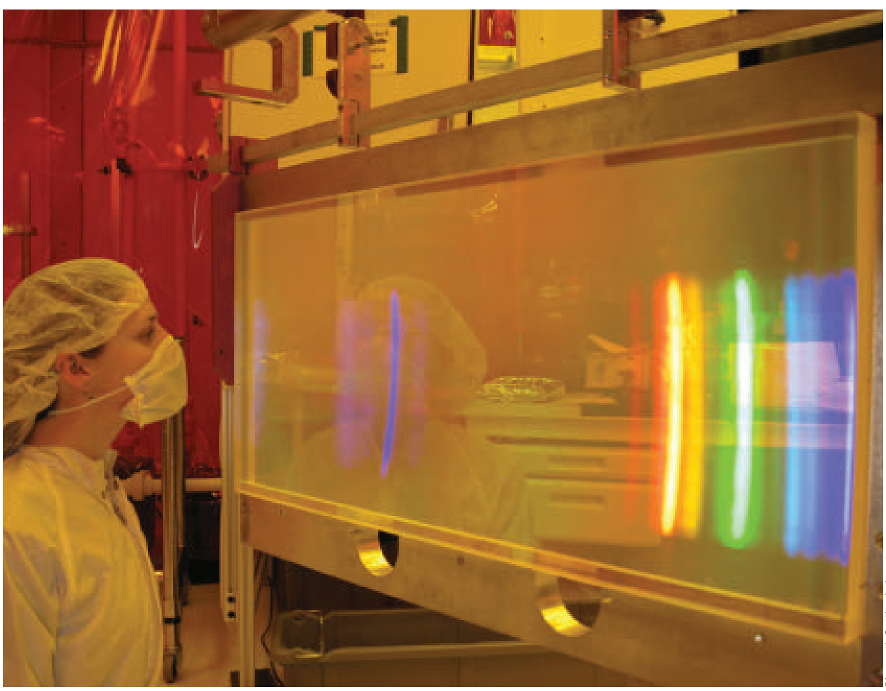
This is a strong motivator for expanding the role and manufacturability of large optics. For example, the authors of a 2019 publication introducing the Nautilus space array concept presented an illuminating commentary on the history and technology drivers of large optics for astronomy[1]. Their analysis showed that by the early 20th century, materials and mass limited the feasibility of refractive telescopes to ~1 m. And while extraordinary efforts could produce monolithic primary mirrors as large as 5 m in diameter — for

The evolution of primary mirror collecting area(s) for individual instruments over time, with remarks indicating the key technology inflection points. The primary mirror collecting area, also known as the light-collecting area, is the total amount of area that reflects light onto the telescope instrument's secondary mirror.





The production of primary mirror segments for the Giant Magellan Telescope commands a hybrid approach to giant aperture mirrors in a lightweight segmented form **(above)**. The seven primary mirrors of the telescope, which is currently under construction, are sized at 8.4 m.



Diffraction gratings are among the optical components that a 2024 report from the Emerging Technology Institute and National Defense Industrial Association cited as necessary to scale up to bolster the directed energy weapons (DEWs) manufacturing base **(left)**.

example, the Hale Telescope Primary Mirror — the technology that is required to create precise wavefront quality ultimately proved to be limiting.

The next major technological leap introduced segmented mirrors with lightweight cores. Materials development, along with enhanced finishing capability provided by computer-controlling polishing, enabled many of the most ambitious telescopes — and, as a result, some of the most ambitious large optics manufacturing projects. These include the Keck Telescopes, the James Webb Space Telescope, and massive primary mirror arrays, such as the Thirty Meter Telescope (TMT), and the 39.3-m-diameter primary mirror for the European Extremely Large Telescope (EELT). In each of these cases, numerous primary mirror segments must be exquisitely fabricated over dimensions on the order of 1.5 m each. The modern-day effort to produce the 8.4-m primary mirror segments for the Giant Magellan Telescope, for example, necessitates a hybrid approach to giant aperture mirrors in a lightweight segmented form.

Construction efforts on the TMT and ELT remain incomplete. It is still unclear, and perhaps doubtful, as to whether this technology will be the preferred solution for even larger terrestrial telescope

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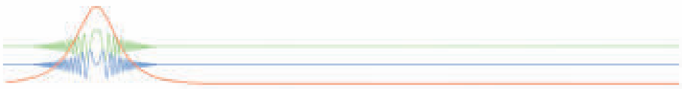

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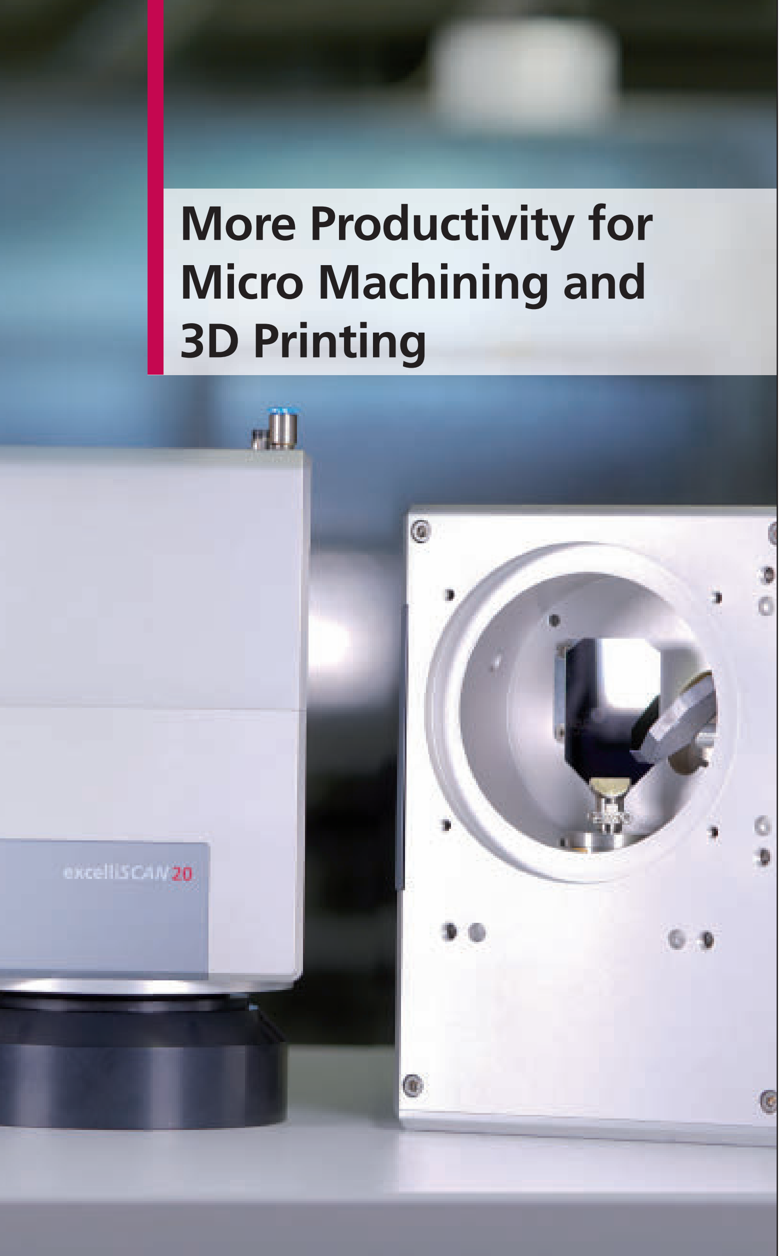

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projects. One such undertaking, the Overwhelmingly Large Telescope (OWL), requires 3264 individual mirror segments to achieve a primary mirror array anticipated to be 100 m in diameter.

The throes of fusion energy

The requirements of the NIF posed an extraordinary question to the teams of designers charged with developing the optics for this device in the early 1990s: “What will it take to make the 7000-m-scale optics required by the facility — a high-energy laser laboratory housing 192 laser beams, each having a cross-sectional aperture of 40 sq cm — in three years?”

This was not the only requirement facing industry. It was necessary to produce the optics for 20% of the present-day cost.

In response, one of the industrial teams produced three scenarios to consider. First, how many people and machines would it take to fabricate the necessary optics using current methods and technology? Second, what would be the effect of modern industrial engineering principles, including production engineering, line balancing, and integrated flow management?

Finally, what would a future production facility look like with new, innovative technologies that are yet to be developed?

Questions two and three ultimately combined to yield the only practical solutions. Even if the entire global capacity was pooled, the designers would still lack a feasible way solve the scale-up problem with brute force capacity expansion.

More than 15 years after the optics manufacturing team first considered these questions, and roughly 10 years since the start of construction on the NIF, researchers prepared to test the facility in early 2009. Looking back on 10 years of operations, the NIF team remarked in 2019[2]:

> On March 9, 2009, a staggering 2 trillion watts of electrical power — 4 times more power than the United States uses at any instant in time — surged through the NIF to generate the intense light that powers the laser. At that moment, 192 laser beams raced down the beam path and converged to deliver an immense blast of energy onto a tiny target. This test shot was a key milestone for NIF, fulfilling one of its first critical design specifications.

According to Chris Stolz, associate program manager for NIF and Photon Science optics supply at LLNL, the journey to realizing a functional NIF imparted valuable lessons that can provide guidance on how to meet demands for large optics in the future.

First, rethinking the ways that optics are specified is a core consideration. The NIF optics worked as designed because the team adopted a new way of characterizing and measuring wavefront error(s). Conventional specifications, such as peak-to-valley wavefront error(s), were replaced in the hierarchy of importance with controls on mid-spatial frequency errors using high-resolution characterization of wavefront slope and placing constraints on errors in the high-, mid-, and low-spatial frequency regime(s). This change ushered in new disciplines and demands on manufacturing and metrology.

The takeaway: Do your best to connect quality metrics as close as possible to performance objectives, even if it means replacing established standards. The future will require its own set of “new” standards.

For a project of the NIF's magnitude and scope, the need to adapt existing capabilities eventually feeds into a need to develop new technology. The NIF project team empowered industry to develop solutions to address capacity, workforce development, and production throughput. Other unrelated technology developments proved to be essential to the available industry solutions. The availability of megapixel cameras and fast computers changed the game, while high-resolution detectors enabled interferometers to see more detail in wavefronts, and faster processing meant that statistical controls could be employed to obtain more accurate results. Better measurement technology ensured better process control as well as more quantitative approaches to optics fabrication.

The NIF team's engagement with industrial experts early in the design stage incubated innovative ideas by funding new technology development. Essential technology development was funded in preparation for the production phase of NIF. These technologies included advancing large-aperture application of magnetorheological finishing; computer-controlled pitch polishing; electrolytic in-process dressing grinding; potassium dihydrogen phosphate (KDP) crystal growing; high-resolution large-format interferometry; and advanced facility and production flow simulation. Successful developments were exploited, and ineffective ideas were excised through a pilot production phase. New technologies were made robust by exercising the tools and methods with sufficient preproduction work to establish reliable methods. These potentially risky innovations proved to be essential because they were championed early.

Large optics in fusion energy: the future

In the landmark demonstration on Dec. 5, 2022, NIF scientists demonstrated the release of 3.15 million joules of energy compared with the 2.05 million joules focused on the target. Fusion energy gain was demonstrated using lasers for the first time. This advancement, along with the proliferation of experimental high-energy laser facilities around the world, portends the necessity of a new age in large optics demand. The awarding of two Nobel Prizes for seminal achievements in this area of photon science since 2018 has only affirmed the vitality of this growing field.

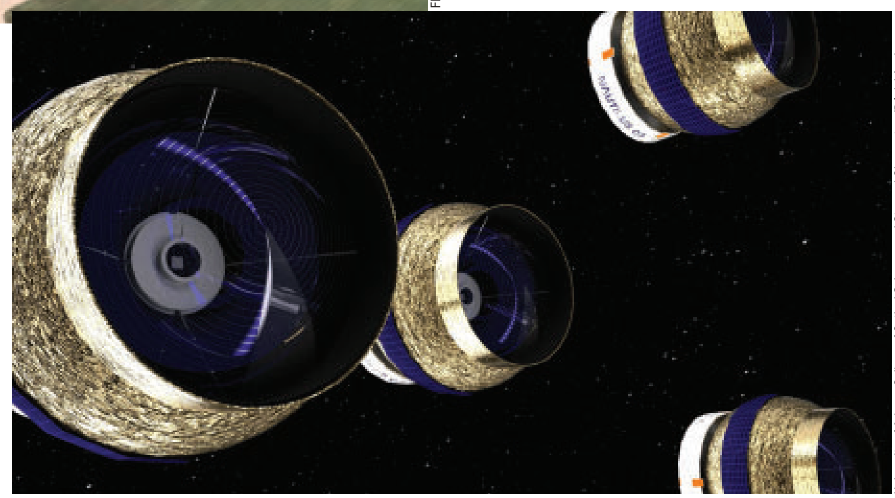
In consideration of the projected demand for large optics in the next two decades, the field must drive several necessary changes. First, and simply, the optics must get larger. Due to fundamental limits in the materials required for reflective coatings, the incident laser energy reflecting off their surfaces progressively destroys today's commercially available coatings. From this consideration of laser-induced damage threshold (LIDT), today's optics have evidently reached a limit.

Researchers from industry and academia are actively studying how to increase LIDT, although the physics imposes barriers. One solution to the problem of keeping today's lasers operational is to create a huge stockpile of spares and immediately replace and recycle them as they fail. Another option is to spread the incident energy over a larger surface area by making the optics larger. This would necessitate that 40-cm beams grow to 60 cm, 80 cm, or even larger to satisfy the demand of greater energy handling. In either case, laser optics must get larger. They must also be made faster, cheaper, and in higher quantity.

Fluor Corporation/Longview Fusion Energy Systems

The functionality of large optics is vital to the successful development and online capabilities of fusion energy plants **(left)**. This conceptual fusion power plant is poised to support the global energy market.

The Nautilus Space Observatory concept uses a constellation of ultralightweight multi-order engineered diffractive (MODE) lenses **(below)**. These optics can be mass-produced quickly, and in cost-efficient ways by precision glass molding. Since they are transmissive optics, they are much less sensitive to misalignment, making them cheaper and easier to replicate.



University of Arizona College of Optical Sciences and Steward Observatory/Daniel Apai

Perhaps the best indicators for the future of large optics in the domain of laser fusion come from purely application considerations.

Stolz made the following observation: Consider the following ratios. The NIF currently believes that gains of 15× may be possible in the next decade, which is what would be needed for a self-sustaining fusion demonstration plant, with gains of 50 to 100× required for a commercial electricity-producing plant. If fusion were to match the scale of fission power today in the U.S., it would require constructing approximately 100 fusion plants. With the rising demands for energy, and preferably clean energy, it is conceivable that the nation will need far more than that, and we would want to build plants at a rate of several fusion power plants per year.

The NIF took 10 years to build. These numbers imply that we need to scale up the industrial capacity for NIF-like large optics by a factor of 100. These are staggering numbers and represent a much larger challenge than those that optics designers and society faced in the 1990s.

Reflecting on the lessons learned, it is necessary to prepare early, rethink specifications, exploit broader industrial advancements, and innovate ways to make laser transport and focusing devices. It is more about developing bigger ideas than making bigger manufacturing machines.

Ultrahigh energy delivery

Fusion energy is not the only tailwind spurring large optics innovation. Under the umbrella of national defense, strategies for missile and drone defense open the door to directed energy weapons (DEWs) that require highly precise large optics.

These optics are similarly vulnerable to the same failure mechanisms as fusion energy optics, highlighted by laser damage threshold. The solutions at hand are also much the same: Make optics larger, and with new advanced materials that can endure higher fluence(s) at longer durations.

A national survey of the U.S. directed energy industrial base, "Directed Energy Weapon Supply Chains," published earlier this year by the Emerging Technology Institute and National Defense Industrial Association, reached several conclusions. First, the report found that the current DEWs manufacturing base is capable of producing only small numbers of systems, rendering it insufficient to support fielding DEWs at scale. Long lead times for the assembly and delivery of these systems further hinders the manufacturing base, and its recipients in the national defense community as a result.

The report further concluded that efforts to scale up production would quickly run into issues, including producing optical components, such as diffraction gratings, mirrors, and lenses, as well as beam directors, batteries, and the regulatory regime governing what the report characterized as, "above-the-horizon DEW testing." The Emerging Technology Institute and National Defense Industrial Association ultimately recommended the establishment of DEW programs of record that provide clarity on future system demands plus the standardization of requirements for DEW systems, components, and testing. And the agencies advised harnessing technology from the commercial industry when possible.

The report additionally cited current DEW workforce shortages in the areas of optics, optical coatings, and energy production. As a result, upscaling production for DEWs faces a challenge: The current DEW workforce is insufficient to support upscaling DEW production, according to the report. “As such, [the Department of Defense] should expand existing workforce development efforts by establishing a DEW University Consortium with the specific goal of creating a strong workforce to meet future DEW needs,” according to the report.

Finally, the report highlighted the vulnerabilities that DEW supply chain(s) face, particularly due to limited suppliers of beam directors, adaptive optics, optical coatings, specialty optical fiber, beam dumps, ceramic laser materials, and fused silica. “While the overall financial health of directed energy companies is relatively stable, the failure of even a single company could have severe repercussions due to limited supplier concerns,” the report said.

Ideas for an evolving industry

Given the volume of work needed to meet the anticipated forthcoming demand for large optics technologies, it is open season for ideas that provide solution paths to current challenges. Diffractive optics is one technology that could hold an answer for very large telescopes. Innovative concepts, such as the Nautilus Space Observatory, may enable extraordinary light collection capability, comparable to a 50-m primary mirror.

The Nautilus concept uses a constellation of ultralightweight multi-order engineered diffractive (MODE) lenses developed at the University of Arizona College of Optical Sciences and Steward Observatory. According to Dániel Apai, principal investigator for the Nautilus Array, MODE lenses can be mass-produced quickly, and in cost-efficient ways by precision glass molding. And, since they are transmissive optics, they are much less sensitive to misalignment, making them cheaper and easier to replicate. This quality, Apai said, is vital for resilient satellite constellations.

Downstream, the continued advent of metamaterials and nanostructured surfaces on large substrates could change the way industry views and uses large optics for high-energy lasers. Companies, such as Desktop Metal, have helped to reshape the additive manufacturing industry and are actively innovating materials-enabled products with advanced printed ceramics for optical applications. Desktop Metal has already brought printed silicon carbide substrates of up to 1.8 m in size to commercial readiness, and the technology to produce wide-area nanostructures is within grasp. These foundational technologies may be the answer to creating large-aperture athermal optics without the need for traditional grinding and polishing.

Further research into additive manufacturing replication and nanostructured diffractive optics could reveal transformative pathways for how large optics will be made in the decades to come. Optics that are more lightweight, better able to manage heat, and more resilient to intense energies will demand changes to the modern optics factory.

Resistance to such changes and challenges in workforce development came within reach of defeating the U.S. optics manufacturing industry in the 1980s. This memory, the need for large optics technologies, and the technologies already deployed today will need to combine to drive change once again to meet the needs of tomorrow.

Meet the author

Flemming Tinker is the founder and president of Aperture Optical Sciences Inc. He has been a developer of large optics and imaging technologies for more than 35 years and has advised optics companies worldwide; email: ftinker@apertureos.com.

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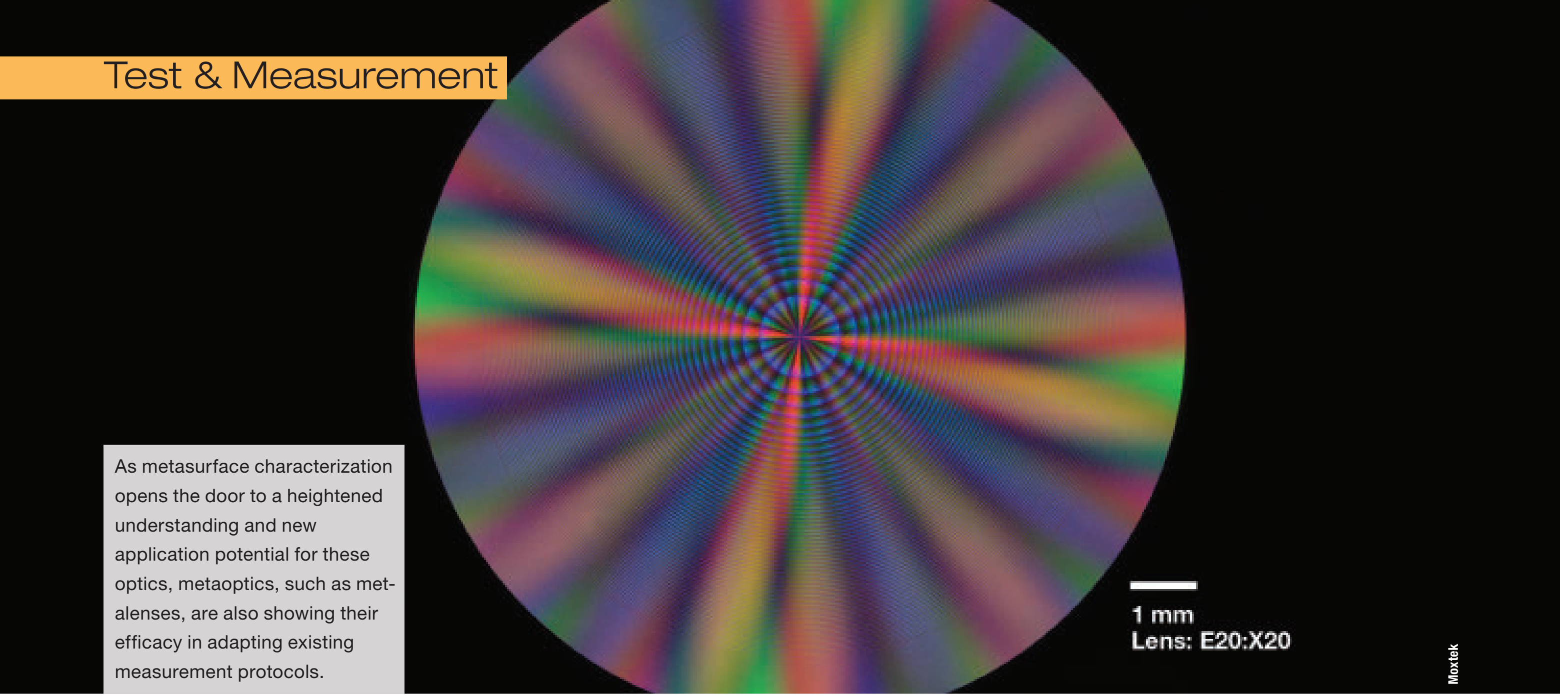


Moxtek

As metasurface characterization opens the door to a heightened understanding and new application potential for these optics, metaoptics, such as metalenses, are also showing their efficacy in adapting existing measurement protocols.

Meta-Optical Metrology

Clears a Path for New Characterization Methods and Products

The symbiotic relationship between metaoptics and optical metrology tools is leading to a rise in the use of metamaterials for commercial solutions as well as improved test and measurement techniques.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

Meta- and nano-optics are on a fast track to a wide array of photonics systems and commercial solutions, enabling advancements that extend beyond the capabilities of more common and traditional optics. At the same time, owing to metaoptics' dynamic physical and performance parameters, the convergence of optical metrology techniques with these optics is poised to reshape existing measurement protocols and pave the way for new approaches.

Metasurfaces, the 2D subset of metamaterials, scatter and manipulate light in exceptional and sometimes unexpected ways. From their subwavelength thickness, engineers can use the structure of metaoptics to create components with previously unattainable properties. The field already attracts large-scale investments from companies such as Apple, Google, and Samsung. These tech giants are at various stages of marketing vision and imaging systems that provide consumers with previously unachievable features and performance in consumer electronics devices and solutions for authentication and telecommunications.

March to market

According to Valentin Genuer, field application manager at PHASICS Corp., a developer of wavefront sensors and optics testing stations, widespread excitement around metaoptics stems from the potential that the field holds to transform optical technologies by providing unparalleled control over light. The field, he said, enables the creation of optical devices that are both compact and versatile, with applications in various domains.

It is also a field that benefits from the influence of stakeholders in multiple disciplines.

"The continual collaboration among researchers from physics, materials science, electrical engineering, and optics fosters ongoing innovation, leading to new breakthroughs and practical applications," Genuer said. As it relates to metamaterials for a company offering the capabilities of PHASICS, for example, opportunity exists in the need to qualify metaoptics and metasurfaces. This can be accomplished using wavefront sensing methodology to measure the nanostructures that compose metasurfaces.

Numerous research groups have reported advancements in metaoptics during the last decade. Upon demonstrating functional prototypes, the focus has shifted to working with optics fabs to produce volume levels for existing applications.

"The reason for the enormous commercial potential of metaoptics for high-volume markets, such as consumer electronics, is that [they] can be manufactured with basically the same fabrication technology to make chips, based on deep-ultraviolet lithography: CMOS-compatible metaoptics," said Federico Capasso, the Robert L. Wallace Professor of Applied Physics at Harvard University.

"This is game-changing. Thus, the major chip foundries are now manufacturing metaoptics."

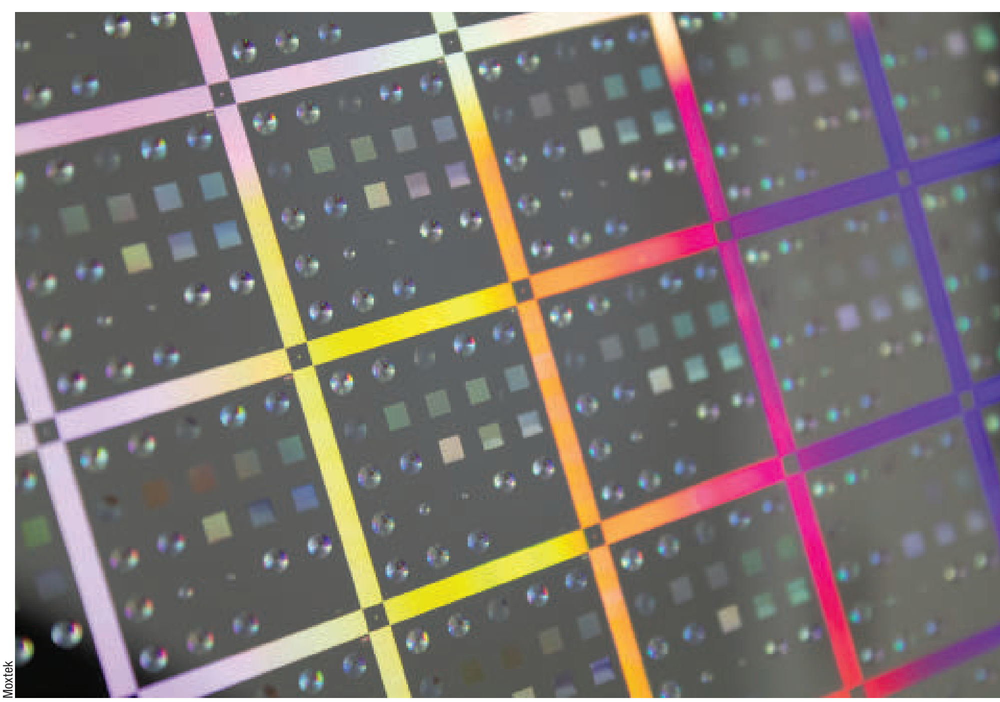
A wave of commercial components using metasurfaces is on the market. Companies such as Metalenz (cofounded by Capasso), Moxtek, and NIL Technology are among the firms manufacturing metalenses. Applications span polarization imaging, microscopy, and biosensing.

Meanwhile, as this class of optics makes its mark on established applications, innovation continues in R&D settings. Capasso's group, for example, has pioneered a class of polarization-sensitive cameras — which Capasso said are being used in two NASA projects. "This new camera principle, using a new metasurface polarization optic, has enabled Metalenz to demonstrate a new product, Polar ID, for secure face authentication," Capasso said.

The use of the Capasso group's polarization-sensitive metasurface in Metalenz's PolarEyes camera allows for the creation of a smaller polarization camera, making the camera portable and a viable consumer device. Unlike traditional polarization cameras that require a complex array of components to analyze Stokes parameters using amplitude or time division, a single metasurface does the job.

"In metaoptics you can have polariza-

A 200-mm-diameter wafer with >1000 metalenses, each of which is designed and optimized for various optical systems.



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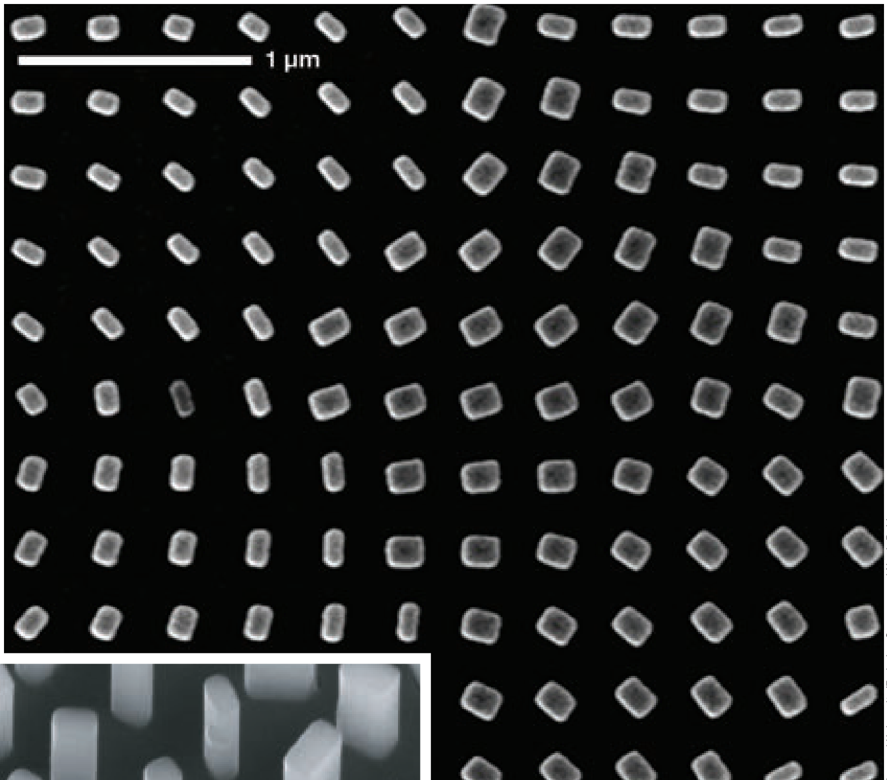

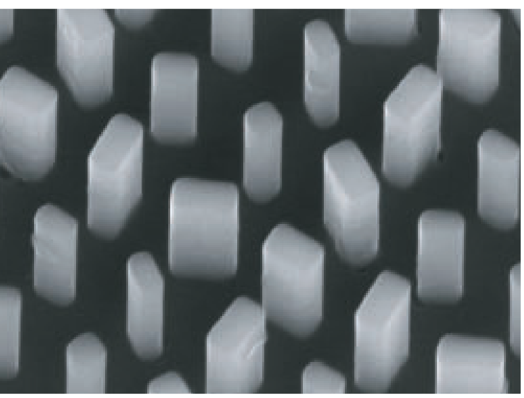

Harvard University/Federico Capasso and Noah Rubin

The micrograph section **(above)** shows a metasurface consisting of titanium dioxide nano-fins with a height of 600 nm. They are tiny waveguides **(magnified, left)** that exhibit structural birefringence due to their anisotropy. Visible light polarized along the short and long sides sees a different effective refractive index. A periodic array of this metasurface, combined with a lens and a CMOS sensor, forms an ultracompact single-shot polarization-sensitive camera capable of capturing, point by point, the polarization of a scene, including elliptical polarization.

tion-controlling elements — analyzers, polarizers, waveplates, etc. — that don't use material birefringence, like standard polarization optics, but structural birefringence, also known as shape birefringence," Capasso said. "Structural birefringence elements are, for example, rectangular nano-pillars, where light sees different effective [indices] when polarized along the two sides of the rectangle."

Elsewhere in industry, semiconductor firm STMicroelectronics has partnered with Metalenz on a solution using metaoptics in facial recognition lidar systems for cellphone cameras. Metaoptics imaging technology developer Tunoptix is developing visible and IR metalens designs, targeting a variety of camera sensor applications.

Still, the popularity and prowess of metaoptics does not necessarily indicate the nascence of this technology. For about 25 years, Utah-based nano- and micro-optics manufacturer Moxtek has mass-produced 1D periodic nanostructured metaoptic gratings, including wire-grid polarizers based on its Nanowire technology. The company uses a nanoimprint replication process to produce large-scale quantities of metasurfaces, which it aims to deploy for new applications due to integration-friendly form factors.

"This production capability allows Moxtek to capitalize on emerging metaoptic designs such as [metalenses] and other diffractive optical elements," said Shaun Ogden, general manager at the company. According to Ogden, companies are evaluating Moxtek metaoptical components to replace or supplement existing conventional approaches.

Characterization: vital to market success

In the lifecycle of optical technologies, metrology is essential not only as a final validation tool but also as an integral aspect of design and manufacturing processes. The early integration of metrology helps to ensure the manufacturability, scalability, and customization of these technologies, smoothing their transition from innovative concepts to mainstream applications. To move into the mainstream and support mass production in a cost-effective manner, highly precise and repeatable measurements must be able to be performed.

Metrology of metaoptics poses significant challenges due to the specialized nanofabrication required for these materials. Traditional test and measurement methods are apt to fall short in accurately capturing the detailed functionalities of these advanced materials.

Metrology tool designers are addressing this bottleneck. "The availability of research-grade metaoptic metrology tools is supporting the growing commercial success of metaoptics," Ogden said. "However, the limited test speed of the current tools needs improvement to support high-volume production. Rapid, specialized, wafer-scale metrology tools will be required as volumes continue to ramp."

Metaoptics designed for visible and near-IR wavelengths require submicron feature sizes with precise tolerances and tightly controlled production processes. At volume production scales, a single wafer may contain hundreds or even thousands of small metaoptics. So, the sheer volume of measurements required for commercialization places major demands on test and measurement tools.

"The number one need is for quality control to be applied in the most automated way, in situ, and in real time, so that faults and imperfections can be identified quickly and efficiently," said Themos Kallos, cofounder and chief science officer of nanotechnology and functional materials company Meta Materials Inc. (META).

"The main challenge is that nanoscale

resolution is required but over large surface areas (around 1 m in length). The depth of the metasurface features can be 10 nm, so this needs to be measured across a length that is 100-m-times larger than the depth."

New measurement capabilities

Producers of lens measurement devices that are actively developing and enhancing tool sets to better measure metaoptics must balance the need to perform accurate measurements at both low and commercial volumes. Moxtek, for example, currently uses a TRIOPTICS ImageMaster measurement test station. It plans to switch to TRIOPTICS' higher-volume tool.

According to Kallos, several key advancements are already underway that are serving to improve metrology for real-world applications — including those using metaoptics. "First is enhanced resolution, to distinguish the nano-features usually present in metaoptics structures; second is real-time, in situ monitoring, for example, adapting the methods for a production environment, not just the laboratory," Kallos said.

"And third is scalability, which means being able to offer quality control over large surface areas and large volumes."

While metrological concerns may hinder aspects of the commercialization of metaoptics, they have also kickstarted innovations that enhance the commercial viability of these technologies. For as much as metrology considerations are essential to the sustained adoption of metaoptical technologies, metaoptics themselves are valuable elements to characterizations elsewhere in the optics value chain.

One example is characterizing focusing efficiency. Conventional lens manufacturers may not perform measurements for focusing efficiency, because significant losses in these lenses owe mainly to surface reflections. For metalenses, in which considerations to physical structure vary considerably from conventional lenses, characterizing focusing efficiency is highly important. Metalens-specific metrology approaches must also be able to capture higher-order focal spot information and zero-order leakage.

To perform this operation, spectrally filtered light is used to illuminate an object using a pinhole or cross aperture. A conventional lens collimates the light from the object and sends the light toward a metalens. The metalens then focuses this light to recreate the object image at its focal plane. Next, a microscope objective is focused onto the same focal plane as the metalens, and the recreated object image is recorded and analyzed to determine the performance of the lens. By adjusting the position of the objective lens, data can also be collected for zero-order and higher-order modes.

"Another method is to illuminate the meta-element with collimated light and project the transmitted light on a scattering screen that can be recorded by a camera," said Daniel Bacon-Brown, an engineer at Moxtek. "This can be useful for studying meta-elements that are non-focusing, such as diffraction gratings and structured light generators."

Metasurfaces also find application in


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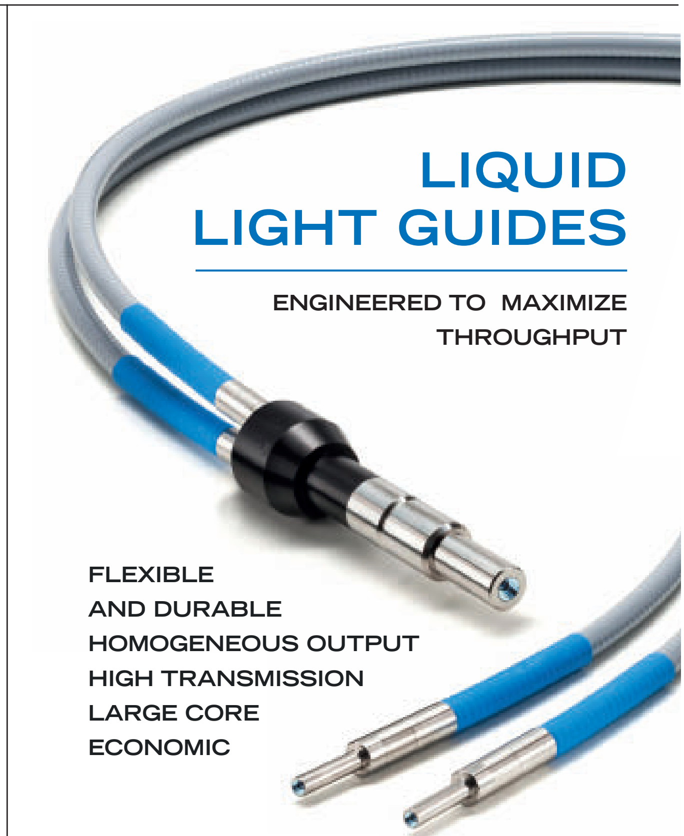

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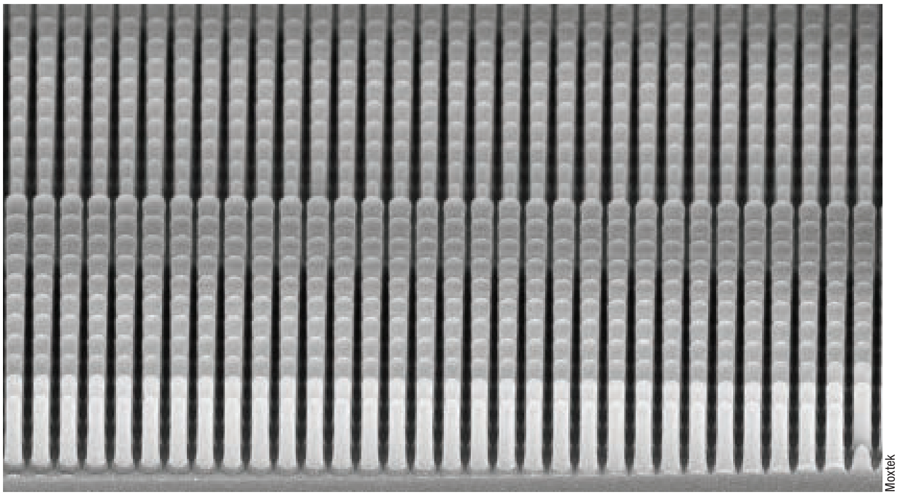


The shape and spacing of the meta-structures, shown as captured via a scanning electron microscope, are critical to achieve optimal performance. Among the metasurfaces that Utah-based Moxtek develops are metalenses, metaoptical elements, and diffractive optical elements.

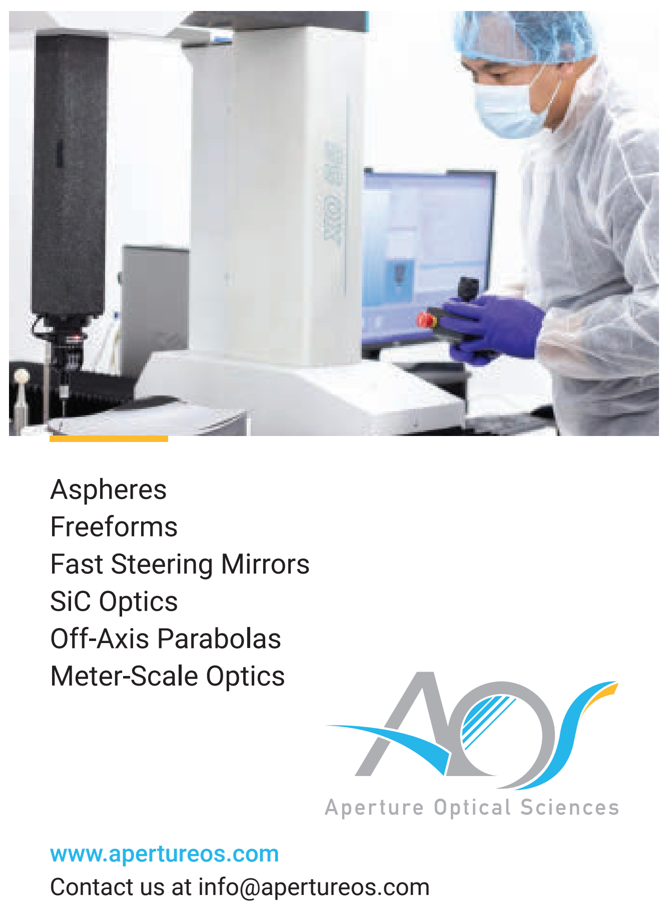
interferometry. A light beam that is transmitted through a metasurface is combined with a second reference beam of the same wavelength. Differences in the pattern of diffraction can be linked to differences in the phase inflicted by the metasurface at a particular location.

According to Kallos, the challenge in this application is to scan a large surface area.

"The interferometric beam needs to be scanned using a movable mirror system, for example, or expanded to cover a large area, then the diffraction pattern imaged onto a sensor," Kallos said.

Evaluating such vast quantities of data may require advanced image processing to distinguish signal variations created by interference caused by the metasurface phase change at a particular location. This change is due to signal variations that stem from the spatially varying structure of a metasurface.

PHASICS' interferometric systems are based on a nonpolarization-dependent and achromatic approach. "This interferometric method and the way we implement it in our instruments make it well adapted to the metrology of metaoptics," Genuer said. "Our main instrument is a camera-like device suitable for in situ measurements. Instead of having to bring the samples/wafer to a metrology room, one can perform measurement in situ or



at least very close to the manufacturing line."

Application considerations

The efforts of product engineers as well as researchers and developers have advanced the application of metasurfaces to optical metrology problems in recent years. The importance of compact components and devices to the constant pursuit of improved levels of precision and control in the optical domain increases the likelihood that a new generation of optical metrology engineers, trained in nanophotonics, will transfer their knowledge and designs into industrial applications. For example, polarization-based optical metrology could benefit from better polarization components that are thinner, exhibit higher polarization contrast, and/or have tighter retardance deviation.

Metasurfaces can already be viewed as a natural evolution of some of the optical components currently used in industrial metrology, such as diffraction gratings. Photolithography company ASML, for example, uses diffraction gratings to carry out overlay metrology between two layers on a chip with an accuracy down to 1 nm in metrology systems used in the semiconductor industry.

"Such metrology targets, currently based on gratings, can be engineered using metasurface concepts for added value [including] higher accuracy, other materials, and smaller feature sizes," said Alberto Curto, a professor at Ghent University and imec. "We have seen impressive demonstrations of displacement sensors with angstrom resolution and related work with single particles, high-finesse meta-mirrors, and, more broadly, the development of picophotonics."

Curto pegs the semiconductor industry as the perfect real-world setting to develop and deploy metasurfaces for optical metrology. "Metasurfaces can be naturally incorporated into wafers as metrology targets," Curto said. "It is an industry that uses typical metasurface materials, such as silicon, with a high refractive index, plasmonic metals, like aluminum or silver, and dielectrics, like silica."

Further, metasurfaces are used for optimized edge detection in analog image processing. Typically, in these cases, a light source illuminates a mask that creates an image that is then "processed" by the metasurface. The resulting image of the mask is used to confirm the sharp edges in real-time optical images, all without the need for a digital computer. According to Kallos at Meta Materials, this science remains an early-stage laboratory concept and deployment, he said, is considered a possibility in the next decade.

Looking forward

Broadly, metamaterials experts who are pursuing applications in metrology stress that more awareness is needed in industry to consider the possibilities offered by both metasurfaces and nanophotonics for designing advanced optical metrology systems. The development of national metrology institutes and the efforts that these institutes would drive would also bolster efforts.

"In-depth engineering is needed to tailor metasurfaces for a specific metrology application, because the potential design space is so vast," Curto said. "From the academic side, it is also necessary to listen to the metrology needs of companies that could potentially benefit from a metasurface-based solution."

These types of dialogues are just now beginning, Curto said.

From within industry, while it is widely understood that the proliferation of advanced optical designs necessitates new measurement capabilities, realizing necessary protocols is a challenge.

Volume production again takes top priority.

"I'm not sure completely new methods can adapt fast enough to industrial scales, but existing ones can be more easily improved," Kallos said. "New product types require adapting optical metrology techniques, such as spectroscopy, ellipsometry, interferometry, and laser scanning confocal microscopy to characterize the features of the metasurfaces at scale."

Capasso agrees that, in general, the same techniques used in the metrology of refractive and diffractive optics can be used in and with metaoptics. He also believes that research on harnessing the distinct capabilities of the metasurface itself can enhance the accuracy of metrology beyond the performance of conventional optics.

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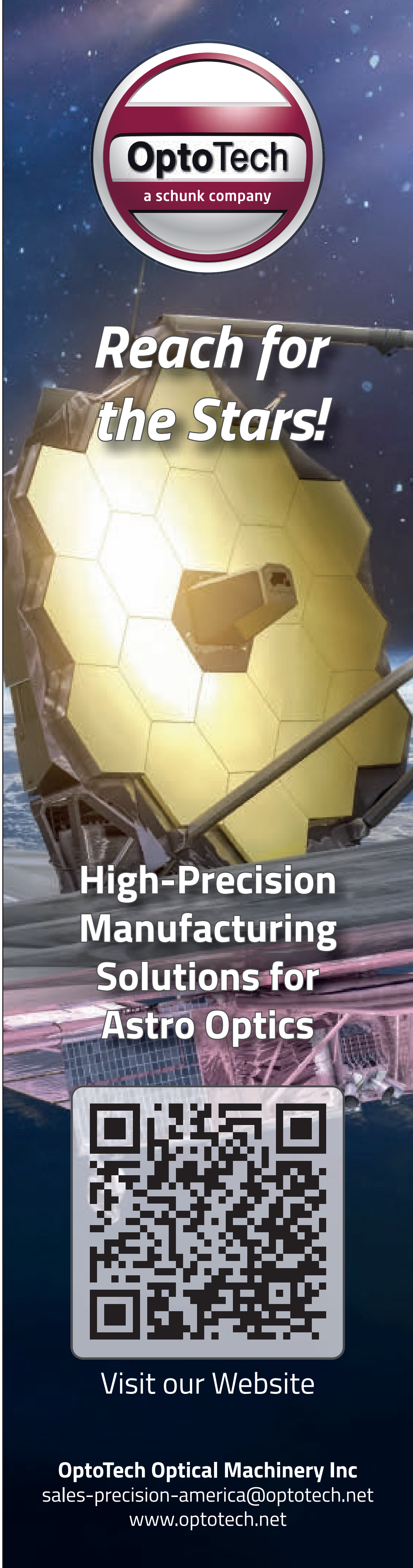

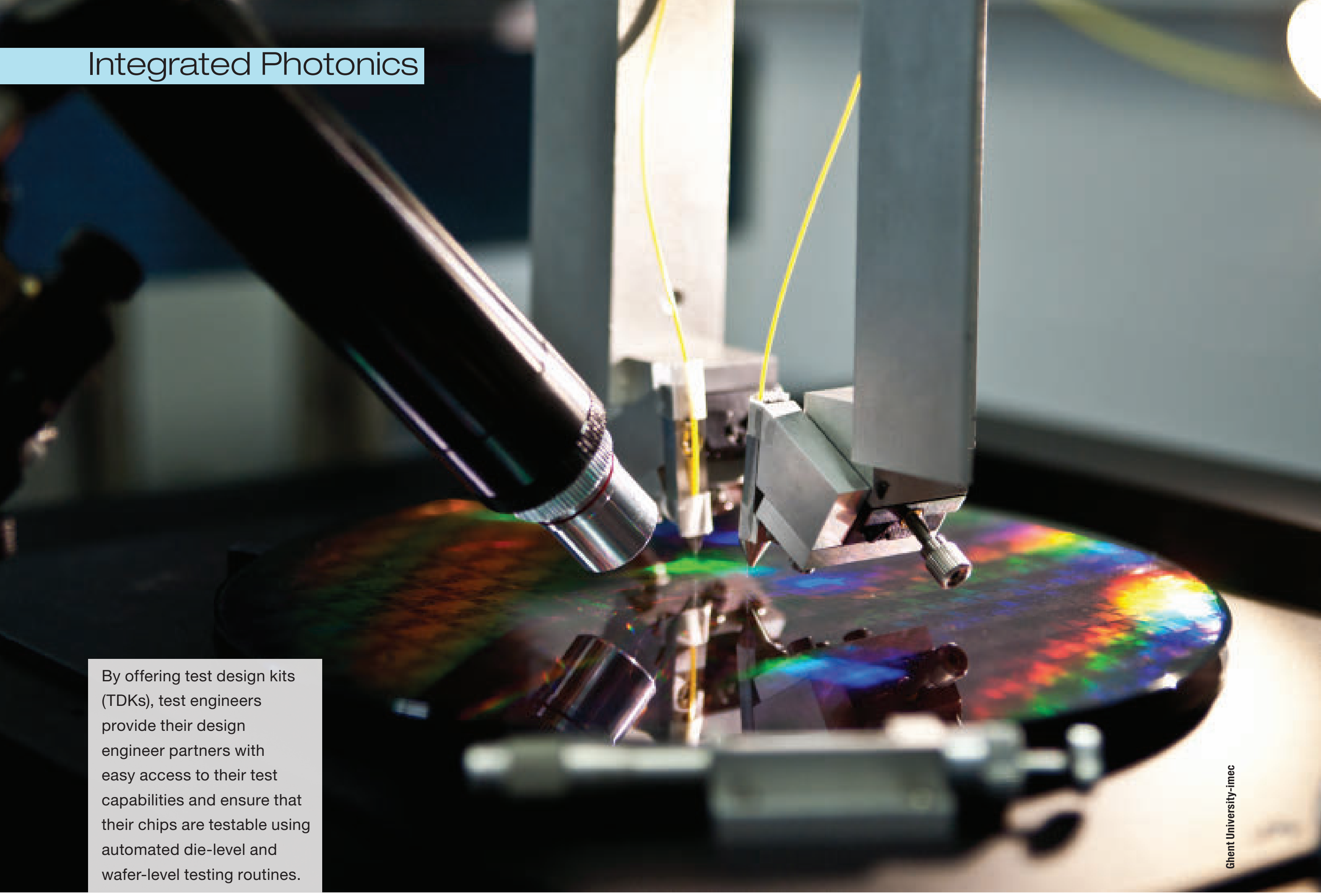

By offering test design kits (TDKs), test engineers provide their design engineer partners with easy access to their test capabilities and ensure that their chips are testable using automated die-level and wafer-level testing routines.

Test Design Kits

Accelerate a ‘Fab-less to Lab-less’ Transition

Limited by legacy test practices amid a ramp-up of photonic integrated circuit production, engineers are turning to test design kits to bridge the gap.

BY CHIARA ALESSANDRI
LUCEDA PHOTONICS, AND
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Increased demand for datacom transceivers and a surge of applications that rely on AI and quantum technology have combined to drive significant growth in integrated photonics. Market research published this spring by IDTechX now values the photonic integrated circuits (PICs) market at more than $20 billion by 2034. As the sector experiences robust advancement in its technologies and markets, this current value indicates only a portion of the potential that integrated photonics appears to be capable of realizing.

For all the promise that market projections offer, forecasts such as these fail to focus on existing challenges that must be met to ensure that integrated photonics maintains and builds on its current momentum. One of the greatest hurdles that currently faces the industry is testing. As the production of photonic chips continues to increase, current test practices, as well as necessary infrastructure, do not scale effectively.

There is more to overcoming this bottleneck than simply identifying it: Testing for PICs is inherently complex, requiring more than sophisticated equipment. It demands extensive know-how in the calibration of this equipment, plus PIC chip design, thermal and polarization control, and high-speed measurements. These requirements demand a depth of expertise held by only a handful of specialists.

In addition, many companies, R&D centers, and academic institutions are unable to afford in-house test equipment, which requires a substantial economic investment to purchase and a skilled workforce to operate. The difficulty in developing and accessing testing knowledge and equipment hinders production scale-up. This emphasizes the need for a more dynamic and accessible testing framework within the industry as well as for standardization.

Test as a service

The concept of testing as a service has been growing steadily in the integrated photonics sector, with momentum both from industry and within foundries, which are beginning to offer complementary test services in addition to their fabrication services. This trend is gradually transforming the landscape by making advanced testing capabilities accessible to a broader range of companies, R&D centers, and academic institutions.

However, a significant challenge persists: The complexity of determining the yield of wafers is often compounded by the fact that many designs are not optimized for testing.

"We often receive wafers and chips that are difficult or even impossible to measure using our standard equipment configurations," said Iñigo Artundo, CEO of VLC Photonics, a design and testing house in Valencia, Spain. "As a result, the biggest challenge becomes developing custom test setup configurations to adapt to layouts that are not properly conceived in the first place."

This mismatch causes delays, reduced throughput, and intensifies the need for manual intervention. The ultimate result is an increase in nonrecurring engineering costs and time investments for stakeholders spanning test providers to end users.

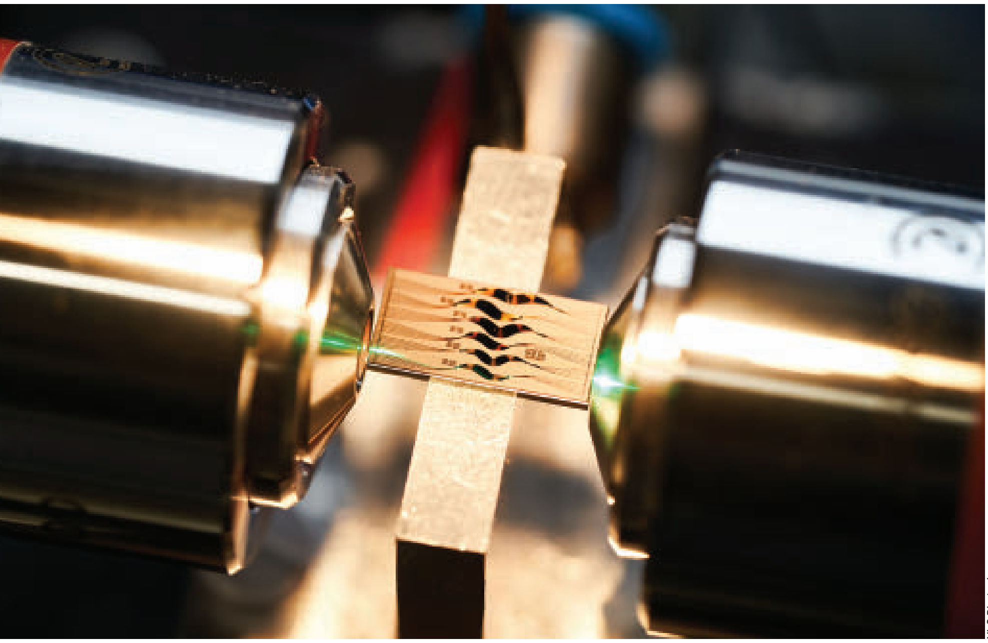
Bridging the gap between design engineers and test engineers is essential to address these challenges. Test providers must create an environment in which design engineers have a thorough understanding of the boundary conditions and limitations of test equipment. At the same time, receiving detailed test plans from designers early in the design phase will benefit the testing process by ensuring that test engineers can swiftly adapt the necessary equipment.

Design for test

Design for test (DfT) involves designing circuits while proactively accounting for test requirements and restrictions from the outset of the design stage. Correct placement of optical and electrical I/Os on the chip, considering compatibility with test equipment and methodologies, is critical to enabling engineers downstream to effectively test the designed circuits. A well-structured test protocol further improves the chances of an efficient

Test engineers conduct measurements of PICs on wafer-level testing platforms. These engineers benefit from early-stage alignment with design engineers to understand the necessary equipment and parameters to optimize testing.

VLC Photonics



Light is coupled into a PIC through an edge coupler: a common means for coupling light in and out of the chip while offering a large operating bandwidth.

transition from the design phase into the testing stage.

The concept of DfT also covers steps to improve testability and understand circuit performance. For example, strategically placing monitor points on functional circuits — implemented by adding unused ports or power taps distinct from the primary product I/O interfaces — provides essential information about the circuit during R&D and early production. "These monitor points facilitate the analysis of the circuit behavior, making it possible to isolate failures," said Chris Barnard, senior director of silicon photonics engineering at OpenLight Photonics, a designer and manufacturer of silicon PICs. "If we measure a high loss between two monitor photodiodes, with several components in between, it becomes impossible to pinpoint which component is causing the loss without adding additional test ports."

Similarly, adding component and subcircuit test structures on the chip can lead to a better understanding of the measurement results, and help engineers debug critical parts of the design. This practice leads to faster iterative design improvements. "Adding debug structures to the layout that can include probing individual circuit blocks or components within the larger PIC is crucial," said Amit Dikshit, design enablement manager at AIM Photonics. "These structures can identify the 'smoking gun' when the PIC does not perform as expected."

Implementing these DfT hallmarks in a design can pose a challenge, especially given the need to balance the requirements of foundries and testing partners. Adherence to design rules ensures manufacturability and compatibility with established, consistent testing methodologies. It is necessary to integrate these rules into the software that engineers use to design and simulate their circuits.

Design software dedicated to the layout and simulation of PICs offers advanced simulation capabilities that allow designers to predict test outcomes and accordingly refine designs. Meanwhile, features such as advanced place-and-route, functional verification, circuit simulation, and model extraction enable the design of clever test structures. Collectively, these considerations offer insight into how test providers may leverage design platforms to align the needs of both test and design engineers.

Test design kits

Foundries enable designers to adhere to their specific fabrication rules by offering process design kits (PDKs) that are compatible with PIC design software platforms. These kits intermediate designers and foundries, democratizing access to manufacturing facilities and ensuring that foundries can easily ramp up production.

This methodology can be similarly transferred to the testing regime, where the development of test design kits (TDKs) compatible with PIC design software effectively facilitates the design-for-test process. In fact, the strength of TDKs is in their orthogonality to PDKs: Both types of design kits can be used simultaneously by designers, creating an environment in which test providers can easily support the testing of any chips coming from any foundries, without needing to know what PDK customers are using.

In this way, TDKs represent an important pathway to a scale-up solution by streamlining communication opportunities between test providers and end users.

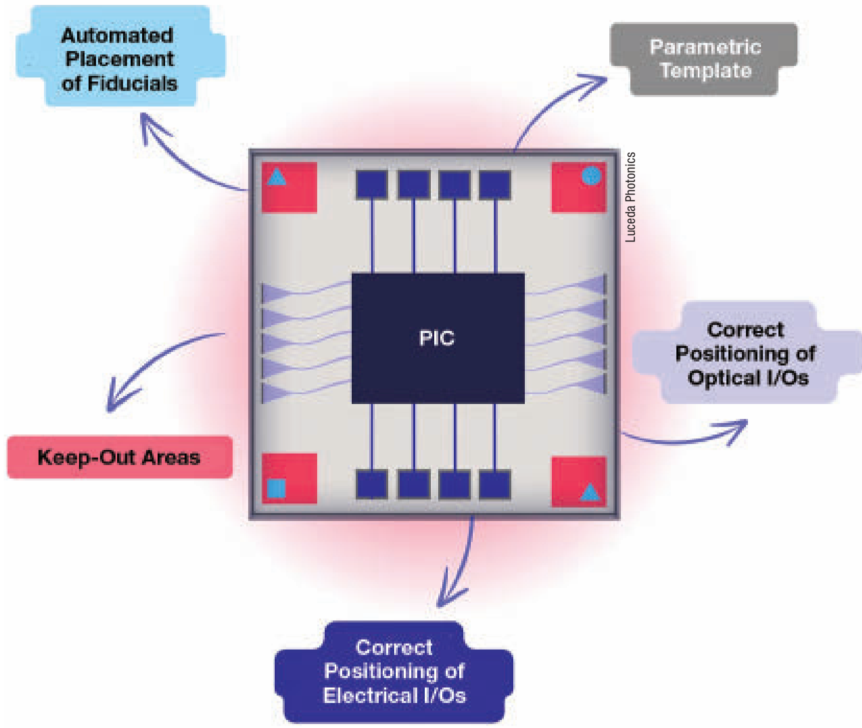
TDKs also raise awareness about the importance of testing early on, ensuring that adequate funds are allocated just as they are for design and fabrication.

"As a design house, we always advise our clients to start with the end in mind," said Kevin McComber, CEO of PIC design services and software firm Spark Photonics. "But even when they do, trying to design using specifications from a written document is time-consuming and prone to errors. Using a TDK solves those issues as there is very little room for ambiguity."

Broadly, TDKs are valuable at any reach on the photonics value chain, serving to reduce the cost barrier and total time required to get chips measured. "This is true for low- and mid-volumes across multiple customers as well as large volumes from individual customers," said Sylwester Latkowski, scientific director at Netherlands-based Photonic Integration Technology Center. "Well-structured test protocols and layout designs enable monitoring of product manufacturing through different stages, understanding the bottlenecks, optimizing the production windows, and overall yield."

Peeling back the layers on TDKs

TDKs provide design rules and layout guidelines that allow engineers and end users alike to correctly position the circuit I/O ports, both optical and electrical, on



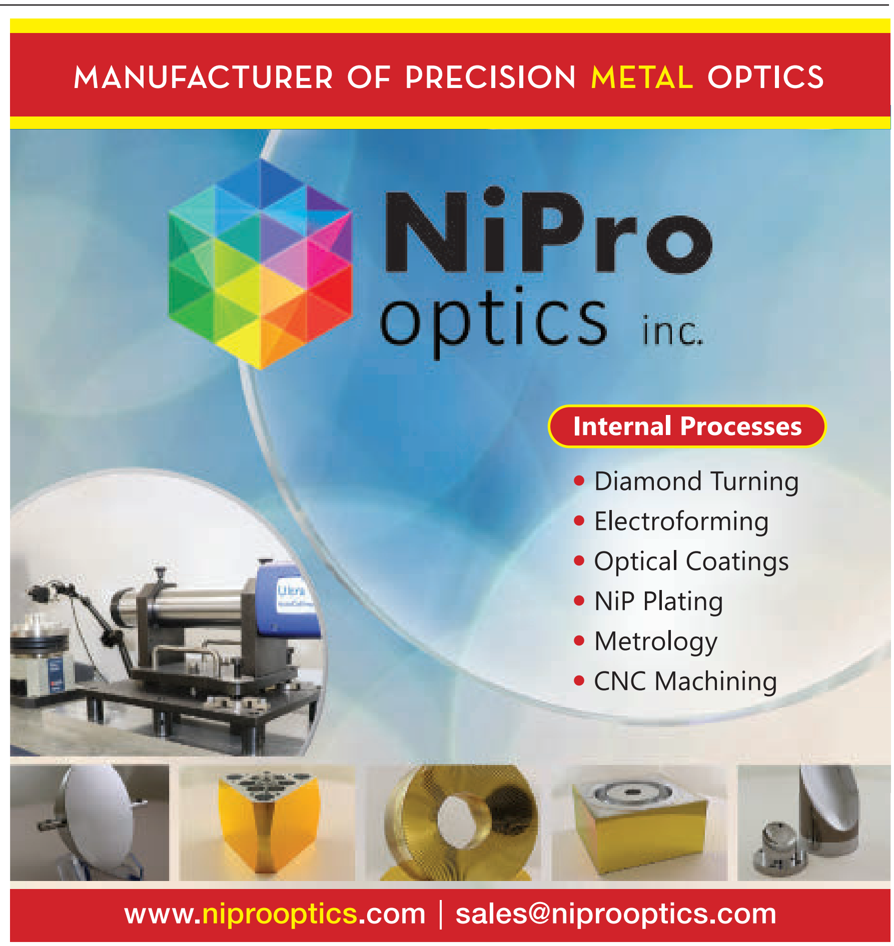
Common test design kit (TDK) features include the automated placement of fiducial markers as well as the definition of "keep-out" areas based on the physical constraints of the measurement equipment. In this way, TDKs provide a set of layout guidelines that can be used to optimize test-stage processes.

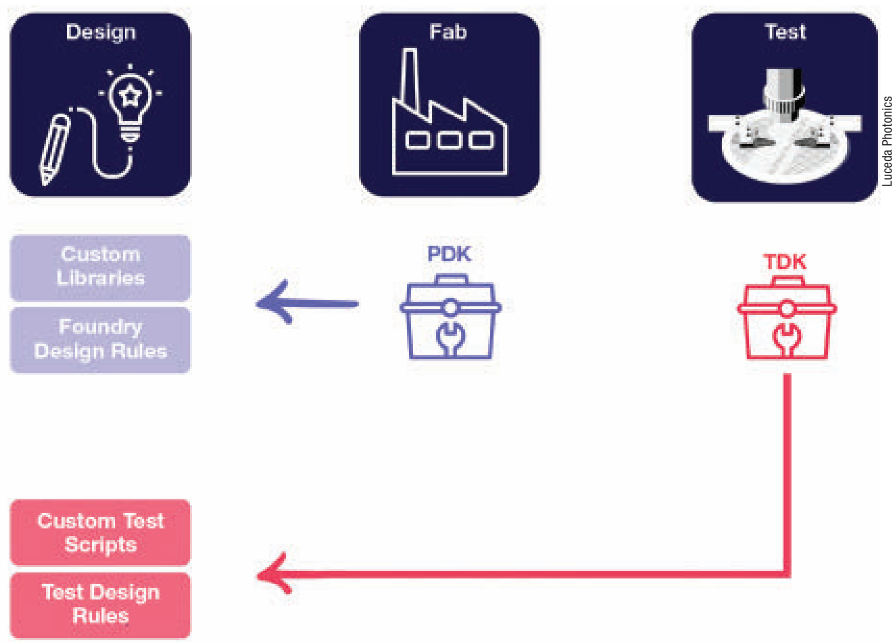
the die design. These kits embed automated rule checks for real-time feedback during the PIC layout preparation, enabling a sequential design flow. The initial design can be virtually evaluated, corrected, and retested iteratively until the completion of the final test-ready design.

According to Siyang Liu at Wuhan, China-based JFS Laboratory, by incorporating features required to test successfully, TDKs — and the tests that they enable — prevent situations in which testing becomes partially or completely unavailable. When measuring photonic chips using fiber arrays, for example, it is necessary to include fiber loopbacks in the design. Rather than manually providing feedback to designers through graphic design system (GDS) and PDF files, test providers can count on TDKs to automatically add loopback structures to the customer's design, minimizing the chance of human error.

There are many other examples of TDK features, including the automated placement of fiducial markers and the definition of "keep-out" areas based on the physical constraints of the measurement equipment. The correct positioning of optical and electrical I/Os, in terms of pitch between the ports, their orientation, and/or their absolute position on the chip, is another possible feature. TDKs may also integrate a device labeling system to support automated wafer-level testing.

After a design is completed, TDKs use existing software features to generate the outputs needed by test providers to perform tests. These outputs include the GDS file of the design. Another important output is a list of components and their connectivity. Each individual component is assigned a name, number, and key parameters so that test providers can easily identify it when initiating the test routine. Fiber grating couplers, for example, which are commonly used as optical I/O interfaces for PICs, are



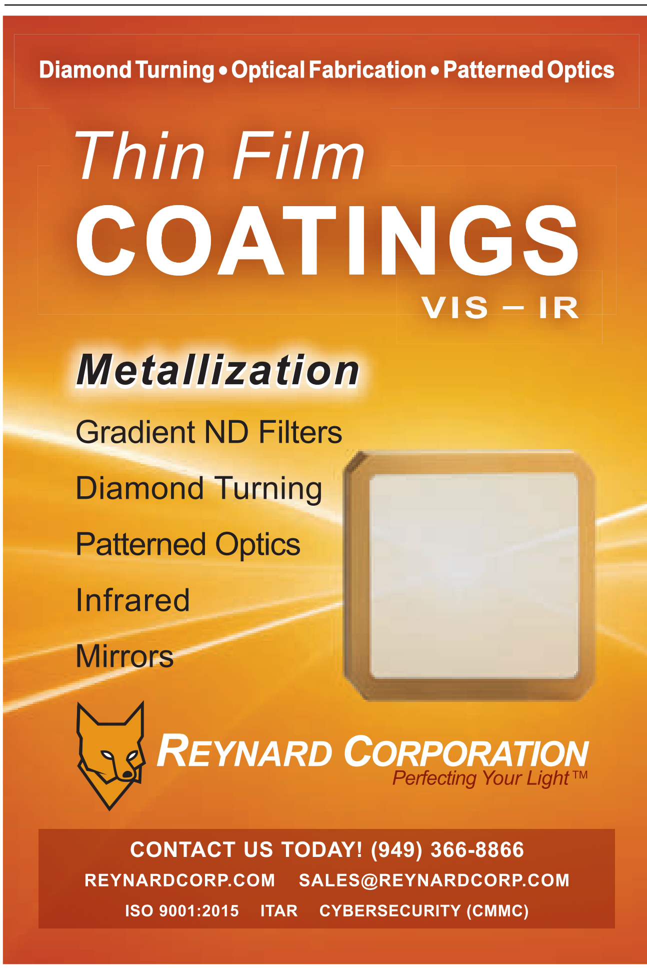


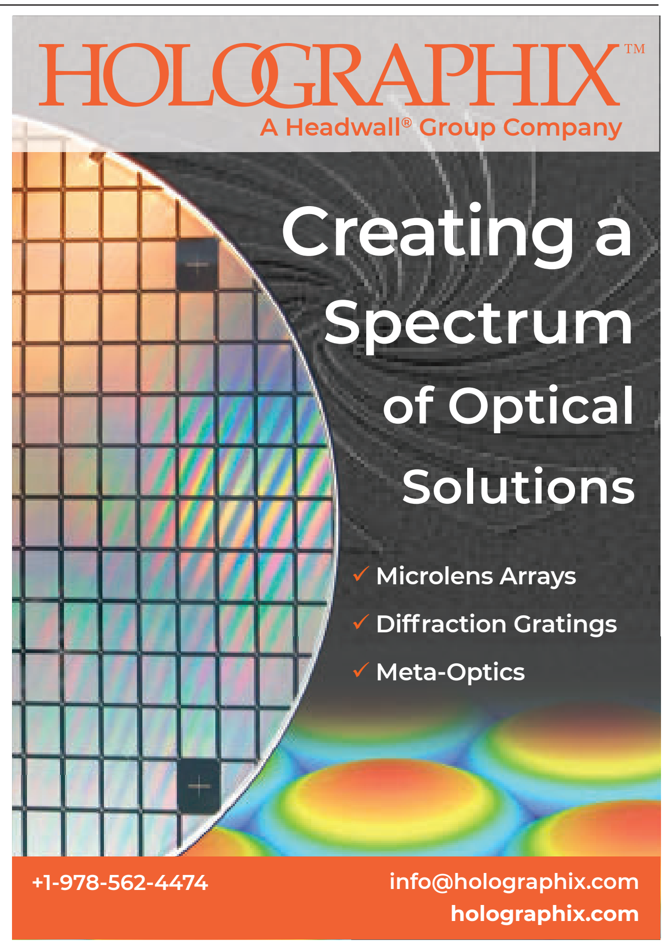
Test design kits (TDKs) facilitate the design-for-test process, providing access to test routines and design rules early in the design process.

characterized by the vertical coupling angle, which affects their testability. Test providers working with these components must know the value of this angle to position optical fibers to ensure the maximum coupling of light into the waveguides on the chip. Structurally accessing such information is crucial for test providers to speed up the testing process.

It is also necessary to optimize the extraction of the positions of both electrical and optical I/Os on the die or wafer. Although the extraction algorithms are embedded in the design software, each TDK outputs this information in a format that is compatible with the measurement software and tools used by each test provider, or with each test routine if multiple tools are available.

TDKs can go even further: Imagine a virtual environment that allows designers to test their circuits in a digital space exactly as they will be tested under regular physical parameters. Design software can offer an ideal digital space, while test partners provide real space. TDKs interface between the two. Running simulations on the PICs beforehand allows designers to validate the testability of circuits, identify the measurement





parameters needed to characterize a specific device or circuit, and estimate the test time.

Such an approach enables design engineers to check which test probes are supported by the test provider, and whether the test equipment capabilities allow measurements within the voltage or wavelength range needed to characterize a specific circuit. If, for example, the test equipment for the high-frequency testing of transceivers for datacom applications supports measurements of up to 50 GHz, but the customer needs to measure responsivity of up to 100 GHz, it is crucial for the test provider to know this requirement in advance to avoid delays. Similarly, measurements of nonlinear effects in a device may require laser powers higher than those which are supported by the available equipment.

Finally, users can align the output file format of such simulation jobs with the output format of the measurement routines, customized per TDK. This way, test providers can provide designers with a straightforward way to compare simulation and measurement data within the design software environment. This automation reduces the time required for data analysis and ensures that all test data is accurately recorded and reported.

Scaling test to industry

The broad adoption of TDKs is poised to revolutionize the PIC industry by enabling more complex designs with guaranteed testability, thereby improving standardization. This will improve efficiency and reliability and is critical to bolster the competitiveness of the integrated photonics industry as heterogeneous integration and advanced chiplet architectures emerge as demand for PICs increases.

TDKs most critically encourage designers to view testing as an integral part of the design process rather than an afterthought, by providing parametric test templates, design rules, and layout guidelines. This shift in mindset reduces engineering costs for both designers and test providers. At the same time, it accelerates the time-to-market for photonics-powered products.

There is one additional advantage: TDKs facilitate developing trained members of the workforce for software-assisted wafer-level characterization. This serves as a necessary assurance that the industry has the talent it needs to continue innovating and growing.

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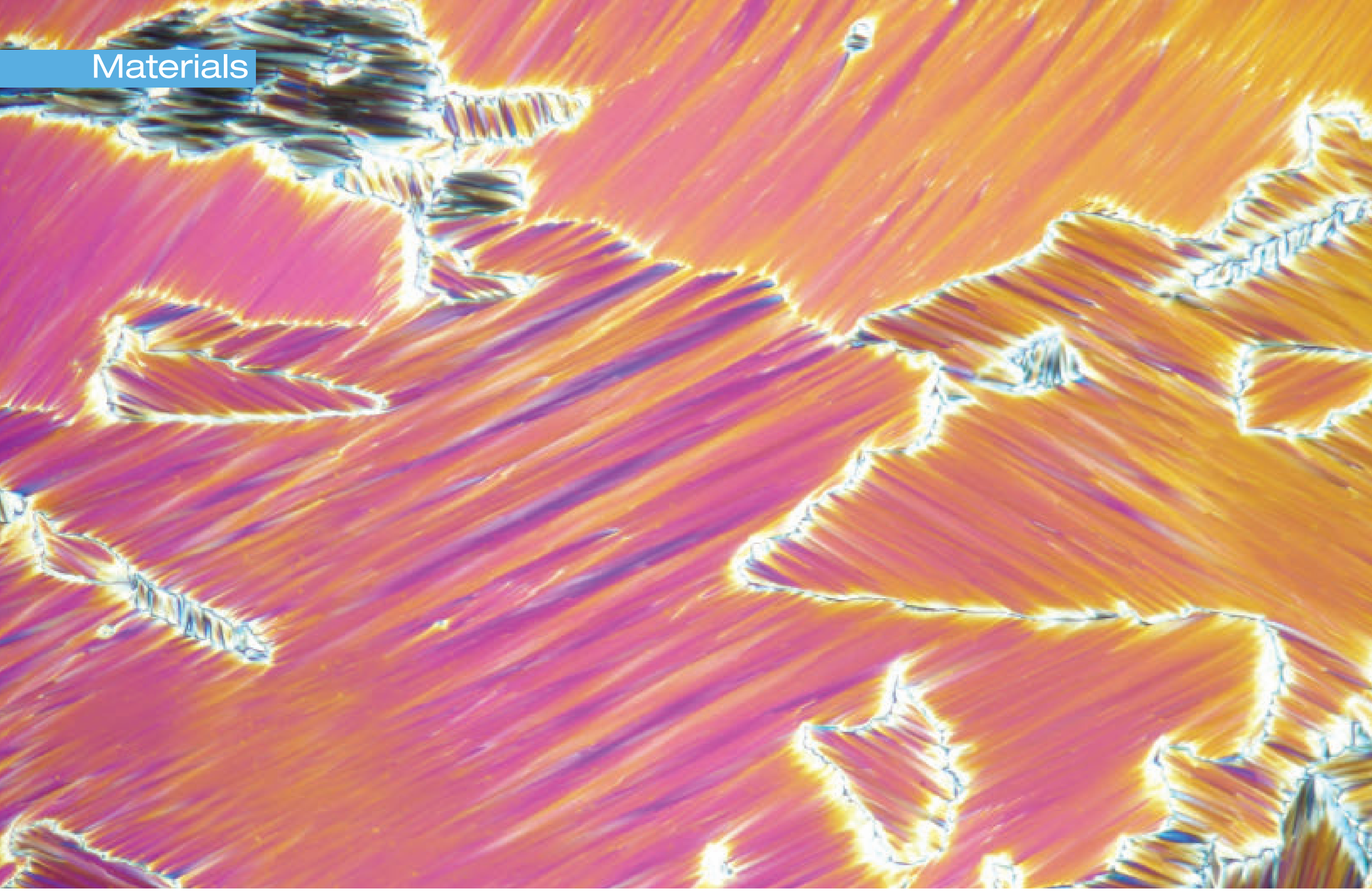

Polymers and Liquid Crystals

Harness the Power of Polarization Control

Polymers and liquid crystals are well-known materials that are critical to perform numerous optical applications. Their distinct properties make them materials of choice for polarization control and measurement.

 Image this page, courtesy of iStock.com/Ad Gr.

BY TOM BAUR AND
MICHAEL KRAEMER
MEADOWLARK OPTICS

In his early works on polarization, luminary physicist William Shurcliff offered a powerful sentiment: "If light is man's most useful tool, then polarized light is the quintessence of utility."

Considerable evidence, both in the form of applications and commercially available products and devices, suggests that Shurcliff's assessment holds true. Optical materials and components that can control and measure polarization are critical enabling technologies.

Leading scientific figures throughout history investigated the polarization of light. One of the earliest methods for polarizing light used double refraction in calcite. The Danish physician Rasmus Bartholin achieved this demonstration in 1669. In 1808, French physicist Étienne-Louis Malus showed oblique reflection from a glass plate. However, calcite of optical quality is rare and limited in aperture to a few centimeters. Meanwhile, glass plate reflection is only a partial linear polarizer, except at Brewster's angle of incidence, which is ~57° for common crown glasses.

Even when Jean-Baptiste Biot discovered in 1815 that tourmaline crystal could also be used in transmission as a linear polarizer due to its strong dichroism, the advancement again used a crystal that was not available with a large clear aperture.

More than 100 years later, Edwin Land pioneered the breakthrough that overcame the centuries-old bottleneck. Land developed the sheet-type polarizer in 1932, using, for the first time, a polymer, dyed polyvinyl alcohol, in a polarization optical component.

Today, sheet polarizers are essential to LCDs, including computer monitors and many mobile phone displays.

But even before achieving this level of ubiquity, Land's breakthrough caught the attention of prominent physics minds.

"The most important event in the modern history of polarized light was the invention of the sheet-type polarizer," Shurcliff said of Land's milestone.

Polarization fundamentals

Polarizers are polarization selectors; they transmit or sometimes reflect one state

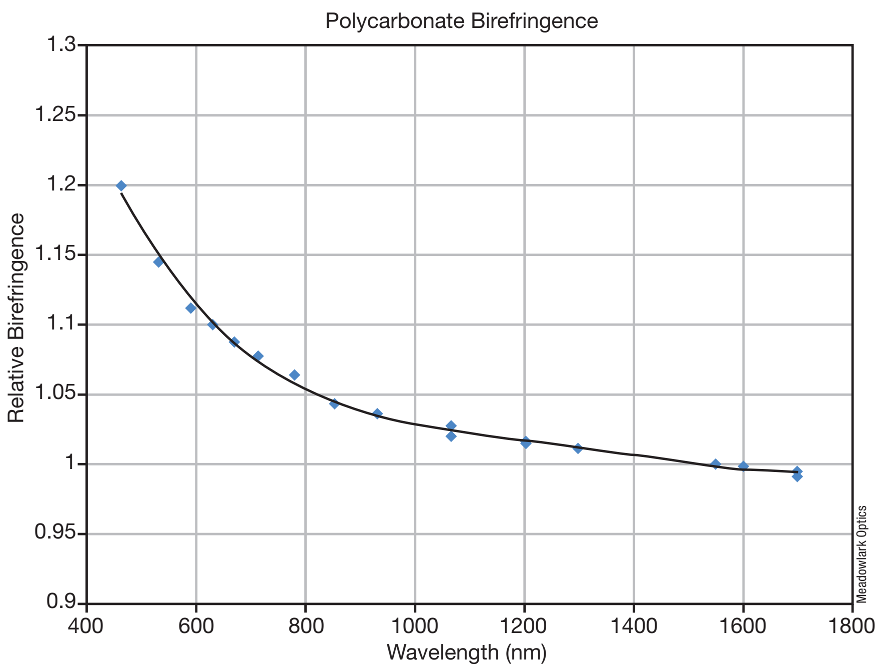

Figure 1. Birefringence, a function of wavelength, is shown for polycarbonate **(above)**. The birefringence variation (with wavelength) is normalized to unity at 1550 nm. The birefringence value depends on stretch process parameters.

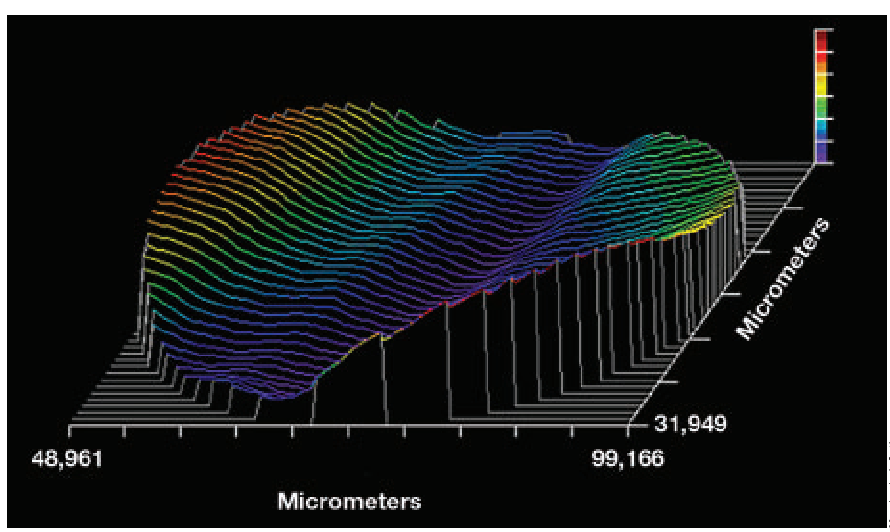

Figure 2. A transmitted wavefront distortion profile for a 50-mm-diameter polymethyl methacrylate (PMMA) film **(right)**. Peak-to-valley variation is one wave at a wavelength of 632.8 nm.

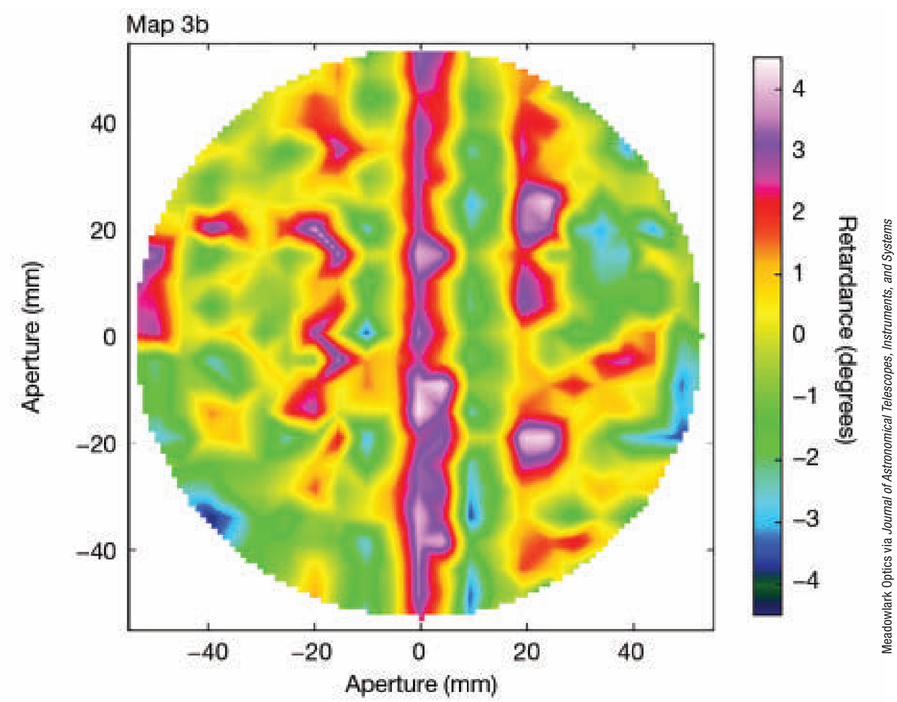

Figure 3. The adapted figure shows measured retardance uniformity of an 11-cm-diameter polymer waveplate, with an average retardance of 157.7 nm at 633 nm.

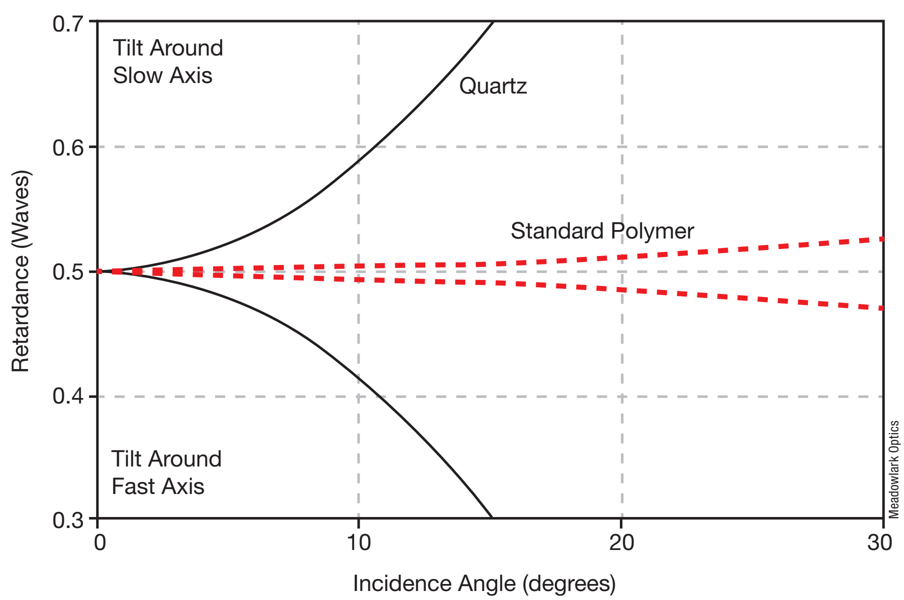

Figure 4. Graph data shows rays in a plane of incidence containing either the fast or slow axis of a waveplate. Rays entering the waveplate at other azimuths will have a smaller change in retardance with the angle of incidence. The graph charts angular dependence of retardance for the worst-case azimuth.

of polarization and block an orthogonal state. Usually, these are orthogonal states of linear polarization, though they can be circular polarization states in certain cases.

Waveplates — polarization modifiers rather than polarization selectors — are another common and important polarization component. Early iterations of these components were made using calcite, quartz, or magnesium fluoride, but each of these materials were size-limited to ~15 cm or less and required precise polishing to tight thickness tolerances to achieve adequate performance. For quartz, the tolerance is often <±100 nm. For calcite, it is <10 nm. This makes these crystal waveplates too expensive for use in mass commercial markets.

Polymers and liquid crystals provide a solution for larger aperture and cheaper polarization modifier components. Polymers can replace static crystal waveplates in most applications. And liquid crystals, though most widely used in and for displays, achieve favorable performance in precision optical and laser applications. Liquid crystals also exhibit a useful property that enables low-voltage electrical control of a polarization state.

Profitability remains the driving force for developing high-quality polymer waveplates and liquid crystals, with a large commercial market enduring for numerous types of displays made from these materials.

The versatility of polymers

Several different polymers are used to fabricate waveplates. Polymers commonly used for this application include polyvinyl alcohol, polycarbonate, polystyrene, cyclic olefin copolymer, polyimide, and polymethyl methacrylate (PMMA). These materials are often made as cast films that are optically isotropic. They can be made birefringent by heating to a softening temperature and then stretching the material(s), which orients the long chain polymer molecules. The resulting anisotropy produces birefringence of an amount that depends both on the softened polymer temperature and the stretch percent amount.

Typical film thickness values range from 50 to 200 µm, and the produced birefringence delivers retardance values — the degree of angular shift in the phase of incoming polarized light — that can range from <10 nm to 3 µm. The birefringence is a function of wavelength in Figure 1 for polycarbonate. The general curve shape shown by Figure 1 is similar for most polymer films, except for polyvinyl alcohol, which has a much lower dispersion of birefringence.

The uniformity of retardance of the oriented films correlates to the thickness uniformity of the cast films. Figure 2 shows the transmitted wavefront distortion for a 50-mm aperture of a sample of 100-µm-thick PMMA film before stretching. Typically, this will improve (from about one wave at 632.8 nm) upon lamination between optically flat windows that possess a good index-matching adhesive. The wavefront distortion on this sample in Figure 2 implies a thickness variation of ~0.43 µm, peak-to-valley, ~0.43% of the film thickness. The retardance uniformity of the films is acceptable for most applications, although it is not necessarily desirable for more elaborate measures, such as polishing crystal quartz.

Figure 3 shows the measured map of spatial variation of retardance over a 105-mm-diameter aperture after stretching one of these polycarbonate films. The peak-to valley retardance variation is ~6.5° or 5% of the retardance. These values correspond to 158° at 640 nm. The fast axis direction variation is <0.25° peak-to-valley for this large waveplate film.

For comparison, a 4.2-mm-thick quartz waveplate of the same clear aperture has a retardance variation of ~0.008 waves or 2.9° at 631 nm, even though the thickness uniformity (inferred from the transmitted wavefront distortion) is 8 nm, and the physical wedge is 0.06 s. This thickness uniformity implies an expected retardance variation of 0.2° peak-to-valley, which is much less than the measured uniformity of 2.9°.

The degradation from the expected uniformity results from variations in the crystal birefringence, possibly due to stress built into the crystal during the growth process. The quartz waveplate is twice as uniform as the polymer one in this example, though the cost of manufacture is >10× higher for the quartz waveplate in small volumes.

Polymer properties

Beyond cost-effectiveness, polymer waveplates also offer a dramatically improved angular field of view compared with crystal waveplates. Figure 4 shows a comparison of the change in retardance with angle of incidence for a compound zero-order quartz waveplate, with a plate thickness of 1 mm to the true zero-order performance of a single polymer layer of 75-µm thickness.

Compound zero-order waveplates are fabricated by subtracting two crystal waveplates, each with slightly different thicknesses. A true zero-order crystal waveplate is generally too thin and fragile to be practical to make or to handle. Figure 4 shows rays in a plane of incidence containing either the fast or slow axis of the waveplate. Rays entering the waveplate at other azimuths will have a smaller retardance change with the angle of incidence.

Layers of polymer waveplates can also be combined in different ways so that the resulting component can be made to be achromatic. Figure 5 shows the measured performance of a five-layer polymer achromatic waveplate. Further improvement is possible with more layers, as shown in the theoretical curves in Figure 6. While such a design architecture can be achieved using crystals, this is an expensive alternative. Also, the angular field of view is much smaller than when using polymer layers.

The measured damage threshold for laminated polycarbonate films is >500 W/cm^2 at visible wavelengths, which is lower than that for crystal quartz. However, the thermal dependence of retardance is higher for crystal quartz at ~0.1% per degree Celsius versus 0.027% per degree Celsius for polyvinyl alcohol and .015% for polystyrene. Retardance decreases with heating in crystal quartz and polystyrene but increases in polyvinyl alcohol. These values are measured near room temperature but are nearly linear over a range of 20 °C.

Polymer waveplates can be a spin-coated layer applied to an optically flat window, or even to another element in an optical system, such as a mirror or a lens. These coatings are typically <10-µm thick and are comprised of a reactive mesogen. These reactive mesogens are liquid crystals that can be polymerized to

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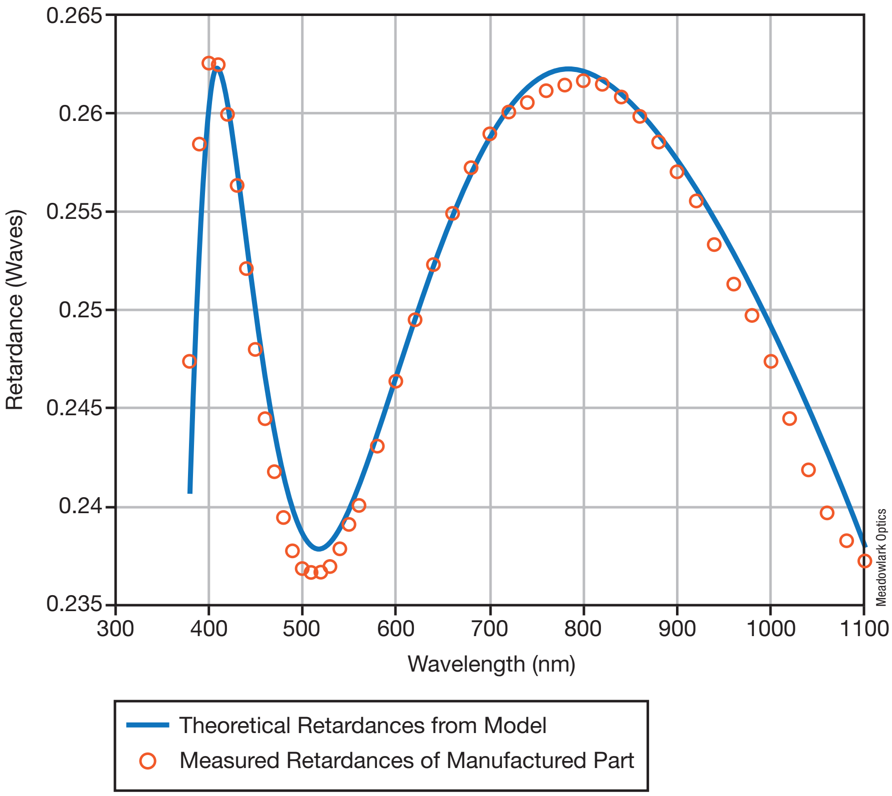
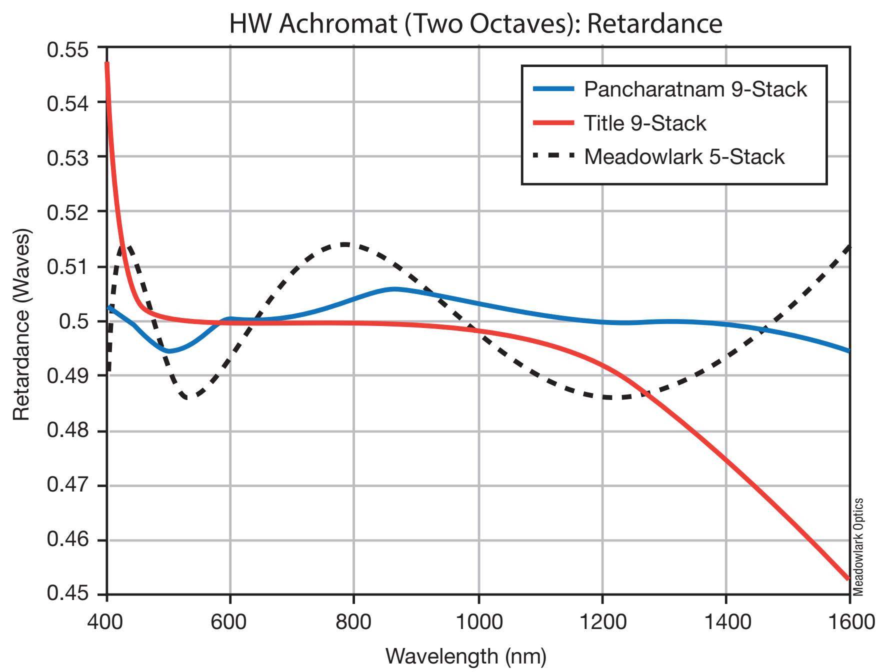


Figure 5. Retardance of a five-polymer layer quarter-wave waveplate **(left)**.

Figure 6. Modeled performance of different multilayer achromatic half-wave (HW) waveplates **(below)**. Whereas Figure 5 **(left)** shows the measured performance of a five-layer polymer achromatic waveplate, further improvement can be achieved upon the addition of layers, as shown in the theoretical curves.



form a high-molecular-weight polymer. They are coated over a photoalignment layer or a buffed polyimide alignment layer photopolymerize, in situ. The result is thin optically birefringent polymers, with ultraviolet light then delivered to cross-link the mesogen monomer.

Moreover, such waveplates can be patterned in their waveplate-axis direction when photoaligned. Patterning in this way into fine scale-diffractive waveplates provides useful functions, such as nonmechanical beam steering over large angles requiring power in the range of 10 V.

Laminating polymer waveplates between optically flat windows considerably reduces transmitted wavefront error. It also reduces spectral fringing in both the transmission spectrum and the retardance spectrum, both of which are undesirable. The fringe amplitude is largest for collimated light and is smaller in imaging beams. In addition, the error that results from the deviation from the expected retardation can be quite large — for example, 7% for an unlaminated polyimide quarter-wave waveplate film of 100-µm thickness.

Liquid crystal waveplates

Liquid crystals can be aligned into a waveplate-suitable configuration to mimic the molecular ordering of uniaxial crystals, such as quartz, magnesium fluoride, and sapphire. They can act as variable waveplate devices with low-voltage electrical control of the effective birefringence, and low-voltage electrical control of the retardance value as a result. This low-voltage electrical control has obvious advantages compared with mechanical motions of polarization optical elements for changing polarization.

The response times of nematic liquid crystals — liquid crystals in what is considered the simplest liquid crystalline phase — are typically a few milliseconds, with faster responses to increasing voltage than to decreasing voltage (Figure 7). Response time is proportional to the square of the liquid crystal layer thickness and therefore to the zero-voltage retardance of the liquid crystal cell. The response times for the two voltage directions for half-wave switching at 633-nm wavelengths are 7 ms and 1 ms for Meadowlark's most-used nematic liquid crystal offerings.

Response times can be improved by using higher birefringence liquid crystals, which allows for a thinner liquid crystal layer. Common nematic liquid crystals have a birefringence between 0.1 and 0.2, and the dispersion of birefringence is similar in nature to that of polymers (Figure 1). Response times for half-wave switching are reduced to <150 µs in both directions by using higher birefringence liquid crystal and special voltage driving techniques. The resulting rise and fall response times are 32 µs and 139 µs, respectively, for half-wave switching at 532 nm.

The liquid crystal devices described here are often combined with other optics to perform functions through nonmechanical polarization control, for example, the rotation of a plane of linear polarization through any angle by the addition of a quarter-wave waveplate. Additional examples are the optical shuttering by the addition of input and output polarizers; the spatial modulation of either phase or amplitude of reflection from a spatial light modulator; and/or measuring polarization of a light beam.

A liquid crystal device can also combine with a polarizer. A useful example of this combination is to vary transmission or reflection.

Liquid crystals can also be used to dynamically generate holograms: In this application, the input light is polarized parallel to the liquid crystal director. These devices, liquid crystal on silicon spatial light modulators, have a 2D pixelated silicon reflective backplane usually with a pixel count of >1 million. Voltage changes to the pixels change the index of refraction in the liquid crystal layer, producing a reflected wavefront shape change. Frame rates here can be as high as 1 KHz.

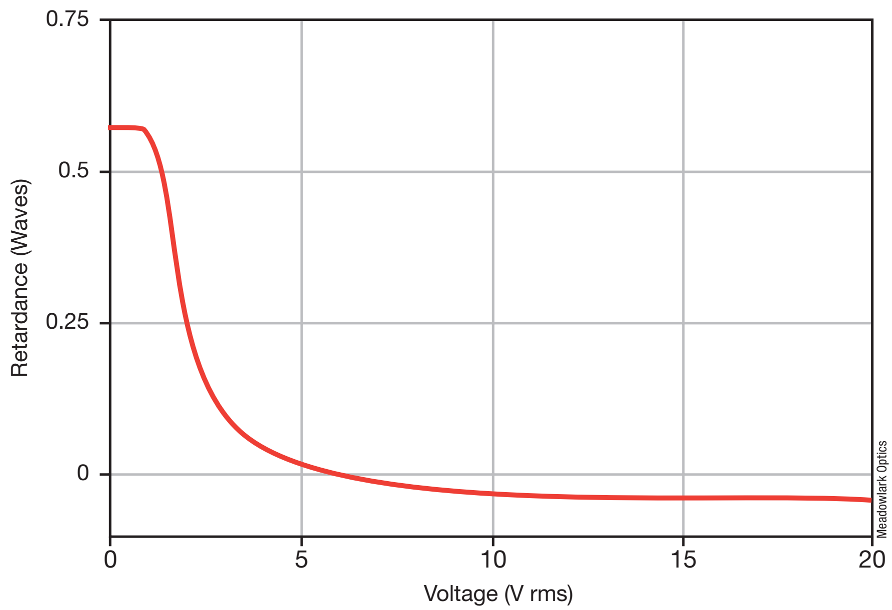


Figure 7. The response of a typical nematic liquid crystal to an applied 2-kHz square wave voltage. The response times of nematic liquid crystals are typically a few milliseconds, with faster responses to increasing voltage. Response time is proportional to the square of the liquid crystal layer thickness, and therefore to the zero-voltage retardance of the liquid crystal cell. RMS: root-mean-square(d).

The future of optical devices

Polymers and liquid crystals have become indispensable materials for developing optical devices for polarization control and the measurement of polarization. The development of consumer products for displays has advanced the quality of the available materials and made them viable options for laser systems, precision optical systems, and research applications.

Notably, in most cases, the functions enabled by these materials cannot be accomplished via commonly used alternative materials or devices. Meanwhile, when physically viable alternatives exist, these solutions are often too costly to carry out in mass.

Meet the authors

Tom Baur is the founder and board chairman of Meadowlark Optics. He focuses on product development, bringing new materials to the photonics community for polarization control and improving metrology for polarization components; email: tbaur@meadowlark.com.

Michael Kraemer holds a master's degree in mathematics and doctorates in both physics and mathematics. He has worked as a software engineer for 24 years. His research interests include tunable filters, ellipsometry, and achromatic polarization devices; email: mkraemer@meadowlark.com.

Acknowledgment

Figure 3 Attribution: The complete rectangular map, measured by Meadowlark Optics, is represented in Figure 32(a) from SPIE JATIS, 6(3), 038001 (2020). https://doi.org/10.1117/1.JATIS.6.3.038001.2. Notice: Reprinted under Creative Commons License CC BY 4.0, see https://creativecommons.org/licenses/by/4.0/.

Reference

1. D. Harrington et al. (2020). Polarization modeling and predictions for Daniel K. Inouye Solar Telescope, part 6: fringe mitigation with polycarbonate modulators and optical contact calibration retarders. *J Astron Telesc Instrum Syst*, Vol. 6, No. 3.

Laser Manufacturers Navigate Shifts as Laser Notice No. 56 Takes Effect

BY WILLIAM BURGESS
POWER TECHNOLOGY INC.

The only constants in life may be death and taxes, but many would argue that regulatory change is another one of life's certainties. Proof of this can be seen in the FDA-initiated transition from the current laser manufacturing safety guidance, Laser Notice No. 50, to a new framework, Laser Notice No. 56, which is set to take effect at the end of this year.

To maintain safety standards, the FDA has issued a series of laser notices as guidance for manufacturers to meet compliance requirements. As defined by the FDA, a laser notice is a document that outlines specific requirements and safety guidelines for laser products. Alongside the Federal Laser Product Performance Standards, outlined in 21 Code of Regulations (CFR) 1010 and 1040, these notices provide regulatory guidance to laser device manufacturers, ensuring consumer safety and product quality. As such, they are crucial to the design, labeling, and manufacturing of laser products intended for sale in the U.S. Certain notices are intended to harmonize with international regulations, enabling U.S. manufacturers to compete more effectively in the global marketplace.

Introduced in May 2019, Laser Notice No. 56, as compared with Laser Notice No. 50, places a stronger emphasis on harmonization and compliance with the latest International Electrotechnical Commission (IEC) standards. Most notably, the new framework prioritizes IEC 60825-1 Ed. 3 (Safety of laser products — Part 1: Equipment classification and requirements); and IEC 60601-2-22 Ed. 3.1 (Particular requirements for basic safety and essential performance of surgical, cosmetic, therapeutic, and diagnostic laser equipment). The FDA plans to withdraw Laser Notice No. 50 on Dec. 31, 2024, and Laser Notice No. 56 will provide regulatory guidance in this area instead.

This upcoming shift affects various stakeholders in the photonics industry. Laser manufacturers that stay ahead of the regulatory curve by proactively implementing these updates can offer significant advantages to their customers. For this reason, it is beneficial to consider how laser providers can effectively anticipate and adapt to regulatory changes.

Considerations for laser manufacturers

The responsibility for implementing these regulatory changes rests mainly on laser manufacturers, which must ensure that their laser products meet the new guidelines before the deadline. Laser products manufactured until Dec. 31, 2024, may continue to use the laser safety labels described in Laser Notice No. 50. Existing products with these older labels will remain acceptable for use. As manufacturers transition to the guidance given in Laser Notice No. 56, lasers manufactured after Jan. 1, 2025, must adopt the new labeling requirements.

Depending on the type of laser, compliance with the newer laser notice may be

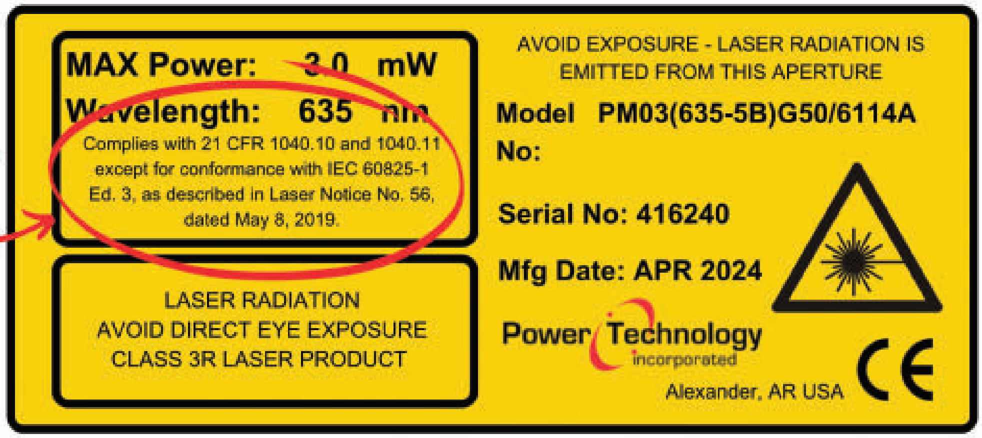
Laser Compliance Timeline

November 1995
IEC 60601-2-22
Second Edition
Published

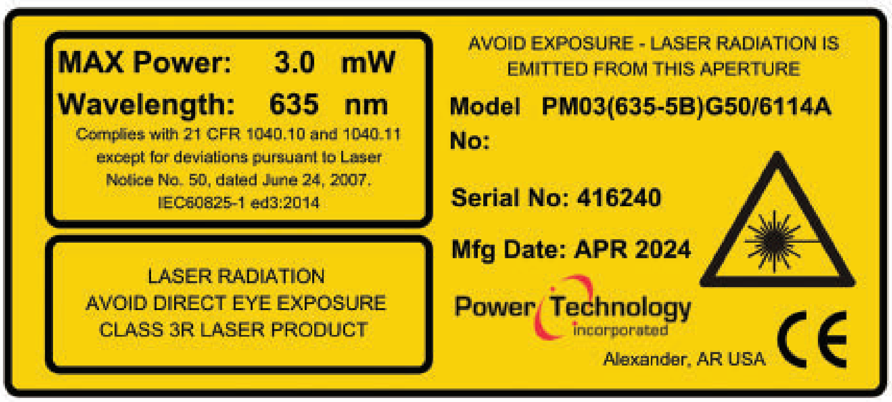
March 2007
IEC 60825-1:2007
First Edition Published

Laser Notice 50
First Edition Published

May 2007
IEC 60601-2-22
Third Edition Published



Following the implementation of Laser Notice No. 56, laser labeling requirements will undergo changes. Updated label verbiage **(right)**. Previous label format **(below)**.



as simple as updating the laser's certification label. Additionally, compliance with Laser Notice No. 56 must be documented and communicated to the FDA's Center for Devices and Radiological Health through a supplemental report submission.

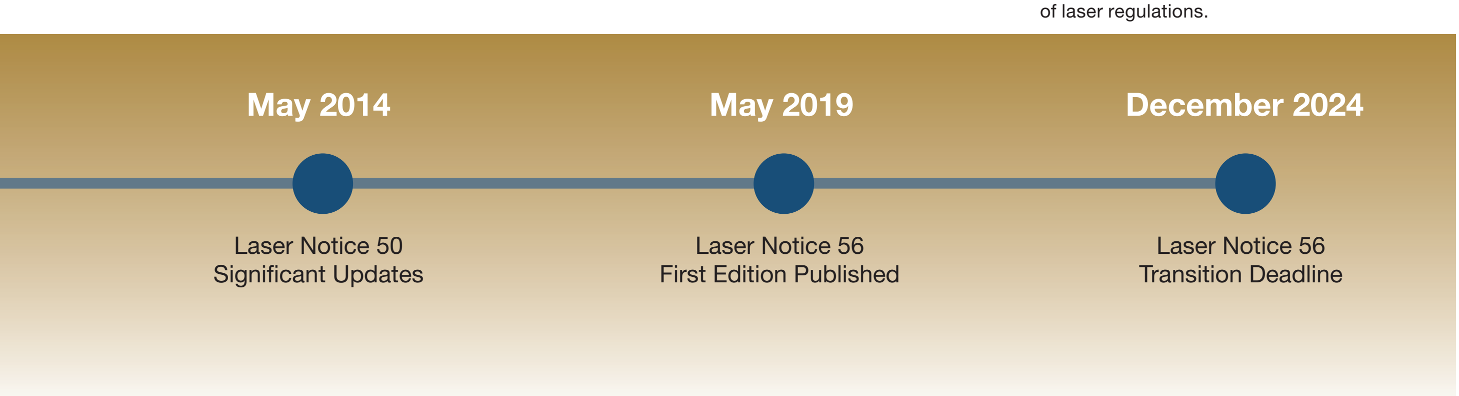
For laser users

Because there is no requirement to update labels on older lasers, laser users have no need to worry about this shift. Simply put, these lasers are just as safe as they have always been. But, with the purchase of any new lasers, completing the necessary research on the laser manufacturer is important. If a user cannot determine the manufacturer's name and where the laser was manufactured, it is advisable to seek an alternative supplier. Users should search for a company that has a long-established track record and appreciates laser safety as well as regulatory compliance. When purchasing a new laser, always review the safety label and ensure that the new language, provided below, is present.

Adjustments for laser safety officers

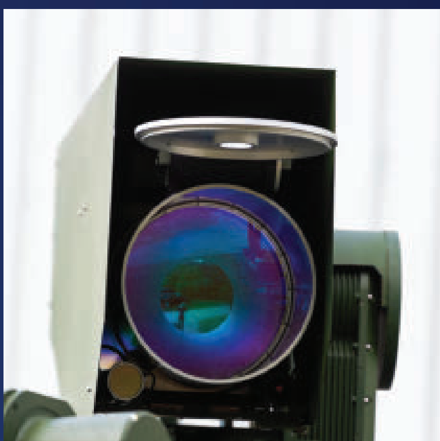
Laser safety officers may want to review the upcoming labeling requirements to ensure that all new lasers received after Jan. 1, 2025, are compliant with Laser Notice No. 56. There is no need to re-evaluate lasers manufactured before Jan. 1, 2025. The existing product and hazard

A timeline showing the evolution of laser regulations.



Altechna and ARO large size optics is successfully used in:

- Direct energy defense systems
- Nuclear fusion systems
- Particle accelerators
- Semiconductor industry
- 3D metal printing



Altechna and ARO produce transmissive, reflective and beam splitting optics for most demanding requirements:

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- 100+ kW CW systems
- TW – PW pulsed systems
- Minimal sub-ppm absorption
- Minimal thermal response, 1° increase per 10 kW input at the center of the beam

Operations in Europe	Operations in US
Altechna	ARO ALPINE RESEARCH OPTICS
altechna.com	arocorp.com
info@altechna.com	sales@arocorp.com
+370 5 272 5738	+1 303 444 3420

labels are still acceptable. But new lasers should have compliant labels with one of the following statements:

> Complies with FDA performance standards for laser products except for conformance with IEC 60825-1 Ed. 3, as described in Laser Notice No. 56, dated May 8, 2019.

Or:

> Complies with 21 CFR 1040.10 and 1040.11 except for conformance with IEC 60825-1 Ed. 3, as described in Laser Notice No. 56, dated May 8, 2019.

Changes for purchasing companies

Manufacturers that use lasers as a component of a larger system may want to implement incoming inspections to ensure that their laser provider is aware of the latest regulations (i.e., the labeling change, etc.). If a manufacturer is not using lasers from a domestic manufacturer, they may need to work with their supplier to ensure that products entering the U.S. are compliant with U.S. federal laws. The photonics industry has seen enough supply chain disruption during the last few years. Avoiding a U.S. customs package “HOLD” while importing noncompliant products is easy to avoid through the proper diligence or the use of a reputable domestic laser supplier.

As the laser industry evolves, so must its safety standards. The withdrawal of Laser Notice No. 50 and the adoption of Laser Notice No. 56 represent a step forward by emphasizing global regulatory alignment while maintaining the safety of laser users in the U.S. and abroad.

For laser manufacturers, it is time to embrace the transition and ensure that their laser products meet the highest safety benchmarks. For the last 55 years, companies, such as Power Technology Inc., have positioned themselves at the forefront of laser technology and regulatory compliance. All laser users are encouraged to keep their lasers shining bright, but always within safe limits.

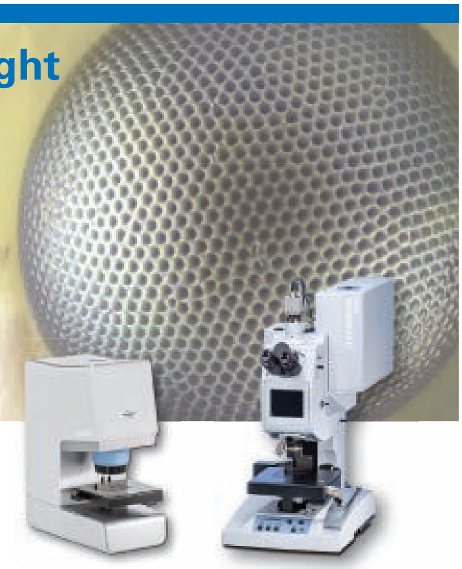
wmburgess@powertechnology.com

BRUKER

To have a deep insight

Bruker’s LUMOS is a fully automated FT-IR microscope with an integrated FT-IR spectrometer. LUMOS is designed to combine highest quality in visible inspection and highest performance in infrared spectral analysis. With motorization and networking of all moveable components, the LUMOS provides an ease of use never before seen in FT-IR microscopy.

Bruker’s HYPERION is the high end R&D microscope for very demanding applications. Next to transmission, refl ection and ATR it also provides a dedicated GIR objective for the analysis of very thin layers at grazing angle. The HYPERION is available with modern focal plane array (FPA) detector technology to study even very complex samples at highest lateral resolution by FT-IR imaging.



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Bruker Scientific LLC
40 Manning Road
Billerica, MA 01821
Phone +1 978 439 9899

FT-IR

Innovation with Integrity

Photonics Provides a Working Sidestep Around Radio Congestion

BY JEAN-FRANÇOIS MORIZUR
CAILABS

The number of satellites orbiting Earth is increasing so rapidly that the European Space Agency has dubbed 2024 a "year of launches." According to the satellite tracking website Orbiting Now, more than 10,100 active satellites are orbiting Earth. Some are equipped to take pictures of our planet, and some capture images of other celestial objects. Some monitor the weather, while certain satellites continue to transmit data, provide internet access, and connect phones.

In each case, losing access to these satellites would disrupt our way of living.

But as the number of satellites rises, so does the demand for connectivity. This in turn pushes the limits of the radio spectrum. Rapidly, radio congestion is becoming a serious issue and is already raising concern.

Broadly speaking, there is a limit to how much data can be sent in a given volume of space, at a given time, in a given portion of the spectrum. In some form, we have all experienced these phenomena. When mobile phones are used in a large group and in the same space, we are apt to face patchy signals and low throughputs.

Similarly, satellites that are attempting to communicate when there are many other satellites in close proximity are subject to interference and poor commun-

A photonics-based solution serves to not only free up room but also ensure our ability to achieve communications that sidestep the congestion problem altogether.

As a rising number of satellites brings the world closer to critical levels of radio congestion, lasers could offer a solution to crowded skies.

Image courtesy of Cailabs.

ication quality. They will need to use different parts of the spectrum to avoid encountering these conditions. However, this presents a challenge: There is not much of this spectrum to go around. Further, the radio spectrum is already a shared space, because it enables, among other things, our phone communication, emergency services, TV, and, of course, satellite communication.

Fortunately, photonics offers a solution to this shortage of spectrum. A photonics-based system serves to not only free up room but also ensure our ability to achieve communications that sidestep the congestion problem altogether.

Shannon's law and the power problem

There is no practical way to outright circumvent radio congestion. According to Shannon's law, every communication channel has a finite capacity for transmitting information. More precisely, it becomes exponentially harder to transmit more bits per second, since it requires exponentially more power to do so. Because there are power limits in any system, such as solar power limits on satellites, there is a fundamental limit to how much data can be sent per unit of time. If more people want to communicate, they must share the same capacity, typically using the same channel in succession. This is called time division multiplexing.

All constituents must recognize the urgent need for more efficient, secure, and scalable communication technology as humanity's footprint in space expands amid tomorrow's communication demands.

The concern that arises calls into question how close we might be to problematic levels of radio congestion. While we do not know with absolute certainty, we do know that the number of satellites in orbit is rising, and countries are already limiting the right to use certain parts of the radio spectrum because they fear that radio congestion is inevitable and will soon restrict their ability to communicate.

Even if some find such fears to be unfounded, they have an effect, nonetheless. A solution would ease these fears and provide a viable alternative for the efficient transfer of data.

How photonics can help

Unlike radio waves, which disperse and are susceptible to interference because they occupy the same information channel, laser light propagates along a narrow, focused beam, making interference unlikely. Every laser beam is a spatially independent channel. And, given that laser light is very high frequency compared to a radio wave, it can carry much more data. A single strand of optical fiber, for example, carries ~50 Tbps of data — the world records are in petabits per second — while achieving ~15 Gbps for a radio satellite link.

As a result, optical communication options are simply not subject to congestion.

And the advantages extend beyond improved speed and efficiency. Lasers produce light that is highly directional, as well as coherent. Parallel light waves maintain both their phase and amplitude over longer distances, compared with radio waves. Since lasers concentrate their energy in a specific direction, they reduce energy dispersal and also allow the light to travel long distances with minimal losses to power.

Radio waves, on the other hand, spread out more than light waves, which leads to significant power spread over distance. This is particularly important for space exploration, where distances are given in astronomical units and not in kilometers, and it is already an obstacle to create a viable moon network, since the moon is ~384,400 km (0.00257 AU) from Earth.

In optical transmission systems, the relationship between data throughput and power consumption depends significantly on the system architecture — and the relationship is, in fact, a bit nuanced. While increasing data throughput typically requires more power in electronic systems, photonic systems modulate data onto the laser beam without a proportional increase in power consumption. The primary energy expenditure in these systems is maintaining the laser beam's integrity and direction over long distances. Once the beam is stable and capable of reaching its target with minimal loss, data throughput can be enhanced by adjusting the modulation techniques — in other words, the method by which data is encoded onto the light. However, the exact effect on power consumption may vary based on the specific architecture and technologies used in the transmission system.

Safe communication in an unsafe world

Security benefits are another perk of the use of lasers, and these benefits have been highly relevant in recent years. According to the Armed Conflict Location and Event Data (ACLED) project, global conflict rates increased 12% in 2023, with >15,000 more attacks, bombings, and assaults compared with 2022, which experienced a 32% increase from 2021. The ACLED says one in six global citizens now live in an area of active conflict; defense budgets are increasing around the world.

Laser communication is difficult to detect and highly resilient to interception and jamming. These benefits illuminate the distinct advantages of laser communication in war zones, where reliable and timely communication is essential to coordinating military strategies, typically conducted in secret.

A paradigm shift

Even with the benefits of laser communication, challenges must be overcome before the number of lasers can be increased in satellite communication, thereby triggering a paradigm shift in this realm of communications. One seemingly intractable historic challenge pertains to atmospheric turbulence, which degrades laser beams in much the same way as frosted glass warps light, for example. Companies, including Cailabs, have developed techniques and technology that overcome the problem. Cailabs' solution involves beam reconstruction, among other, varying approaches.

A present issue is that lasers for large-volume communications have not been tested at the necessary industrial scale. For this reason, many view the technology alternative as unproven and prefer to stick with the legacy radio technology. Though often mindful of the need for new forms of communication, skeptics fear investing in what they consider experimental technology.

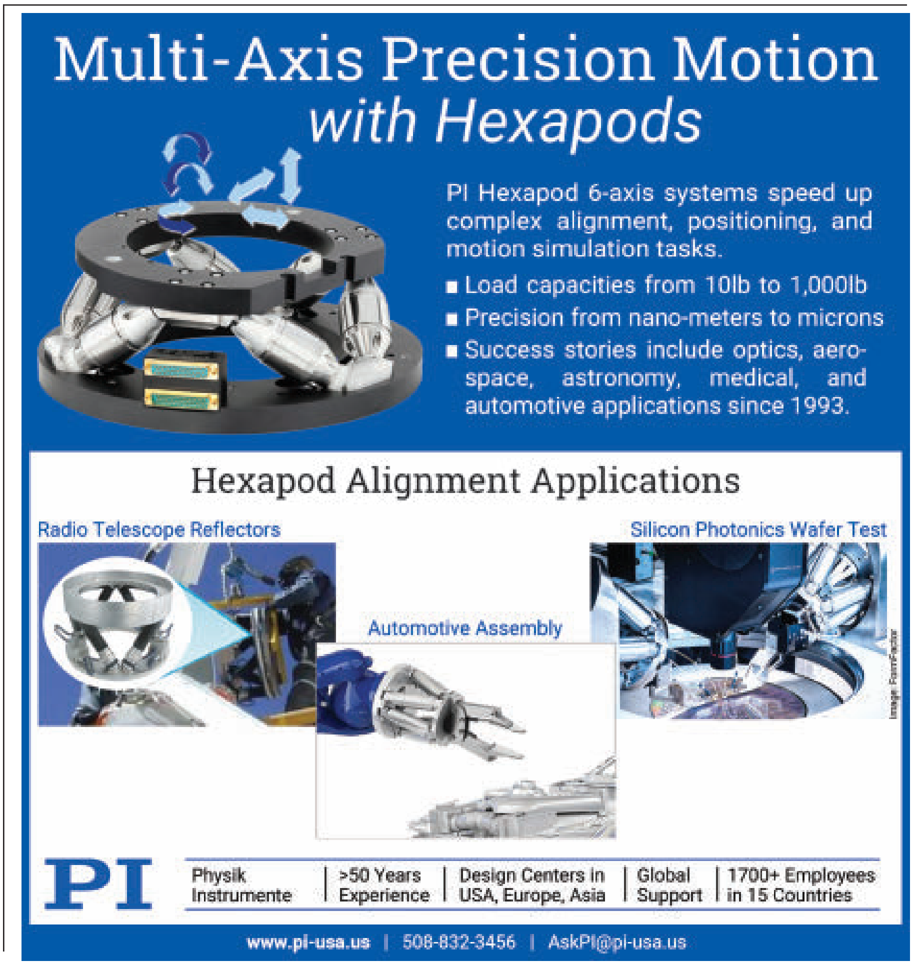
Instead, it is up to those of us in photonics to demonstrate the field's reliability and cost-effectiveness of laser communications in practical, real-world contexts.

Advancing this technology also demands changes to the regulatory and economic environments. The current system for managing radio frequencies is mired in complex legal and bureaucratic procedures, which are both expensive and time-consuming. Photonics can simplify communication efforts but will require a concerted response from industry leaders, regulators, and policymakers. All constituents must recognize the urgent need for more efficient, secure, and scalable communication technology as humanity's footprint in space expands amid tomorrow's communication demands.

At the same time, this is not a call to replace radio, which is time-honored and still delivers irrefutable benefits. Photonics can instead supply a helping hand. The skies are only going to become more crowded, with both private and public players launching satellites with enthusiasm and demands for faster and more reliable connectivity increasing at a rapid pace.

Photonics promises higher data rates, lower power consumption, excellent security, and outstanding reliability. In respect to creating a safe, globally connected world, it is an important piece of the puzzle.

jf@cailabs.com

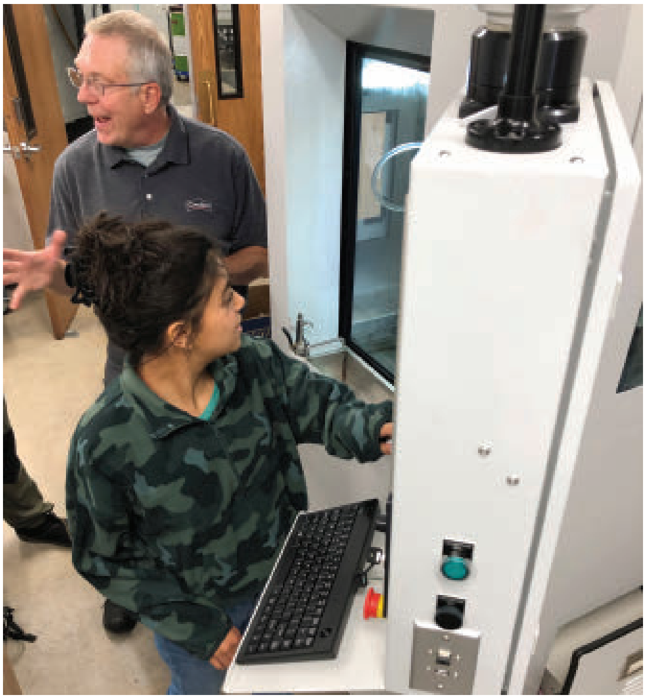


Front Range Community College
Longmont, Colorado

LASER-TEC is the Center for Laser and Fiber Optics Education, founded in 2013 by the National Science Foundation (NSF) and headquartered at Indian River State College in Florida. It was established to help meet the goals of educating and sourcing domestic talent in the areas of optics and photonics. As a service to students, recent graduates, and prospective employers, Photonics Spectra *runs a profile of one of the LASER-TEC colleges each month.*

Front Range Community College (FRCC) offers both a one-semester and one-year certificate program that stack into a two-year associate of applied science (AAS) degree program in Optics & Laser Technology. These certificate and degree programs were developed with the support of the Colorado Photonics Industry Association (CPIA), the American Center for Optics Manufacturing (AmeriCOM), and an industry advisory board that enables a photonics workforce ecosystem for growth in lab equipment, curriculum, and outreach initiatives. FRCC students in this ecosystem are able to network with relevant employers including Excelitas Technologies, Meadowlark Optics, Thorlabs, and others.

Students in the Front Range Community College (FRCC) Optics & Laser Technology program train with Dave Mohring from OptiPro on a computer numerical control (CNC) optics generator.



Program

FRCC's program is designed for students who want to complete a certificate or degree pathway and enter the workforce. Students are prepared for entry-level positions in optics fabrication and assembly, focusing on laboratory safety including cleanroom environments and test equipment, quality assurance standards, and manual and computer numerical control (CNC) fabrication. Students explore the production processes of precision optics used in cameras, projectors, eyewear, microscopes, telescopes, appliances, and binoculars. Students will learn about optical engineering drawings/prints, lean manufacturing, statistical process control, geometric dimensioning, and tolerancing for optics, focusing on the unique metrology practices and tool sets within each. The program will prepare students for laser and photonics technician positions with increased electronics, laser, and system-level skill development including advanced topics, such as fiber optics, along with additional writing and mathematics courses — all culminating in a work-based internship or problem-based capstone project.

 Images courtesy of Front Range Community College.

Graduates of FRCC's degree and certificate programs have the skills to:

- Demonstrate an understanding of the nature and properties of light and lasers using basic geometrical and physical optics.
- Demonstrate safe and proper handling and operation of laboratory, optics fabrication, and test equipment.
- Use tools and techniques to measure optical parameters and systems, and collect, organize, and interpret data to draw proper conclusions.
- Define the documentation of design intent using prints and the interpretation of tolerancing symbols.
- Understand, build, and learn about electrical and electronic instrumentation as it applies to optical and photonic systems.
- Define and demonstrate optics manufacturing, fabrication, quality testing, and troubleshooting techniques.
- Explain how efficient manufacturing processes affect optics manufacturing.
- Apply written and verbal communication skills to effectively execute work instructions and report information.
- Demonstrate optical alignment, building, and testing of optical systems.
- Understand and practice safe use of light sources, including lasers.

How to recruit from this college

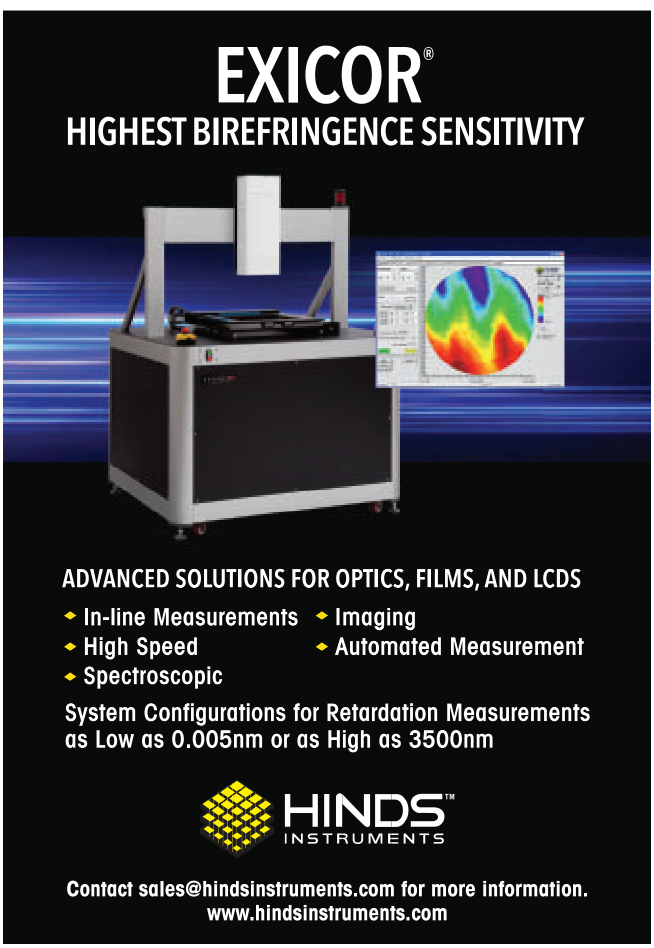
Send job postings to the contact information below. If possible, visit FRCC to present your company and employment opportunities to our students. A private room to interview interested students will be provided. Please see the contact information to schedule a recruiting visit. Graduates are available every December and May.

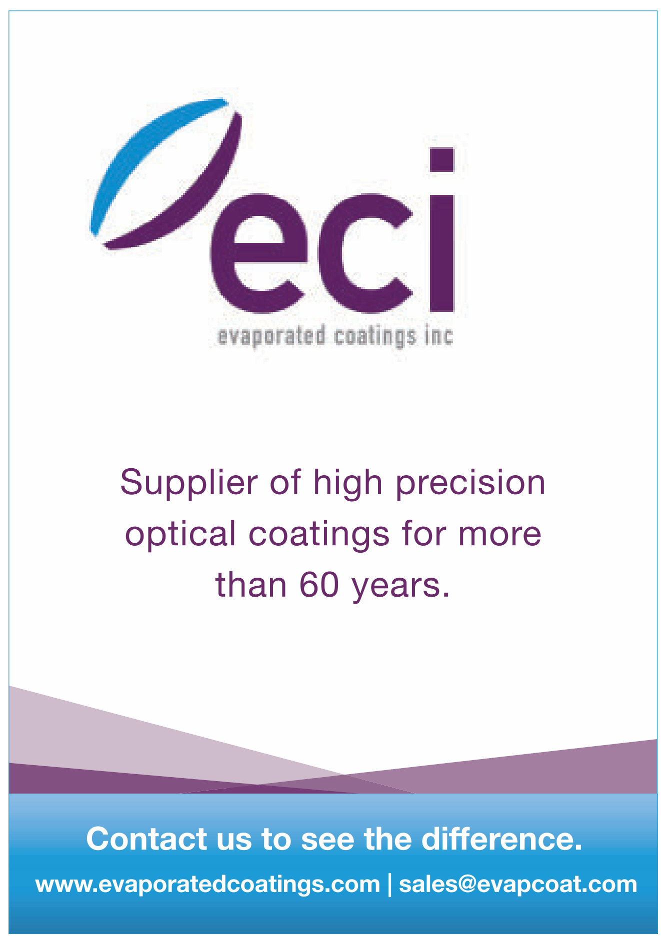
Contact information

FRCC Center for Integrated Manufacturing
+1 303-678-3790
FRCCMfg@frontrange.edu
1351 S. Sunset St.
Longmont, CO 80501

Program website

www.frontrange.edu/optics





Product News

Femtosecond Laser

The Satsuma X from **Amplitude** is a femtosecond laser designed to meet requirements in percussive glass drilling, silicon cutting, stainless steel texturing, and medical applications. The laser has an available energy level of 500 µJ at 100 kHz as a single femtosecond pulse and up to 1.5 mJ with the optional SuperBurst mode. The Satsuma X also features an adjustable repetition rate with a single shot setting at 40 MHz, a compact design, and a real gigahertz process from 30 to 3000 pulses with megahertz/gigahertz mode changeover.
info@amplitude-laser.com

FBG Reflectors

The WaveShift Series from **TeraXion** are fiber Bragg grating (FBG) reflectors for Raman fiber lasers in applications such as spectroscopy, laser pumping, and telecommunications. The reflectors can be used to generate high-power outputs at specific wavelengths with a side mode suppression ratio. The WaveShift Series features a high wavelength accuracy, high reflectivity, and low insertion loss.
info@teraxion.com

Cesium Atomic Clocks

The OSA 3300 SHP and OSA 3350 Super ePRC+ from **Adtran** are optical cesium atomic clocks designed to meet applications such as positioning and navigation as well as in scientific research and timing infrastructure. The OSA 3300 SHP uses Allan variance for stability and accuracy. The OSA 3350 SePRC+ can maintain 100 days of 100-ns precision for continuous and accurate timing in environments in which a global navigation satellite system (GNSS), such as GPS, is unavailable.
info@adtran.com

MIR Sensor

Seegnus from **Lynred** is a MIR high-operating temperature infrared sensor for conducting long-range imaging in tactical gear including unmanned aerial vehicle gimbals, tactical goggles, armored vehicle sights, remote control weapon sights, and submarine optronic masts. The 7.5-µm pixel pitch sensor uses a 1280 × 1024 SXGA format and can detect individuals at up to 14.5 km away in a 630-m width imaged scene when combined with 220-mm folded compact f/4 commercial off-the-shelf optics in favorable conditions. Seegnus features a high cooler reliability of 32,000 h, a power consumption of <3.5 W, and a 300- × 300- × 300-cm form factor.
info@lynred.com

Phase Lock Servo Controller

The SLICE-OPL from **Vescent** is an offset phase lock servo controller for locking follower lasers to master lasers or frequency comb teeth. The controller features a touchscreen interface, allowing users to view error signals on the unit without the need of an oscilloscope. All-analog circuitry enables performance at speed and with low noise. The SLICE-OPL has a user-adjustable offset from 10 MHz to >9 GHz and remote access capabilities.
sales@vescent.com

Far-UVC LED

The SF1-3M1FWL1 from **Silanna UV** is a quad high-power far-ultraviolet C (UVC) LED meant for surface disinfection, air purification, medical device sterilization, and more. Emitting a peak wavelength of 235 nm, the far-UVC LED has a typical viewing angle of 125° and a typical output power of >3 mW at 30 mA. The SF1-3M1FWL1 is mercury-free and includes electrostatic discharge protection integrated in a 6.8- × 6.8-mm package.
sales_uv@silanna.com

MIR Frequency Comb

The Mid-IR Comb from **Menlo Systems** is a frequency comb laser for metrology applications in the 3- to 5-µm and 5- to 14-µm MIR spectral

range and for measurements for MIR Fourier-transform spectroscopy (FTIR), nano-FTIR, MIR dual-comb spectroscopy, and frequency-locking of MIR quantum cascade lasers. The carrier-envelope-offset (CEO)-free optical frequency comb provides up to 200-mW average optical power within a large spectral bandwidth of 50 to 300 cm^{-1}. The Mid-IR Comb can also be fully CEO-stabilized to obtain comb lines featuring hertz-level linewidths in the MIR.
sales@menlosystems.com

Sampling Sphere

The ISMS-30-VAS from **Gigahertz-Optik** is a dual-use integrating (sampling) sphere light source for reflection measurements on flat, convex, and concave displays and annulus design for separating specular, haze, and Lambertian reflection. The sphere is built around a 300-nm-diameter integrating sphere with two LED-based light sources. The ISMS-30-VAS includes port adapters, which are mounted on both sides, for making the annulus method and sampling sphere method, and magnetic holders for individual port adapters for the measurement of displays with different curvatures.
info-us@gigahertz-optik.com

Wavelength Meters

The WS8 series of wavelength meters from **HighFinesse** are for test and measurement and metrology applications. Fully compatible with

HighFinesse's photonic crystal switches, the meters can solve range limitations of single-mode switches with a versatile graphical user interface. The WS8 series provides single-mode operation from 390 to 2000 nm and features an absolute accuracy of 2 MHz, a measurement resolution of 100 kHz, a measurement rate of 1000 kHz, and compatibility with Ubuntu 22.04 and other Linux distributions.
info@highfinesse.de

Dual-Axis Pitch Stages

The YP100-45 Series from **Optimal Engineering Systems** comprise compact dual-axis yaw pitch stages using rotary stages capable of ~90° of rotation and goniometers with +/−45° of travel. The YP100-45-02 **(shown)** is driven by a three-phase brushless servo motor with quadrature incremental optical encoder, while the YP100-45-03 is driven by a direct current brushed servo motor with quadrature incremental optical encoder. The YP100-45-01 and -04

stages are driven by two-phase stepper motors with micro-stepping capabilities. The YP100-45 Series models are made of black anodized aluminum with a load capacity of 10 kg and a rotation center height of 68 mm.
sales@oesincorp.com

Ultrashort-Pulse Laser Platform

The LXR platform from **Luxinar** is an ultrashort-pulse laser source for applications in industrial laser processing, such as micromachining. With high dynamic range of pulse repetition frequencies and pulse energies of up to 160 µJ, the platform uses a synchronization signal for maintaining control in dynamic applications as well as a burst mode and pulse-on-demand mode. The LXR platform has available wavelength options of 1030, 515, and 343 nm while

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microcircuitlabs.com

featuring an average power of up to 160 W, a pulse duration of 800 +/−150 fs, and a burst energy of 0.8 mJ.
info@luxinar.com

Laser Cutting Systems

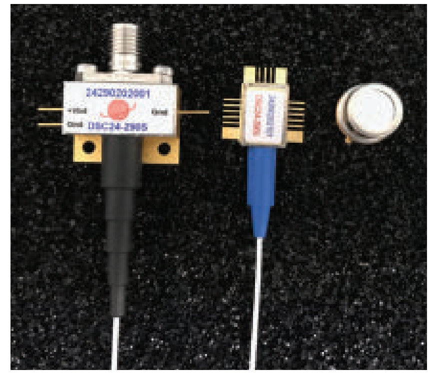
Products in the SaberTech line of laser cutting systems from **Laser Photonics Corporation** are developed for industrial cutting in the aerospace, automotive, maritime, and defense industries. The line includes newer versions of the company's TiTAN Express and TiTAN FX laser cutting systems and Laser Photonics' Turbo Piercing technology, which minimizes the heat-affected zone of the material being processed and reduces material distortion caused by laser heat throughout the cutting operation. The SaberTech line can be used in applications such as working with highly reflective materials, shuttling components down production lines, or reducing warping in materials.
fiberlaser@laserphotonics.com

Edge AI Computing System

The EAC-4000 from **Vecow** is an edge-AI computing system for space-constrained applications such as auto optical inspection and other edge AI use cases. Powered by NVIDIA Jetson Orin NX and Jetson OrinNano system-on-modules, the system has a processing power of up to 100 trillions of operations per second (TOPS) while supporting both in-band and optional out-of-band remote edge device management as well as Linux and the NVIDIA JetPack SDK. The EAC-4000 features a 112- × 103- × 45-mm footprint, a local area network port, four USB 3.1 ports, two COM RS-232/422/485 ports, a nano SIM card socket, and two antennas for WiFi/4G connectivity.
info@vecow.com

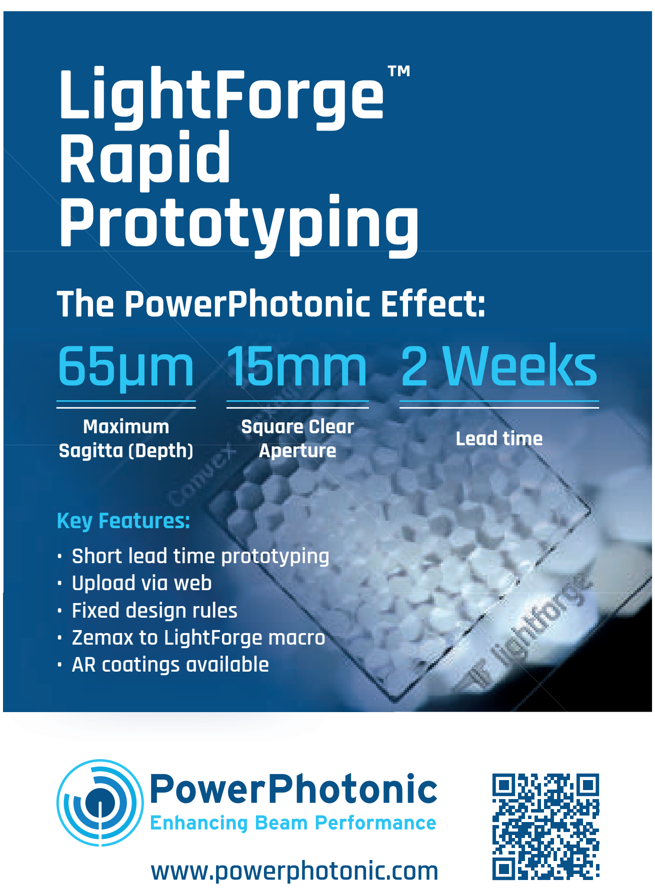
Fiber Laser

The VALO Tidal from **HÜBNER Photonics** is a femtosecond fiber laser that can be used for simultaneous second and third harmonic imaging using standard microscope objectives, broadband terahertz generation, and nonlinear wafer inspection. The laser delivers a typically higher optical bandwidth than its gain bandwidth, allowing its optical pulses to have durations <50 fs and peak power levels >2 mW. The VALO Tidal's spectral bandwidth covers a range of 1000 to 1100 nm and features an integrated dispersion precompensation unit.
info.de@hubner-photonics.com



InGaAs Photodiodes and Receivers

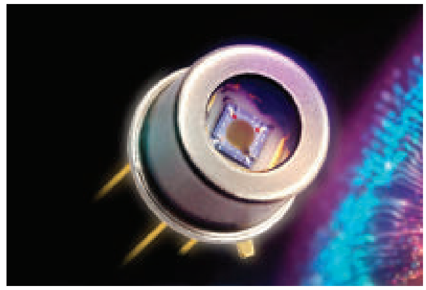
Discovery Semiconductors' extended indium gallium arsenide (InGaAs) photodiodes and photoreceptors can be used in space applications, including spectroscopy, optical communication links, and rapid doppler shift lidar. These devices come in single photodiode, balanced photodiode, and amplified optical receiver



configurations in packages such as fiber-coupled butterfly modules with a K or SMA connector, fiber coupled surface mount technology modules with no coaxial connectors, and free space TO-5 packages with broad antireflection coatings. The extended InGaAs photodiodes and photoreceptors operate over a temperature range from extreme cryogenic up to +125 °C and feature a bandwidth of up to +10 GHz, an optical dynamic range of up to 50 mW, and a wavelength coverage between 800 and 2400 nm.
info@discoverysemi.com

Color LEDs
The XLamp XP-L Color LEDs from **Cree LED** are multicolor RGBW LEDs. The individually addressable LEDs come in both high density and high intensity versions and can achieve acceptable color mixing at 3 cm from a wall. The XLamp XP-L Color LEDs feature a maximum driver current of 1 A per LED die, a max power of 12 W, and a 3.45- × 3.45-mm form factor.
salessupport@cree-led.com

FTIR Spectrometers
The PYRONEER series from **InfraTec** are Fourier transform infrared (FTIR) spectrometers made with deuterated L-alanine doped triglycine sulphate (DLaTGS) instead of single-crystalline



lithium tantalate ($LiTaO_3$). The detectors have a high pyroelectric coefficient, low heat capacity, and low relative permittivity, allowing for a favorable signal-to-noise ratio at high modulation frequencies. The PYRONEER series features pyroelectric elements with a 1.3-mm diameter, low-noise junction field effect transistors, detectivity of ~3 Jones at 1 kHz, and a 110° field of view.
sensor@infratec.de

Optics Simulation Framework
The VPIdeviceDesigner version 2.7 from **VPIphotonics** is a simulation framework for analyzing and optimizing optical devices, waveguides, and fibers for integrated photonics applications. The design tool offers 2D and 3D full-vectorial finite-difference beam propagation and eigenmode expansion solvers for modeling optical devices and a set of semi- and full-vectorial finite-difference mode solvers for modeling straight and bent waveguides and fibers made of iso- and anisotropic materials. The VPIdeviceDesigner version 2.7 features a reworked S-matrix interface, an upgraded 3D geometry kernel, and dedicated classes for dispersive anisotropic and graded-index materials.
sales@vpiphotonics.com

Dual Thermal-Visible Cameras
The Hadron 640+ and 640R+ from **Teledyne FLIR** are dual visible and radiometric, respectively, camera modules for integration into uncrewed aircraft systems, uncrewed ground vehicles, robotic platforms, and AI applications. The modules include a 640 × 512 resolution Boson+ LWIR camera module with a thermal sensitivity of 20 mK or better and the ability to see through total darkness, smoke, most fog, and glare. The Hadron 640R+ provides temperature measurements for every pixel in the scene, while the 64-MP Hadron 640+ provides both thermal and visible imagery within a single camera module.
flir@flir.com

Isolated Probing System
The R&S RT-ZISO from **Rohde & Schwarz** is an isolated probing system that can be used for

measuring fast switching signals in environments with high common-mode voltages and currents. The system provides differential measurements of up to ±3 kV on reference voltages of ±60 kV with a rise time of <450 ps and suppresses fast common-mode signals that can distort and interfere with accurate measurements. The R&S RT-ZISO includes power-over-fiber architecture that galvanically isolates the devices under test from the measurement setup and bandwidth options of up to 100 MHz to 1 GHz with a common mode rejection ratio of >90 dB at 1 GHz.
info@rsa.rohde-schwarz.com

Surface-Enhanced Raman Substrate

The RCT4M from **Thorlabs** is a textured surface-enhanced Raman spectroscopy substrate for sensing applications, including analysis of chemical mixtures, substances, quality inspection for pharmaceuticals and food, and monitoring chemical processes at production sites. The substrate uses the nanotextured surface of a UV fused silica substrate, with a gold plasmonic layer deposited on top of the texturing, to provide parts per billion sensitivities in biosensing applications. The RCT4M measures 4.5 × 4.5 × 0.5 mm and features an absorption of 785 nm.
techsales@thorlabs.com

Industrial Quality Assurance System

The Vision & Weld from **Kistler** in collaboration with Nidec SYS is an optical quality insurance system for finding and removing not OK (NOK) parts in the production of punched parts. The system combines the KVC 621 optical inspection cell from Kistler with the Cutting Welding 2.0 system from Nidec SYS and examines individual test parts for defects so that it can separate the part and weld the punching strip back together. The Vision & Weld accommodates up to four integrated camera stations in its 1100-mm-wide housing and uses close-meshed programmable logic controller monitoring to inspect parts at cycle times of up to 2000 parts per minute.
info.de@kistler.com

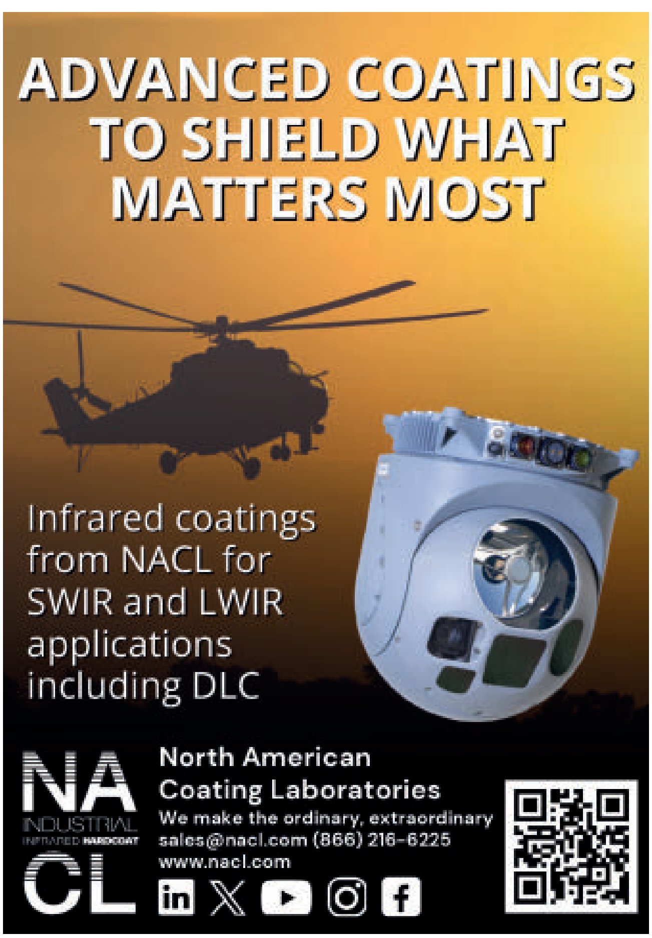
SWIR Cameras

The ace 2 X visSWIR family of cameras from **Basler AG** comprises high-resolution SWIR vision cameras. Equipped with Sony's IMX992 and IMX993 SenSWIR sensors with 5-MP and

3-MP resolution, the cameras capture images in the spectrum from 0.4 to 1.7 µm. The ace 2 X visSWIR camera family comes with a Pixel Correction Beyond feature that detects pixel defects typical of indium gallium arsenide sensors and features a 29- × 29-mm design as well as an optional USB 3.0 or GigE interface.
sales.europe@baslerweb.com

Dual-Chip UVC LEDs

The MTE2350F-UV2 and MTE2550F-UV2 from **Marktech Optoelectronics** are dual-chip UVC LEDs in 235- and 255-nm wavelengths, respectively, for disinfection applications in water quality sensors, air, and surfaces. Placed within hermetic TO-can packages, the LEDs have a doubled light output due to integrating two LEDs within a single package. The MTE2350F-UV2 and MTE2550F-UV2 have a low energy consumption, are mercury-free, and are designed to be safer for the environment as well as end users.
info@marktechopto.com



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 FLEET Events GmbH, **w3plus@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) Bromont, Québec.
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.scixconference.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.

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.

PAPERS

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.

5th Annual Conference on Lasers, Optics, Photonics Sensors, Bio Photonics, Ultrafast Nonlinear Optics & Structured Light 2025
(May 30-June 1) Boca Raton, Fla.
Deadline: Abstracts, Nov. 1
Contact Keerthi Rajana, +1 647-952-4467, **support@lopsnews.com**; www.exceleve.com/photonoptics.

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

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, **customer service@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, **customer service@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, **customer service@spie.org**; www.spie.org/conferences-and-exhibitions/medical-imaging.

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

MARCH

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

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

APRIL

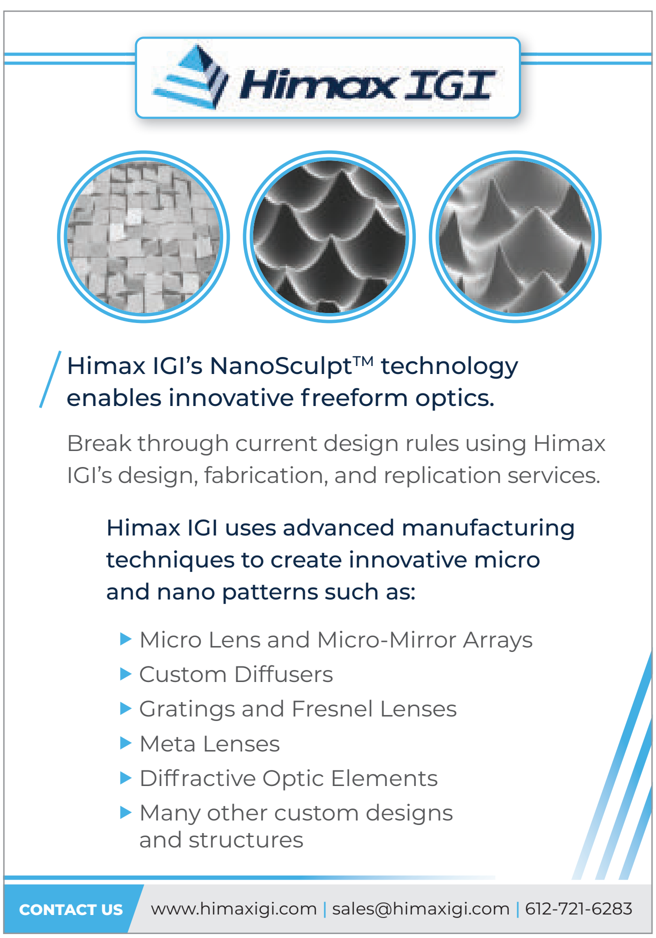
PIC International Conference
(April 7-9) Brussels.
Contact Angel Business Communications, +44 0-24-76718970, **info@picinternational.net**; www.picinternational.net/.

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

Optica Biophotonics Congress: Optics in the Life Sciences
(April 21-24) Coronado, Calif.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/biophotonics_congress/.

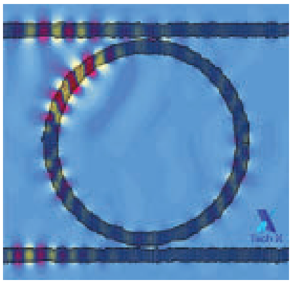
OPIE
(April 23-25) Yokohama, Japan.
Contact OPIE, **event@optronics.co.jp**; www.opie.jp/en/.

ASLMS Annual Conference
(April 24-27) Orlando, Fla.
Contact ASLMS, +1 715-845-9283 / +1 877-258-6028, **information@aslms.org**; www.aslms.org/home.



PHOTONICS SHOWCASE

Tech-X Corporation XSim



XSim is a powerful GPU-enabled FDTD tool for precise time-dependent EM simulations. With multi-GPU scalability, start on your laptop and seamlessly transition to AWS for faster, cost-effective results. Ideal for photonic integrated circuit designers, convert GDS files to detailed 3D simulations, optimizing performance and ensuring robustness against manufacturing variations. Achieve unmatched accuracy and efficiency.

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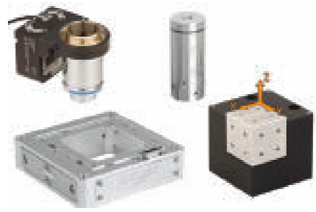

High-performance nanopositioning stages for photonics, laser communication, microscopy.

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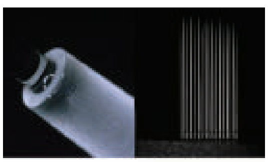
The NYFORS SMARTSPLICER



NYFORS

The NYFORS SMARTSPLICER offers CO_2 laser glass-processing capabilities designed to produce high-power and sensitive photonic components and complex structures. It offers contamination-free fiber array splicing, ball lensing, end-capping, and many other challenging processes. NYFORS also provides automated high-precision solutions for fiber preparation, such as stripping, cleaving, recoating, and end-face analyzing. NYFORS also offers custom workcell automation solutions.

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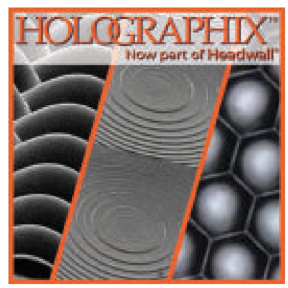

Holographix™, now part of Headwall®, makes cost-effective, high-quality custom microlens arrays for aerospace, automotive, medical, and consumer electronic apps. Double-sided MLAs with micron-level alignment, thickness control, and aperture coatings. AR- and mirror-coating options available. We meet the most demanding solder-reflow and environmental specs.

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info.bopt.us@bruker.com
www.bruker.com/hyperion

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PHOTONICS SHOWCASE

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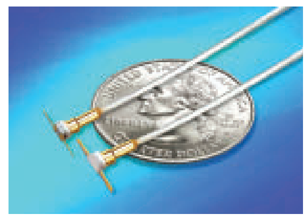
Compact InGaAs Photodiode



Fermionics Opto-Technology introduces high-speed, low-dark-current, low-capacitance indium gallium arsenide FD80 Series photodiodes with space-saving surface-mount packaging. Ultracompact ceramic fiber pigtail photodiodes are specially designed for extremely tight spaces and ideal for high-speed communication systems. The planar-passivated device with 80-µm active area on a horizontal- or vertical-mount S8 ceramic package can be coupled directly to a single- or multimode pigtail fiber.

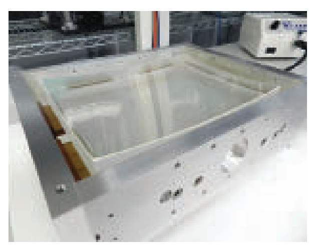
Fermionics Opto-Technology **(805) 582-0155**
j.shin@fermionics.com **www.fermionics.com/files/FD80series.pdf**

Mid-IR LED for Gas Detection

Hamamatsu's new lineup of mid-infrared LEDs includes L15893-0330CA, featuring 3.3 µm peak emission wavelength, high-speed response, and low power consumption. It delivers significantly higher output compared to previous products and was developed using Hamamatsu's unique crystal growth technology and process technology. The L15893-0330CA LED comes in ceramic packaging and is a suitable light source for methane (CH_4) gas detection.

Hamamatsu **(908) 231-0960**
photonics@hamamatsu.com **bit.ly/3SDibNe**

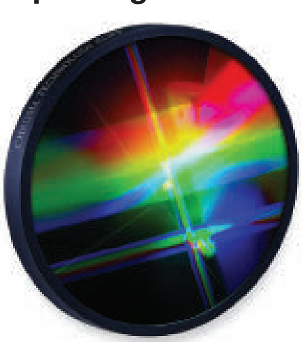
Off-Axis Parabolas



AOS produces off-axis parabolas for the most demanding applications in technology today including high energy lasers, analytic instruments, and satellite imaging. Our special tolerancing system optimizes performance. We manufacture custom components in a variety of materials including silicon carbide, glass, silicon and other advanced ceramics. AOS aspheric optics can be found in high technology companies and laboratories around the globe.

Aperture Optical Sciences Inc. **(860) 316-2589**
info@apertureos.com **www.apertureos.com**

Improving Performance in the SWIR



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PHOTONICS SHOWCASE

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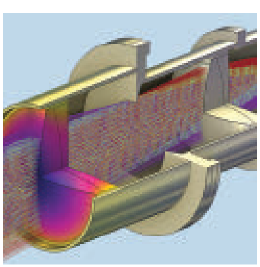
Multiphysics Modeling and Simulation



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

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Liquid Light Guides

Liquid Light Guides are flexible, unbreakable, and very durable, and they have significantly better transmission, more homogeneous illumination, and a larger aperture than fiber bundles at lower costs! They are the perfect solutions for applications that demand uniform, high-intensity light. We offer four different series designed for diverse spectra ranging from ultraviolet to infrared and a broad selection of end fittings.

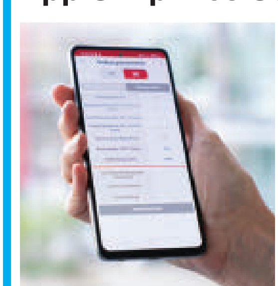
Lumatec GmbH **+49 89-742822-0**
sales@lumatec.de **www.lumatec.de**

New! Precision Micropositioning

Mad City Labs MMP Series of stepper motor driven micropositioners has been newly updated to include 25mm and 50mm travel ranges with step size of 95nm. This update includes the ability to mix and match travel ranges to create multi-axis positioning systems with ease. Our proprietary intelligent control scheme results in exceptional stability with high native precision ensuring nanoscale compatibility.

Mad City Labs Inc. **(608) 298-0855**
sales@madcitylabs.com **www.madcitylabs.com/mmpseries.html**

App Simplifies Scan Calculations



Updated functional scope of 'SCANcalc' app: The free app simplifies calculations for users when checking scan parameters for their individual requirements. Since 2017, the app has been able to calculate the focus diameter and display the accuracy of various 2D scan systems at a selected focal length. The new app version now also includes 3D systems. This means that also spot size and Rayleigh length can be calculated at the touch of a button.

SCANLAB **+49 89 800 746 0**
info@scanlab.de **www.scanlab.de**

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Dual-Band Infrared AR Coatings

Infrared imaging systems require simultaneous performance MWIR (midwave, typically 3 to 5 µm) and LWIR (longwave, typically 8 to 12 or 7.5 to 13.5 µm) spectral bands. Our dual-band IR AR coatings achieve measured peak transmission values over 99.5% in both bands. High-performance dual-band AR coatings are applied to a variety of IR materials, large to small, on plano or curved surfaces, with excellent environmental durability and spectral performance. ISO9001:2015.

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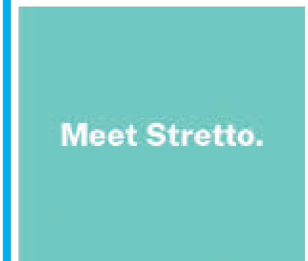
Meet Stretto



DRS Daylight Solutions introduces Stretto, a family of high-precision tunable lasers. Designed to enable quantum information science applications, Stretto provides wavelengths from UV to infrared, maintaining a common footprint and interface. This simplicity facilitates transition from laboratory experiments to OEM integration without redesign. Leveraging Daylight's military ruggedized designs, Stretto provides performance-at-scale, enabling our customers to succeed in what's next.

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

Pixelink PL-D7924 24-MP Camera

Pixelink's PL-D7924 24MP camera, with the Sony IMX540 Pregius S sensor, offers reliable, high-performance imaging. Features include global shutter to capture fast-moving objects without distortion and legible text within images, excellent readout speed, and HD-image capture of wider areas. With 2.74 µm and 17 fps, this 1.2-in. color or mono camera is ideal for inspection, testing, and analysis.

Pixelink **(613) 247-1211**
sales.pixelink@ametek.com **www.navitar.com/pixelink-cameras**

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Using our rapid optical prototyping capabilities, we can deliver multi-element assemblies in as little as four weeks and engineered components in as little as one week. We offer engineering design, clean-room assembly, coating, and custom metrology and testing. We can design and manufacture spherical and plano optics from 4 - 380 mm as well as aspheric, cylindrical, and acylindrical optics in a variety of sizes. Contact us for your next project!

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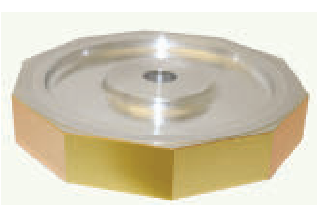
Scanner Wheels



NiPro Manufactures Precision mirrors of all types and sizes but is also a supplier of precision scanner wheels of any prototype or production quantity. All scanners are produced using Precitech, 4-axis diamond flycutting machines, Taylor Hobson automated autocollimator, 4D interferometer and a Zygo Z gauge. The finish is routinely measured at 5nm's, flatness at 1/4 wave, positioning accuracy of +/− 0.1 arcseconds and tilt less than 20 arcseconds.

NiPro Optics **(949) 215-1151**
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Fiber Focusers and Accessories

Our FC10 Fiber Collimator paired with our Focusing Modules gives micron size spots and eliminates extra optical mounts. From 1:1 imaging of fiber's MFD to longer focal lengths, small spots can be generated from near UV to 2 microns. Besides focusing, polarizers, lines and other optic modules can be attached for a compact optical module. These can be customized for a complete optical assembly and be made very compact.

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Optris Infrared Sensing LLC **(603) 766-6060**
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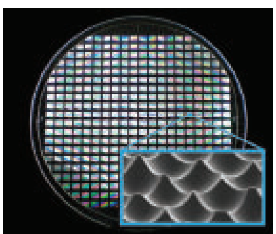
Wafer-Level Optics



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

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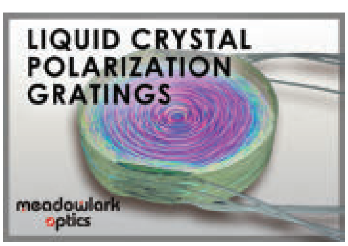
sales@evapcoat.com **www.evaporatedcoatings.com**

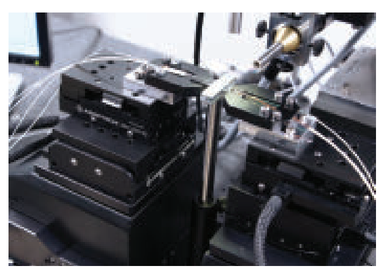
Liquid Crystal Polarization Gratings



Liquid crystal polarization gratings (LCPGs) are diffractive elements that provide near-100% diffraction for circularly polarized light. When layered with thin polarization-controlling liquid crystal elements, LCPGs provide a means of nonmechanically reconfiguring light into different states, such as for beam steering or focusing. Using LCPGs in nonmechanical beam steering is a novel technique and Meadowlark has the patent on this approach.

Meadowlark Optics Inc. **(303) 833-4333**
sales@meadowlark.com **www.meadowlark.com**

Multi-Axis Fiber Alignment System



The FiberMax®HP 3- to 6-axis photonics alignment platform is built on Aerotech's ANT nanopositioning product line. It is designed to meet the demanding needs of critical photonics alignment in a highly automated, 24/7 production environment with no compromise in speed, accuracy, and resolution.

Aerotech Inc. **+1 (412) 963-7470**
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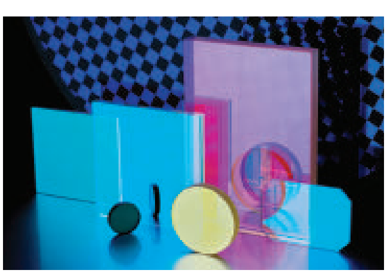
SIRRUS™ PVD Platform



Alluxa's innovative, next-generation SIRRUS™ plasma physical vapor deposition (PVD) platform offers full spectral coverage from ultraviolet (200 µm) to infrared (14 µm). The proprietary process enables optical filters with the steepest edges, highest transmission, and deepest blocking available while maintaining high performance, precision wavelength control, and extremely uniform coatings.

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Neo High-End Spectrometer

Admesy's new Neo Series offers a versatile solution for different spectral measurement needs, fit for a wide array of applications. Its well-thought-out optical and mechanical construction assures the highest optical performance, even under tough conditions. Creating an OEM solution? Integrating spectral measurements into your production testing? Needing spectrometer answering to the highest expectations for development applications? Neo is your choice.

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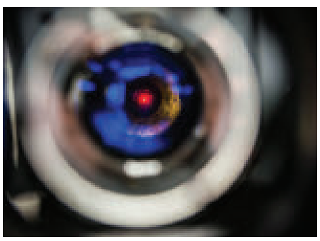
Large-Size High-Power Optics



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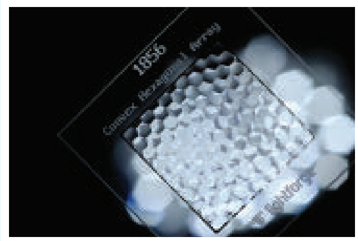
LightForge™



Reduce lead times and cost using LightForge™ low-cost rapid fabrication service. This service gives optical designers the ability to have their own freeform surfaces manufactured in fused silica. After uploading your design to the LightForge™ section of our website, your optic will be ready to ship in as little as 2 weeks. LightForge™ is used to create a range of refractive optical elements, such as beam shapers and aberration compensators.

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Removing obstacles to reach your GOAL!!!

Let's paint a picture: It is a beautiful summer afternoon. A cloudless sky hangs over a stadium where two soccer (football) teams are about to play the match of a lifetime. Unable to get tickets to the sold-out event, you and millions of spectators sit on the edge of your couch cushions as the whistle blows to signal the start of the game. Eighty-seven of the scheduled 90 minutes pass with both sides deadlocked in a 1-1 tie. Any mistake could result in victory for the opposition.

But then, as a 50-50 ball is intercepted by one of your team's strikers, you watch as they make a clean break across the pitch, pivot, and sail a perfectly kicked ball just beyond the goalkeeper's outstretched fingers to seal the match in the final minute. The crowd goes wild, the announcers shout at the top of their lungs, and you feel the vibrations of millions of feet jumping simultaneously in excitement in living rooms across the world.

Except, you never saw the goal.

As the camera pans to the net, it captures a different camera crew instead, which is perfectly obstructing your view of one of the greatest moments in sports history and leaving those lucky few thousand ticket holders to be the only true spectators of the goal.

Perhaps with similar fears in mind for fans of all sports, a research team from Kaunas University of Technology (Lithuania) developed an end-to-end system that eliminates visual distractions caused by overlapping camera angles. The system detects and classifies objects in images in a single pass, making it ideal for real-time events, such as live sports broadcasts. Using a combination of computer vision, AI, and other technologies, the system analyzes video frames from incoming camera feeds to detect unwanted objects, such as errant cameramen (bad), or the occasional on-field streaker (worse). Each frame becomes an image that the AI element divides into grids to better recognize all objects within them.

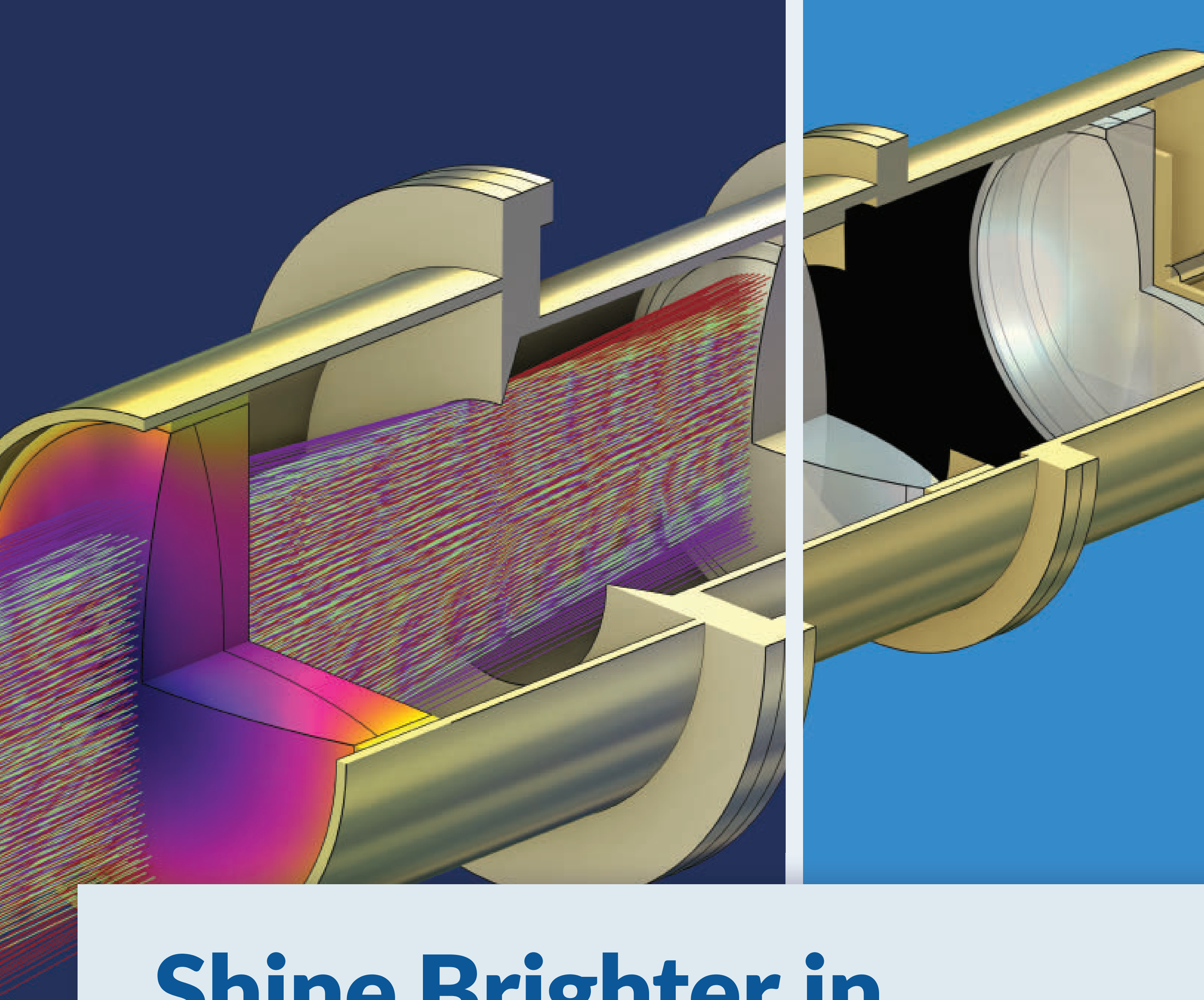
A deep learning technique called inpainting is then implemented to systematically remove the unwanted crew from each frame, while simultaneously filling in the negative space with relevant background details. These frames are integrated back with the livestream and sent to your TV — with audiences none the wiser that any type of distraction appeared in the first place.

The best part: The researchers predict that on TV servers, the algorithm should be quick enough to complete the entire process within a few-second delay while on-air, meaning that not only will it be quicker and easier than scoring on an open net, but it will also prevent additional delays to the standard live broadcast.

The researchers see this as an absolute win for live broadcasts, which they think will have a much more professional feel once the system is implemented.

As for the fans: They will never have to worry about missing another moment of glorious victory from their favorite team.

Image courtesy of iStock.com/Dmytro Aksonov.



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