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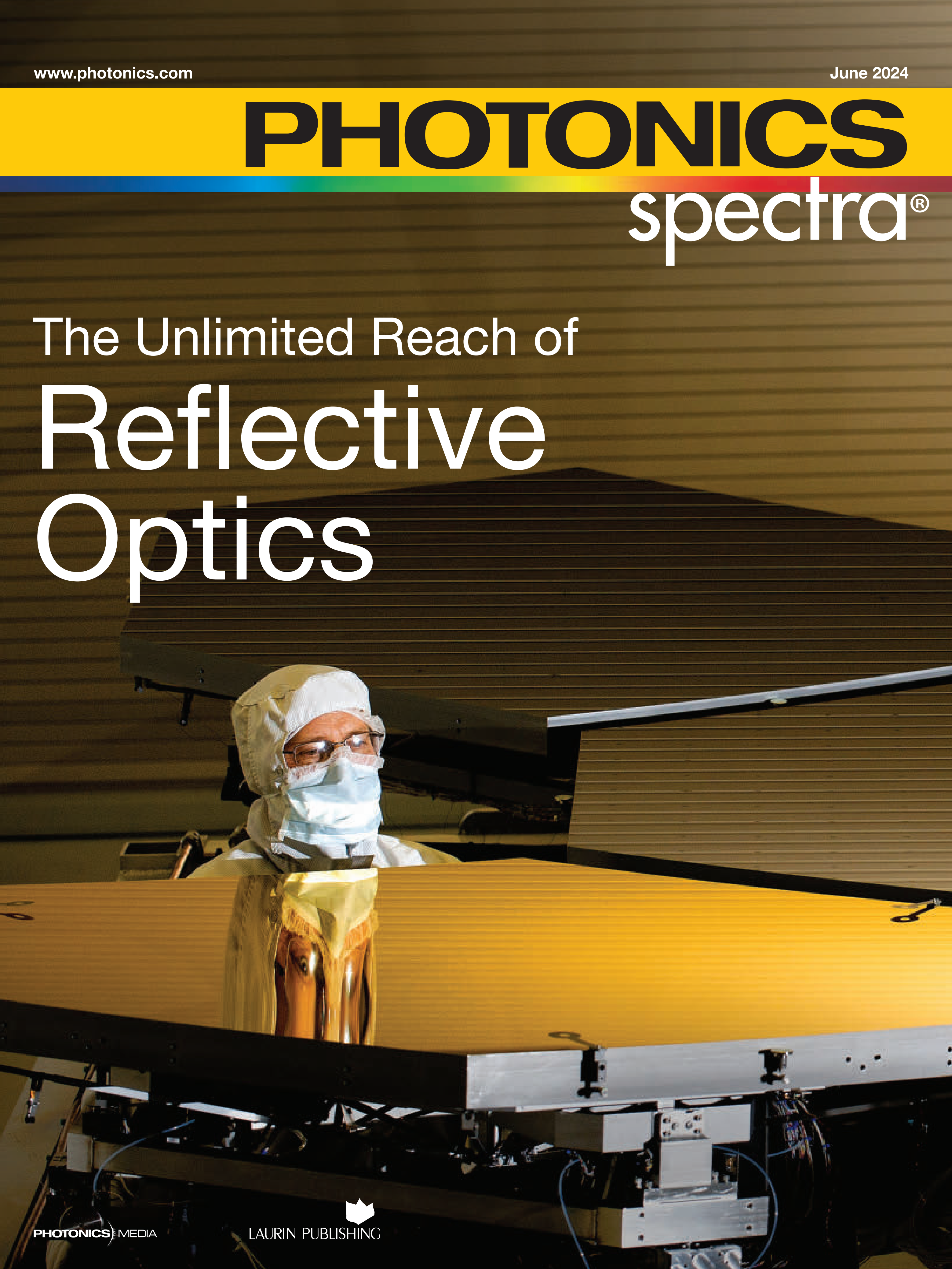

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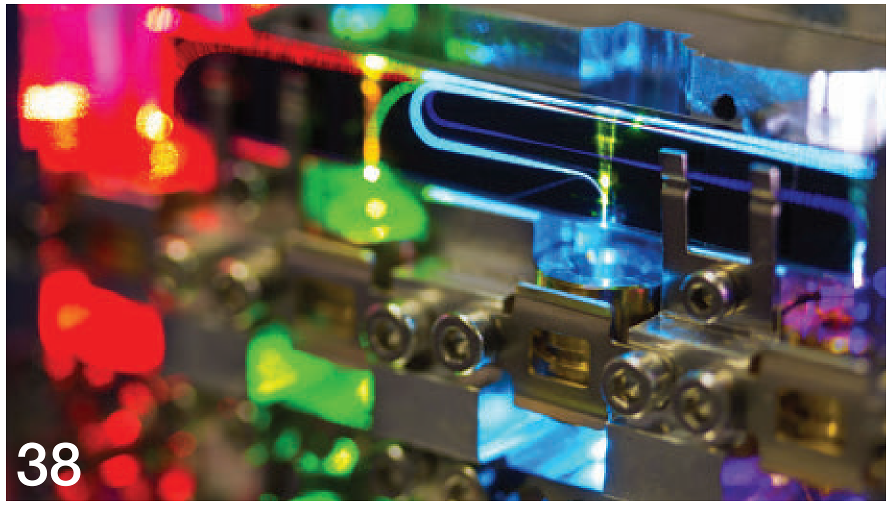
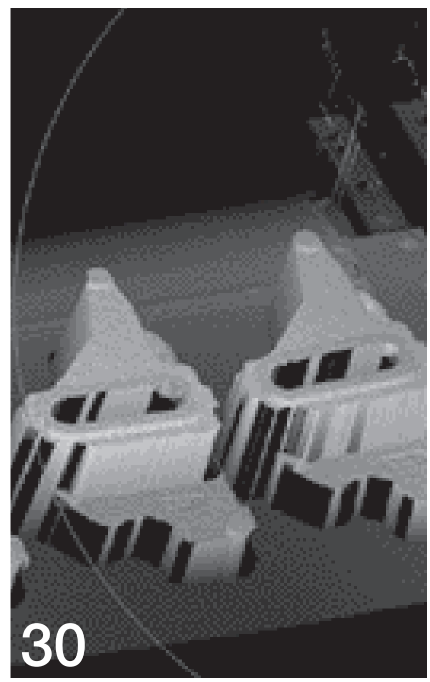
Features





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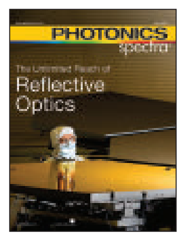
Departments

Columns

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



The Cover

The James Webb Space Telescope's primary mirror showcases the depth and durability of contemporary reflective optics technology, which envelops a class of some of industry's most widely used components. Cover design by Senior Art Director Lisa N. Comstock.

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Editorial Offices

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

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Advertising Offices

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

Japan Sakae Shibasaki
The Optronics Co. Ltd.
Sanken Bldg., 5-5 Shin Ogawamachi
Shinjuku-ku, Tokyo 162-0814, Japan
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Photonics navigates all conditions

During his appearance on the "All Things Photonics" podcast this spring, Mario Paniccia took the conversation to an unexpected setting: a fruit orchard. It was not a scene — like the cleanroom, or the fab, or the foundry — that one might expect to backdrop a discussion with a silicon photonics luminary.

Venturing to such a nonphotonic destination did not signal, as it might have, an odd turn in the conversation. Rather, the orchard has proved to be a dynamic environment that has become the scene of breakthrough innovations in optical sensing.

Paniccia is CEO of silicon photonics optical gyroscope (SiPhOG) developer ANELLO Photonics. The orchard, he said, presents an ideal candidate for optical positioning and navigation sensors to replace traditional systems like GPS. Leaves and trees during harvest season are often just as apt to restrict a legacy sensor as, for example, the full depth of the ocean, or obstructions on the battlefield.

In this way, a photonic positioning, navigation, and timing (PNT) solution that bypasses the limitations of GPS, and which cannot be jammed or spoofed in the same way as radio frequency signals, is as much a game-changer for almond harvesters as it is for the warfighter. It is an especially important consideration in this burgeoning era of autonomous navigation.

This of course elicits an obvious contrast: The orchard hardly connotes the brutal conditions and scenarios that are found in other GPS-denied environments. Aside from the ocean floor and battlefield, other classic extreme environments where PNT solutions hold the key to critical functions include the interior of mines, low Earth orbit, and deep space. Photonic (and nonphotonic) PNT solutions are making headway in these areas, too. Still, if a sensor based on silicon photonics technology can at once prove to be effective in the physically differentiated settings of the agriculture and aerospace and defense sectors, how many other fields might benefit from innovative photonic PNT solutions?

Perhaps a better phrasing: Is anything, anywhere beyond the bounds of photonics?

As you ponder this question, also consider the market for photonics PNT technology — it may be the best indicator of the promise of these solutions. PNT and automated testing company Spirent Communications is the apple of Keysight's eye, after Keysight submitted an acquisition offer for the company. Keysight isn't the only potential suitor; its takeover bid came only after VIAVI filed an acquisition bid for Spirent. Meanwhile, in what appears to be a more conventional acquisition proceeding, Honeywell is completing its purchase of optical gyroscopy specialist Civitanavi Systems.

Details on both acquisitions, as well as how visible laser integration is poised to drive growth in precision timekeeping, among other applications, can be found in Industry News in this issue.

jake.saltzman@photonics.com

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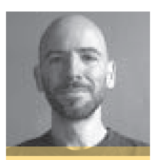
Contributors

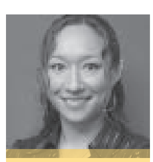
William Benner
William R. Benner Jr. is president and CTO of Pangolin Laser Systems and project leader for the ScannerMAX division. He holds more than 50 patents spanning actuators, position sensors, and lenses used for laser projection applications. Page 59.

Robert Bourdelais
Robert Bourdelais is senior global business manager for MKS/Newport. He has more than 30 years of industry experience, including in engineering, R&D, operations management, and product management. He is also the author of more than 200 issued patents. Page 45.

David Dechow
David Dechow is an engineer, programmer, and technologist widely considered to be an expert and thought leader in the integration of machine vision, robotics, and other automation technologies. Page 30.



Michael Eisenstein
Contributing editor Michael Eisenstein studied biology at Brown University and Rockefeller University. He has worked as a freelance science journalist and as an editor for the past 10 years. Page 52.



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 38.

Andreas Thoss
Andreas Thoss, Ph.D., is a laser physicist, founder of THOSS Media, and a contributing editor to *Photonics Spectra*. He has been writing and editing technical texts, with a focus on the field of photonics, for two decades. Page 10.

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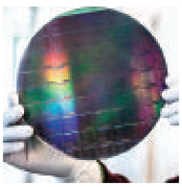
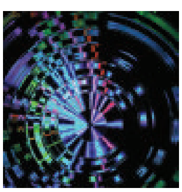
Integrated Photonics for Quantum Computing



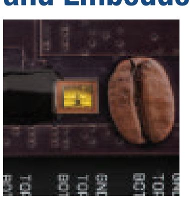
Realizing photonic quantum technologies will require the development of novel photonic components. Monolithic silicon or silicon nitride photonic platforms are falling short with respect to the requirements of the quantum domain, and it is envisioned that a hybrid solution is needed. Christian Haffner of imec discusses what hybrid solutions the silicon photonic platform can offer in terms of detectors, sources, and modulators. His primary focus lies on the electro-optical modulator covering the requirements that the quantum world enforces. He compares the classical and quantum theoretical framework and describes the performance metrics that a quantum electro-optical modulator needs to fulfill.
To view, visit **www.photonics.com/w993**.



Let's Talk About Metalenses

From the moment of their initial introduction, metalenses have ignited the creative minds of engineers working in the realms of optics and photonics. In this webinar, Frank Wyrowski addresses considerations such as constructing and modeling metalenses and the procedures to replace a smooth lens surface with a flat one. The use of metalenses in lens systems leads to a multiscale configuration that necessitates the use of sophisticated simulation methods to ensure an appropriate balance between simulation accuracy and speed. During this webinar, he outlines strategies to handle this scenario. Presented by LightTrans International.
To view, visit **www.photonics.com/w913**.

OLED-on-Silicon for Microdisplays in AR/VR/MR and Embedded Sensing



Microdisplays are essential for wearable AR/VR/MR devices, such as smart glasses. Emissive microdisplays, such as OLEDs or micro-LEDs, provide significant advantages compared to their nonemissive counterparts. Uwe Vogel of Fraunhofer IPMS discusses achievements in high-resolution and ultralow power OLED microdisplay and sensing devices. Additionally, he will discuss their backplane integrated circuit design architectures and OLED-on-silicon frontplane process technology. He considers micro-LEDs as upcoming options for high-brightness applications and compares them to OLEDs in terms of application requirements and performance features.
To view, visit **www.photonics.com/w978**.

The Winds of Change Are Blowing Through the Photonics Industry

BY ANDREAS THOSS
CONTRIBUTING EDITOR

Every even year, the industrial laser community meets in the medieval city of Aachen, Germany, for the International Laser Technology Congress AKL. The three-day event convened 525 participants and 81 speakers from 21 countries this year for the congress' 14th iteration. The event is organized by the Fraunhofer Institute for Laser Technology ILT (Fraunhofer ILT), which hosts one of Europe's largest research and application labs. The event includes the Innovation Award Laser Technology presentation and ceremony as well as an open house event on the Aachen premises.

What is so special about AKL? Attendees will witness people from industry and applied research discuss their work in exceptional detail. For example, digitalization has been discussed for decades — many of the talks covering the topic at past industry conferences and symposia shared informative slide decks — but during AKL'24, two subsequent talks presented real details from the digitalization project that automotive titan Mercedes Benz has undertaken with laser machine producer TRUMPF. The insights ranged from contracts for automation data (for example, on who owns which data, and, what happens to processed data) to figures on how far TRUMPF increased availability in production at Mercedes Benz. Both teams are continuing to use their experiences to blueprint similar projects in digitalization.

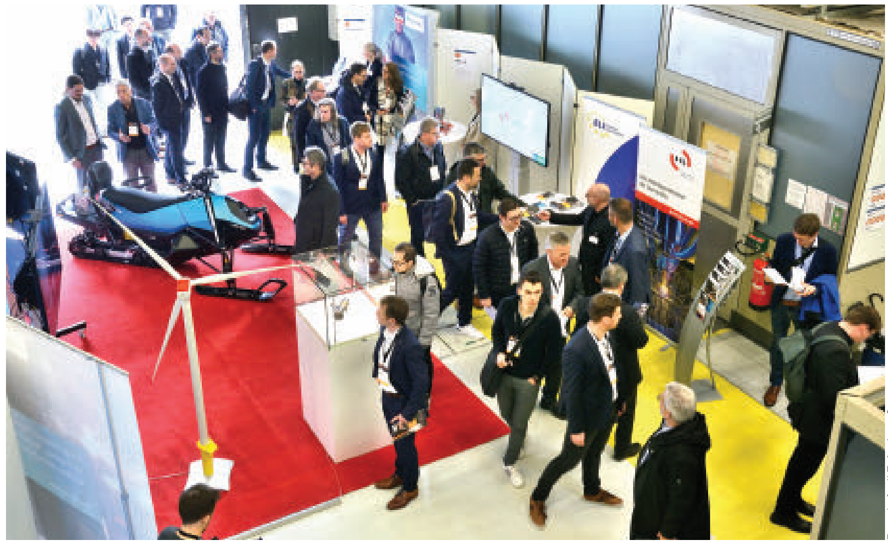
To further explain the significance of digitalization, it describes the application of digital technologies to industrial processes, and has been a hot topic and pursuit in this industry for decades. Currently, digitalization starts with a digital twin — a piece of software and data that describes a machine, a part in processing, or even a manufacturing process. With the use of a digital twin for every part in a company's production, users or designers can build and test a factory on a computer. Then, when the factory is built, every part can be traced while it is being processed.

Fraunhofer ILT, Aachen, Germany

Constantin Haefner, director of the Fraunhofer Institute for Laser Technology ILT (Fraunhofer ILT) discusses the present and future of laser-driven fusion efforts in Germany and globally.

Digitalization also enables users to learn about their machines from their real data. TRUMPF's specialization in this area is in predictive maintenance, that is, a software tool that predicts machine failure in advance. In the Mercedes project, the TRUMPF team observed thousands of systems and predicted >90% of all maintenance cases, related to only 300 lasers, over the course of one year.

These were only two of the impressive presentations on relevant topics, and of course, one can speak with the experts on this initiative, or any other. The atmosphere in Aachen is profes-



Fraunhofer ILT, Aachen, Germany

A unique chance to meet and speak with an expert: the open house event at Fraunhofer ILT, with ~60 labs open for visiting. The International Laser Technology Congress AKL was held in April, with more than 500 participants from R&D, industry, academia, and more.

sional but equally informal. Many former students, experts from Fraunhofer ILT, and the nearby RWTH Aachen University have moved to industry. At AKL, they all reconvene. Although AKL is a sort of family meeting, the event embraces those from outside ILT, as I can personally attest.

What (else) was remarkable?

I have written reports on AKL congresses for eight years now. I have seen big topics arise over the years, with some to subsequently vanish. This year, one big trend was not totally visible — namely, the laser has become a commodity, at least in the case of fiber and direct diode laser systems.

This, of course, has many consequences. Bo Gu, founder and president of BOS Photonics, reported on a market cleanup for these systems in China. The commoditization of these laser systems also enables many new large-scale applications, such as laser cleaning and laser heating.

Further, many specialized laser systems are still apt to undergo further technical developments. In silicon annealing for display production, where large excimer lasers have been used for 20 years to convert amorphous silicon into polycrystalline silicon, a transition is underway — from excimer to solid-state lasers. This may shake up a market in which a dominant excimer laser manufacturer is now poised to face competition from established solid-state laser developers.

Finally, blue diodes, with 5 kW per system, are emerging, as are ever-stronger ultrashort-pulse lasers and a number of special wavelength lasers. This leads to one more important conclu-

Arbeitskreis Lasertechnik eV/ Andreas Steindl

The Innovation Award for Laser Technology third place winners from Cailabs, along with representatives of AKL. **(From left)** Ulrich Berners, AKL eV; Ivan Gusachenko, Adeline Orieux, Jean-François Morizur, Thibaut Atché, Gwenn Pallier, Cailabs; Alexander Olowinsky, ELI; Kristina zur Mühlen, ceremony moderator.

sion from the commodity trend: If laser vendors are striving to excel, then they need more than a laser. They need process know-how, special optics, reliability, and, maybe, new tools such as digitalized machines and production lines.

In the pipeline?

The AKL'24 program highlights state-of-the-art technology in additive manufacturing, cutting and welding, and surface technology, to name only a few application areas. The program also spanned topics that are more future-looking, and that have much less maturity.

Quantum technology, for example, was a big topic this year. Two teams, from the Delft, Netherlands-based research institute QuTech and New York-based Qunnect Inc. arrived in Aachen and presented "real" quantum networks — networks in which entanglement is established and shared between three distant nodes. They assume a quantum storage device, which the teams used for the first time in multicity networks. The technology is impressive, though network operators, such as Deutsche Telekom, which owns a majority of T-Mobile, are still hesitant when it comes to progress. "We're not there," said Marc Geitz, head of Deutsche Telekom's T-Labs research unit.

And there is a new topic beyond quantum: laser or inertial fusion. After decades of research, successful experiments highlighted by the 2022 advancement at the National Ignition Facility (NIF) have captivated the realms of science and beyond in recent years. Many additional facilities and teams have contributed to this scientific success, although it was NIF that made it to the evening news. One may ask how this feat can be built upon.

Two presentations broached this question with bold statements of their own. The first, from Peter Leibinger, chairman of the supervisory board of the TRUMPF group, was mentioned during the keynote lecture at the presentation of this year's Innovation Award Laser Technology. Leibinger, who is an expert in the field of innovation management, shared his thoughts about the culture of innovation. He referred to an almost impossible machine — ASML's extreme-ultraviolet lithography machine. AMSL developed the machine in a high-tech ecosystem. In the end, though, only a few key managers believed in the idea and made decisions that drove the development.

Would such an accomplishment be possible for quantum technologies and laser fusion, too? Yes, but huge challenges lie ahead. Advancements in these areas require orchestrated efforts from all partners. Road maps must be established. And access to venture capital must be supplied. "In the end, it comes down to the people," Leibinger said.

Two days later, the director of Fraunhofer ILT, Constantin Haefner, went a few steps further in his conference-concluding remarks. Haefner formerly headed the laser division at Lawrence Livermore National Laboratory (LLNL) before he moved to Aachen. He is currently closely involved with German initiatives for laser fusion research programs.

Haefner put numbers on the wall: a fusion power plant should not make one shot per day, but 15 per second. It would need a new laser architecture based on laser diode arrays with at least 15% wall plug-to-laser efficiency. Haefner envisions a laser beamline unit that is 50× stronger than LLNL's High-Repetition-Rate Advanced Petawatt Laser System. And for the power station, 400 such units would be required, Haefner said.

That is not a vague vision; rather, this is the starting point for coordinated actions such as those to which Leibinger referred. A first, the Fraunhofer ILT-led funding program for the development of optical components for fusion systems, for example, recently garnered €18 million ($19.2 million).

The next call for laser development will follow in due course. Haefner assumes that it will take three years to develop a prototype for a beamline and 10 years to turn it into a real workhorse that can be produced in large quantities. If such a power plant were to cost €10 billion, then ~40% would be spent on lasers and optics. This would be a game changer in the laser and photonics market.

Today, Europe and Germany are well positioned to compete in this field, with the U.S. being the leader and China wanting to bring a fusion power plant online in 2050.

It was all a furious finish. AKL'26 will reveal how much has been realized.

th@thoss-media.de

Industry News

European industry leaders unite to accelerate quantum computing

Leaders in Europe's quantum photonics ecosystem are coming together to achieve a demonstrable quantum advancement. Under the umbrella of the Eurostars project "SupremeQ," ORCA Computing, Pixel Photonics, Sparrow Quantum, and the Niels Bohr Institute (NBI) formalized a collaboration to accelerate the development and commercialization of photonic quantum computing technologies.

The project aims to address challenges in quantum computing, including system engineering for scale, high acquisition and operation costs, and the need for specialized expertise. Specifically, the collaborators will draw upon full-stack photonic quantum computing system architecture from ORCA Computing, single-photon detectors from Pixel Photonics, and single-photon sources from Sparrow Quantum and NBI.

Per the project, Sparrow Quantum's single-photon sources and Pixel Photonics' detectors will be engineered to coexist within a single cryostat, providing a path to multiplying qubits while offering advantages in manufacturability and cost. ORCA Computing will integrate these developments and demonstrate photon processing efficiencies and reconfigurability within a standard data center rack.

Eurostars, a European funding program, aims to assist small and medium R&D enterprises in commercialization.

ORCA Computing via Business Wire

The ORCA PT-1 computer in an assembly room. Quantum innovations from ORCA Computing, Pixel Photonics, Sparrow Quantum, and the Niels Bohr Institute (NBI) will unite to boost photonic quantum computing toward quantum supremacy.

Keysight outbids VIAVI with $1.5B late-stage offer for Spirent

Keysight Technologies issued a bid to acquire Spirent Communications in a deal worth £1.2 billion ($1.5 billion), which is an increase compared to VIAVI Solutions' $1.3 billion offer earlier this spring. Keysight said that Spirent's board of directors has unanimously withdrawn its recommendation to accept VIAVI's offer and intends to accept the proposal from Keysight.

Spirent is a provider of products, services, and managed solutions for test assurance and automation of technologies including 5G, software-defined wide area networks, cloud, and autonomous vehicles. The company's international positioning, navigation, and timing business serves customers in R&D, verification, and integration testing, including the testing of hybrid positioning and sensor fusion under real-world conditions.

With Spirent's offerings, Keysight said that it expects to address new serviceable available market opportunities of up to $1.5 billion. Keysight expects greater efficiency post-integration by leveraging its existing administrative and sales infrastructure and consolidating its office space, equipment, and other optimization measures.

According to Keysight CEO Satish Dhanasekaran, the proposed acquisition would provide Spirent with the capital and resources to accelerate growth and drive product development.

In a statement regarding Keysight's offer, VIAVI said, "VIAVI believes that the proposed combination of Keysight and Spirent would further entrench Keysight's leading position in many product segments, which would limit customer choice."

Keysight, a 2014 spinoff of Agilent Technologies, is a developer and manufacturer of test and measurement equipment and software. The company provides oscilloscopes, optical inspection equipment, lasers, and other equipment and software for the telecommunications, aerospace and defense, industrial, computer, and semiconductor industries.

In addition to the bidding companies, Spirent itself previously acquired wireless testing company octoScope in a 2021 deal, bolstering its capabilities in WiFi and 5G.

Luxium Solutions to acquire Inrad Optics

Luxium Solutions, a provider of advanced engineered materials and solutions, entered into a definitive agreement to acquire Inrad Optics Inc., a provider of advanced optical components, assemblies, and systems. The deal values Inrad Optics at approximately $19 million.

According to Luxium CEO Michael Cahill, the acquisition will provide complementary additions to Luxium's portfolio. Inrad CEO Amy Eskilson said that the merger will enable enhanced flexibility and additional financial resources to drive future growth and capture market opportunities.

Following the merger, Inrad will be able to accelerate investments in technologies that are vital to the development of next-generation bent x-ray crystal monochromators for spectroscopy and plasma fusion applications, and large-format, ultrahigh-precision optical components and assemblies.

Luxium entered into an agreement to acquire monolithic optics company PLX Inc. and its subsidiary PLX UK Ltd. in March, making the acquisition from an investor group led by Tinicum. The PLX acquisition adds photonics assembly solutions and subsystem and system integration capabilities to Luxium's portfolio, including solutions for emerging lidar, laser tracking, and free space optics applications.

6.2%

— the predicted compound annual growth rate of the global terrestrial laser scanning market by 2032, according to IMARC Group

This month in history

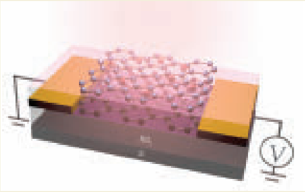
What were you working on five, 10, 20, or even 30 years ago? *Photonics Spectra* editors have perused past June issues and unearthed the following:

1994

England-based Computer Recognition Systems developed a number plate reading system for use in traffic control. Using four cameras in a triggered mode, the system could recognize plate numbers at speeds of up to 150 mph and was capable of monitoring multilane and exit situations.

2004

Scientists from the universities of Kassel and Technology Darmstadt in Germany and the Royal Institute of Technology in Kista, Sweden, fabricated an optically pumped MEMS-based VCSEL with a curved mirror that enhanced single-transverse-mode operation for use in telecom lasers.

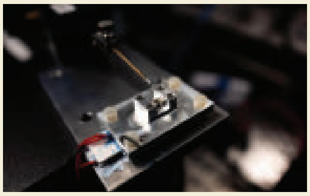


2014

A team at the University of Michigan developed a room temperature, graphene-based detector that could be made thin enough to be stacked on a contact lens or integrated with a cellphone. The detector could sense the full IR spectrum, carrying the potential for advancements in heat-vision technology.

2019

Researchers from Ruhr-Universität Bochum used a semiconductor spin laser to enable room temperature modulation frequencies >200 GHz as an approach to data transfer. This frequency level was nearly an order of magnitude faster than the best conventional semiconductor lasers and used modulated polarized light as the basis of the system.



Oriole Networks raises $13M seed round

Oriole Networks, a startup focused on light-based technology for AI systems and data centers, raised £10 million ($13 million) in seed funding. The 2023 spin-out of University College London (UCL) founded by Georgios Zervas, James Regan, Alessandro Ottino, and Joshua Benjamin holds intellectual property licensed through UCL's technology transfer company, UCLB.

"AI computational needs are increasing by 10× every 18 months. This leads to distributed training and inference across large numbers of xPUs," said Zervas, Oriole's CTO. "Collective data movement across the servers in the data center becomes a bottleneck, which in turn limits the training and inference completion time. This requires a fundamental shift in the co-design of next-generation networked systems."

With Oriole's approach, large language models can be trained up to 100× faster, and with a 40× improvement in power efficiency. As a result, machine learning algorithms can run with a thousandth of the latency, enabling time-critical tasks, such as algorithmic trading, and accelerating AI adoption and AI algorithmic progress.

The round was co-led by UCL Technology Fund, Clean Growth Fund, XTX Ventures, and Dorilton Ventures, with support from Innovate UK Investor Partnership. Regan, Oriole's CEO, previously spun out and founded EFFECT Photonics.

Oriole Networks

Oriole Networks' leadership team **(from left)** Joshua Benjamin, Georgios Zervas, James Regan, and Alessandro Ottino.

$15.4B — the estimated size of the global 3D metrology market by 2031, according to Straits Research

People in the News

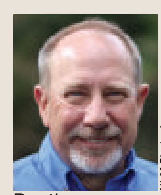
QED Technologies appointed **Michael Mohammadi** president and CEO. Mohammadi succeeds president and CEO **Andrew Kulawiec**, who will remain a member of the QED board of directors. Mohammadi served as vice president of global sales and business development at Thorlabs. He previously held sales and business development positions at Andor Technology and Olympus America.

Michael Mohammadi

Mohammadi.

Luna Innovations appointed **Richard Roedel** interim executive chairman and interim president. The appointment follows the announcement that current president and CEO **Scott Graeff** is retiring. Roedel has served as chairman of Luna's board since 2010. The company has begun a search for a new president and CEO, and it has appointed **Mary Beth Vitale** to serve as lead independent director during Roedel's service as executive chair. Graeff's departure, after more than 20 years at the company, comes after Luna announced that it would delay sharing its fourth quarter and fiscal year 2023 financial results.

Networking photonics solutions developer NLM Photonics appointed **Brad Booth** CEO, replacing cofounder **Gerard Zytnicki**, who will serve as COO and chairman of the board. Booth is a current board member of NLM Photonics and previously served at Meta Platforms and Microsoft Azure, where he focused on developing optical connectivity solutions for cloud and AI data centers. He also led the formation of the Ultra Ethernet Consortium, the Ethernet Technology Consortium, the Consortium for On-Board Optics, and the Ethernet Alliance.



NLM Photonics

Booth.

CEO of integrated chips and lasers supplier Sivers Semiconductors AB, **Anders Storm**, resigned from his position. Storm has been CEO of Sivers since 2016 and previously served as the company's COO in 2015. Storm will remain in his position until a new CEO has taken office or until the end of his six-month notice period.

EPIC names recipients of lifetime achievement, CEO awards

The European Photonics Industry Consortium (EPIC) named the winners of the EPIC Lifetime Achievement Award and the EPIC CEO Award. Viacheslav Artyushenko was named the recipient of the EPIC Lifetime Achievement Award for his contributions and leadership in the optical fiber industry. Artyushenko is founder and CEO of art photonics GmbH, a manufacturer of fiber cables, bundles, and spectroscopy probes for industrial, medical, and scientific applications. The company was acquired last year by the Nynomic Group.

EPIC

Viacheslav Artyushenko is the recipient of the 2024 EPIC Lifetime Achievement Award.

Also at EPIC's Annual General Meeting 2024, the consortium named Axel Kupisiewicz, founder and CEO of LASEA, recipient of the EPIC CEO Award for leadership and contributions to the photonics industry. LASEA specializes in manufacturing micromachining machines that enable precision cutting, marking, engraving, and drilling. Its main sectors include medical, watchmaking, and electronics, with prestigious clients worldwide, including two GAFAMs (Google, Apple, Facebook, Amazon, and Microsoft).

EPIC

Axel Kupisiewicz received the 2024 EPIC CEO Award.

During EPIC's Annual General Meeting 2023, it confirmed the selection of Shahida Imani, CEO of Chromacity, to its board of directors. Additionally, the consortium named Håkan Karlsson as the recipient of the EPIC CEO Award 2023. Karlsson is head of the photonics division at HÜBNER Group and CEO of Cobolt. EPIC also recognized Kestutis Jasiunas, chairman of the board of EKSPLA, with the EPIC Lifetime Achievement Award for his leadership in the laser industry.

$8.2B

— the expected size of the global fiber optics market by 2027, according to MarketsandMarkets

Fermilab details photon detection, 3D integrated sensing efforts

Fermi National Accelerator Laboratory (Fermilab) scientists are engaged in a pair of photonics-related projects under the umbrella of the Accelerate Innovations program of the U.S. Department of Energy (DoE). The initiatives aim to develop and extend the capabilities of existing superconducting nanowire single-photon detectors (SNSPDs) and enable large-scale particle sensors with 3D integrated circuits to process much smaller, faster signals at a higher level of precision.

The Fermilab projects are among 11 DoE national lab projects awarded a total of $73 million in funding over a two-year period. The funding aims to accelerate the transition of technology from the laboratory to industry.

The SNSPDs that are under development at Fermilab will use very little energy and be well suited to detect faint photon signals formed by particle interactions that may indicate the existence of axions. The project aims to enable scientists to seek low-energy light from axions with masses in the mid-infrared range, equivalent to 0.05-1 eV. To date, this mass range has remained unexplored; no previous detection technology is sensitive enough to such low-energy signals.

“Our project and funding are specifically for particle physics applications including dark matter searches,” said Fermilab’s Si Xie, principal investigator for the project. “But the result could have wide-ranging impact on diverse fields of science including the search for faraway planets, environmental monitoring and climate change applications, and studying some biochemical processes.”


Fermilab/Christina Wang

Fermilab scientist Si Xie mounts a superconducting nanowire single-photon detector inside a cryostat. Xie and his colleagues will use the detector to look for light created by dark matter particles.

As part of their work, the project team will develop specialized antenna structures. These will enable mid-infrared SNSPDs with an active sensor area >1 sq mm. They will also focus on improving the ultrafast signal readout by developing novel sensor electronics that extract and detect particle signals at a greater resolution than existing SNSPDs.

Participants in the second DoE-funded project, led by SLAC National Accelerator Laboratory, will seek to enable large-scale particle sensors with 3D integrated circuits to process much smaller, faster signals at a higher level of precision. The sensors developed in the project will be part of 3D heterogeneously integrated detectors. The wafers are connected at the micrometer scale. This eliminates traditional larger interconnections and significantly improves the fidelity of signals all along the chain.

While the current generation of this technology uses rather large pixels of ~1 mm, the goal is to scale this down to 50-µm pixels.

“We want to demonstrate 3D integrated sensors that utilize low gain avalanche detector particle sensors that provide very fast timing information,” said Davide Braga, a Fermilab group leader of the project. “We intend to simultaneously achieve 10-µm position resolution and 10-ps precision timing while consuming low power and reaching high throughput rates.”

In addition, the project team is partnering with a commercial chip company to develop advanced manufacturing capability for this novel technology. The company’s fabrication know-how will be essential for the co-design of sensors and electronics for scaling, according to Braga.

Luminate NY names companies in seventh cohort

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

nextcorps LUMINATE

Luminate

The companies in the seventh cohort include:

AI Optics Inc., a developer of a handheld imaging technology that integrates AI to provide a new standard of care for disease screening, starting with preventing vision loss.

CureVision, pursuing automatic, rapid 3D wound measurement, analysis, and reporting for hospitals, nursing homes, and ambulatory and home care.

Enlipsium, creating advanced nanomaterials for future x-ray imaging devices, anticounterfeiting, and self-cleaning coatings.

iLoF (Intelligent Lab on Fiber), providing noninvasive tracking, screening, and stratification for drug discovery using a cloud-based library of optical fingerprints, powered by photonics and AI.

Nicslab Inc., a fabless chip company developing electronics and photonic integrated circuits for future optical solutions in data centers, AI, instrumentation, and quantum computing.

Photosynthetic, developing a manufacturing method for complex 3D geometries to be produced at mass-production speeds while retaining submicron feature sizes.

Q-Block Computing, making fault-tolerant quantum devices for advanced computation, communication, and sensing.

SaferStreet Solutions, working on traffic safety devices that target unsafe driving behavior and collect data to help communities reduce speeding, distracted driving, car crashes, and lack of seat belt usage.

SeeTrue Technologies, providing advanced eye-tracking technology that features a robust sensing solution for health care, AR/VR, and industry applications.

VoxelSensors, developing a single-photon active event sensor that enables power-efficient and intuitive interaction for spatial interfaces and mobile extended reality.

The participating companies were selected from a pool of 137 applications sent from 25 different countries, Luminate said. Since its inception, Luminate has invested $18 million in 63 startups.

Funding for the program, which is administered by NextCorps, is provided through the Finger Lakes Forward Upstate Revitalization Initiative. Companies in the Luminate portfolio have raised an additional $260.1 million and now share an estimated net worth of $675 million. In addition, many of the companies are establishing U.S. operations or some aspect of research and manufacturing in the Rochester region.

The seventh cohort launched this spring and will conclude in early fall.

Celestial AI adds $175M to commercialize photonic fabric platform

Celestial AI, creator of the Photonic Fabric optical interconnect technology platform, raised $175 million in a series C funding round. The funding will enable Celestial AI to execute multiple large-scale customer collaborations focused on commercializing its Photonic Fabric technology platform, the company said.

Celestial AI's Photonic Fabric optical connectivity solution enables the disaggregation of compute and memory, which allows each component to be effectively leveraged and scaled. The technology delivers >25× larger bandwidth and memory capacity, while reducing latency and power consumption by up to 10× compared to existing optical interconnect alternatives and copper.

The technology is suited for applications that require high levels of memory capacity and bandwidth, such as artificial intelligence models, in addition to cloud services and data centers.

The funding round was led by Thomas Tull's U.S. Innovative Technology Fund and included participation from investors such as AMD Ventures, Samsung Catalyst, Porsche Automobil Holding SE, M Ventures, and Tyche Partners.

Mergers & Acquisitions

inTEST Corporation, a supplier of test and process technology solutions, acquired **Alfamation SpA**, a provider of test and measurement solutions for the automotive, life sciences, and specialty consumer electronics markets. The acquisition strengthens inTEST's position in these markets and broadens the company's footprint in Europe. Alfamation designs, builds, and supports products from individual functional test modules to fully automated systems for production quality control and product development. The company's range of automated test solutions also includes wafer-level optical component testers and fully automated display and instrument cluster testers with integrated robotics for haptic and touch test functionality.

North American Coating Laboratories (**NACL**) acquired **Optical Filter Source LLC**. The combined company will have 15 coating chambers and approximately 42 employees operating in two locations. Following the transaction, Optical Filter Source's Round Rock, Texas, location will be named **OFS by NACL LLC**. NACL's Brian Wilson will serve as its CEO, and current Optical Filter Source CEO Frank Calcagni will serve as president. Terms of the deal were not disclosed.

STEMMER IMAGING AG agreed to acquire New York-based **Phase 1 Technology**, a fellow machine vision technology supplier. The acquisition expands STEMMER's presence in North America. The company also has locations in Mexico and Latin America. The acquisition is expected to close in the second quarter of 2024. Phase 1 Technology is a vertically integrated distributor of machine vision technology, including cameras, sensors, lenses, industrial lighting, frame grabbers, and interface boards.

Engineering services firm **Bowman Consulting Group Ltd.** acquired St. Louis-based **Surdex Corporation**. Surdex is a geospatial and engineering services company with capabilities in high-resolution lidar, digital orthoimagery, digital mapping, 3D hydrography, and disaster mapping.

Through merger, **International Light Technologies** (**ILT**) will become a division of **Labsphere**, a designer and manufacturer of light metrology solutions for the LED/solid-state lighting industry. ILT will retain its name and brand identity, and gain access to Labsphere's global distribution network, manufacturing partnerships, and engineering.

Prima Additive entered into an agreement with **Sodick Co. Ltd.** under which Sodick will acquire a minority stake of 9.5% in Prima Additive through a reserved capital increase. The agreement also lays the foundation for a business alliance to expand the company's respective portfolios in laser technologies for materials processing in additive manufacturing. Prima Additive was formed in 2022 following the merger of 3D New Technologies with Prima Industrie's additive manufacturing business unit. Prima Industrie remains the majority shareholder and industrial partner of the company.

Honeywell to acquire optical gyroscope specialist Civitanavi Systems

Honeywell will acquire Civitanavi Systems, a provider of position navigation and timing technology for the aerospace and defense and industrial markets. Honeywell will initiate a voluntary tender offer to acquire all outstanding shares, a transaction worth approximately €200 million ($217.4 million) at closing.

The acquisition will strengthen Honeywell's capabilities in autonomous operations in aircraft and other vehicles. Civitanavi, like Honeywell, develops inertial navigation solutions that are used to track the position and orientation of a vehicle by using accelerometers, gyroscopes, and other sensors. Civitanavi specializes in high-performance fiber optic gyroscope technology that Honeywell has not previously offered in its navigation portfolio.

According to Jim Currier, president and CEO of Honeywell Aerospace Technologies, integrating Civitanavi's inertial technologies and sensors across Honeywell's existing commercial, military, space, and industrial platforms will bolster the company's portfolio of aerospace navigation solutions and allow customers greater support in pursuit of autonomous operations. Honeywell further specified that Civitanavi's product offerings of inertial navigation, georeference, and stabilization systems complement technologies in its existing navigation and sensor business.

Briefs

A group of networking, semiconductor, and optics companies formed the **Linear Pluggable Optics Multi-Source Agreement (LPO MSA)** to develop the specifications for networking equipment and optical modules required to enable a broad ecosystem of interoperable LPO solutions. Founded by **Semtech Corp.**, **NVIDIA**, **Intel**, and **Broadcom**, these specifications target the industry-wide challenge of reducing the power, cost, and latency of high-speed optical interconnects while improving reliability. The initial goal of the MSA is to develop an optimized optical interconnect with LPO modules on both ends of the link. This will define the electrical and optical requirements to ensure interoperability between multiple vendors of networking equipment and optics modules.

Micro-LED developer **Porotech** partnered with integrated touch solution company **General Interface Solution Holding Ltd.** The collaborators will produce high pixel density augmented reality products for consumer applications. Porotech has also partnered with **Hon Hai Technology Group** and **Powerchip Semiconductor Manufacturing Corp.** to produce these products.

Coherent established capability for 6-in. indium phosphide (InP) wafer fabrication in the company's Sherman, Texas, and Järfälla, Sweden, wafer fabs. Coherent is qualifying several existing products on its 6-in. InP platform, and the company expects to transition the bulk of its production from 3-in. InP to 6-in. InP in the next few years. The transition, Coherent said, aims to leverage the benefits of larger wafer size, higher yield, and improved performance that will be required to provide a sustainable competitive advantage in its communications and sensing markets.

Quintessent, a developer of heterogeneous silicon photonics and quantum dot laser technology, closed an oversubscribed seed funding round that will secure $11.5 million for the company. According to CEO and cofounder Alan Liu, the funding will be used to expand staff and accelerate the development of scalable optical interconnects built on the company's multiwavelength comb laser, among other technologies. Quintessent seeks to address infrastructure bottlenecks for data centers and computing technologies by implementing advanced materials, device/circuit design, and link architecture to reduce power consumption and required component count.

imec signed a memorandum of understanding with the Spanish government and the regional government of Andalusia outlining the intent to establish a specialized chip technology pilot line in Málaga, Spain. The facility will join imec's existing production line in Leuven, Belgium, for the development of 300-mm CMOS manufacturing processes.

OpenLight, a developer and manufacturer of photonics application-specific integrated chips, partnered with **VLC Photonics**, an end-to-end integrated photonics services firm. Per the collaboration, VLC Photonics will offer design and test services using the OpenLight process design kit. The expansion of design services increases the number of designs that OpenLight can support at any one time on the Tower Semiconductor PH18DA process. Additionally, OpenLight entered into a strategic partnership with **Jabil** to expedite manufacturing. The partnership is expected to allow OpenLight customers to fast-track the manufacturing and delivery of integrated PICs across a range of applications and markets.

Pilot Photonics secured €2.5 million ($2.7 million) from the European Innovation Council to develop, integrate, and commercialize key technology blocks relevant to a coherent co-packaged optics solution to overcome future scaling challenges in data centers. The company will mature its patented technologies including comb lasers, ring resonator IQ modulators, and comb-enhanced digital signal processing algorithms.

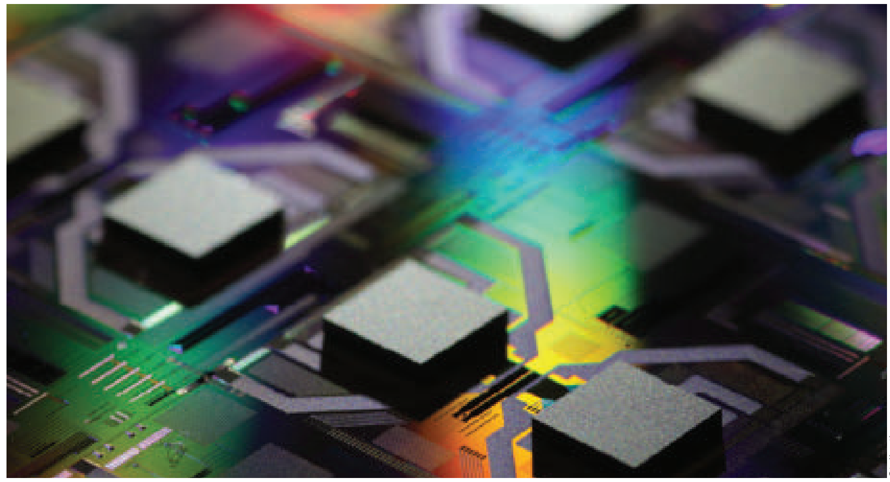
EFFECT Photonics secured $38 million in series D funding to further accelerate the development and commercialization of integrated photonics solutions and to support ramping up production to meet customer demand. The company is focused on advancing its portfolio in support of high-speed fiber optics communications solutions. EFFECT raised $40 million in funding in 2023. The company has formalized collaborations with partners including **Jabil Photonics**, **Credo**, and **Fabrinet**.

Stellantis strengthens ADAS commitment with SteerLight investment

Stellantis Ventures, the corporate venture fund of automotive manufacturer Stellantis N.V., invested in lidar technology company SteerLight, a producer of compact frequency modulated continuous wave (FMCW) lidar systems based on silicon photonics technology. The CEA-Leti spinoff is targeting advanced driver-assistance systems (ADAS) — an area of focus for Stellantis.

Terms of the investment were not disclosed. SteerLight also plans to address industrial and mobility applications.

SteerLight's FMCW technology provides accurate depth and velocity data while resisting interference from the surrounding environment and other users. According to SteerLight, its lidar systems offer higher resolution and precision with lower production costs than those that are currently available. Other developers of FMCW lidar solutions include Scantinel Photonics, SiLC Technologies, Ommatidia, and Aeva.


Stellantis

SteerLight aims to use frequency modulated continuous wave (FMCW) lidar to deliver higher performance capabilities for advanced driver-assistance systems (ADAS) applications.

15.7%

— the expected compound annual growth rate of the global solar energy systems market by 2030, according to Grand View Research

Immersion lens focuses polarized beam for laser nanoprocessing

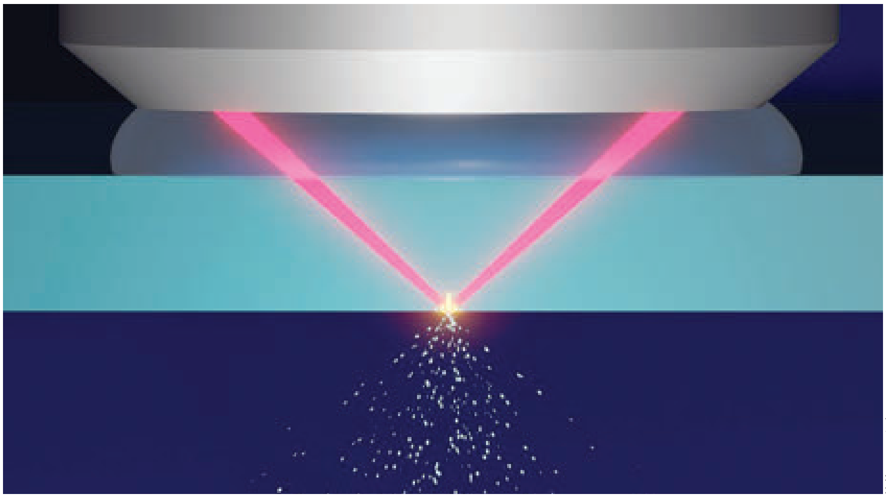
SENDAI, Japan — High spatial resolution in ultrafast laser processing is becoming increasingly important in semiconductor fabrication, the automotive parts industry, and medical device manufacturing, among other fields. In laser processing, precision and spatial resolution are primarily influenced by the focal spot size of the laser beam. The diffraction of light typically limits the achievable spot size, depending on the numerical aperture (NA) of the lens and the wavelength of the focused laser beam.

A research team at Tohoku University investigated the use of radially polarized laser beams, also known as vector beams, to enhance processing accuracy and resolution in ultrafast laser processing. A radially polarized beam generates a longitudinal electric field at the focus spot. Compared to conventional beams with linear or circular polarization, a radially polarized beam produces a small focal spot, especially when it is tightly focused using a high-NA lens.

Although radially polarized beams show promise for increasing precision and resolution in laser nanoprocessing, the radially polarized beam's longitudinal field has been found to weaken inside the material, due to light refraction at the air-material interface.

To better understand how the interface affects the longitudinal field at the focus, the researchers implemented a single-shot laser ablation of a transparent glass sample using a radially polarized beam that was tightly focused on the surface of the glass. They examined the effect of the boundary conditions at the interface under high-NA conditions.

When the researchers focused the radially polarized beam on the back surface of the glass from the inside, using an immersion lens, the longitudinal electric field at the focus was significantly enhanced. The researchers produced a small focal spot, which they attributed to the enhanced longitudinal field on the glass surface. This enabled direct laser processing.


Y. Kozawa et al.

Single-shot laser processing by an annular-shaped, radially polarized beam, which is focused on the back surface of a glass plate. Enhancing precision in laser-based materials processing will enable advancements in nanoprocessing and supported applications in machining.

The researchers used an oil immersion objective lens, similar to those found in biological microscopes, professor Yuichi Kozawa said. "Because the immersion oil and glass have nearly identical refractive indices, the light that passes through them does not bend."

By focusing a radially polarized beam on the back surface of the glass from the inside, the researchers enhanced the longitudinal field even inside the material, directly inducing a light-matter interaction. Then, they created a small focal spot using an annular-shaped, radially polarized beam. The small focal spot formed by the beam's longitudinal field allowed the researchers to fabricate a fine, spot-shaped, 67-nm ablation hole, ~1/16 of the laser beam's wavelength, through total internal reflection.

The experimental results demonstrate a potential approach to shrinking the scale of laser material processing and achieving laser nanoprocessing using a radially polarized beam. The findings could advance the development of laser ablation processes using radially polarized beams in high-NA environments.

Further, the results could offer the chance to advance laser machining, in addition to laser and laser materials processing. Laser machining is widely used across industries to produce electronic components, machine parts, precision machinery, and medical devices. Ultrashort laser pulses, with widths from picoseconds to femtoseconds, enable precise processing at the micrometer scale. However, laser machine processing <100 nm is challenging to achieve with existing methods.

"This breakthrough enables direct material processing with enhanced precision using the enhanced longitudinal electric field," Kozawa said. "It offers a simple approach to realize processing scales below 100 nm and opens new possibilities for laser nanoprocessing in various industries and scientific fields." The research was published in *Optics Letters* (www.doi.org/10.1364/OL.517382).

Fiber oscillator extends femtosecond lasing into the visible band

SIMING, China — Femtosecond fiber oscillators offer a compact design and outstanding performance, and they are cost-effective. However, the operating wavelengths for these oscillators are located primarily in the infrared region. Extending their reach to the visible range, so they can be used in a variety of applications that require visible light sources, has been a long-standing goal of laser science.

In an advancement for ultrafast laser technology, researchers at Xiamen University developed a visible-wavelength, 635-nm, soliton, mode-locked femtosecond fiber oscillator and amplifier. They constructed the oscillator on a phase-biased nonlinear amplifying loop mirror (PB-NALM).

The researchers' soliton, mode-locked femtosecond fiber oscillator and amplifier system enables users to source femtosecond laser pulses from visible fiber lasers, enabling a potential breakthrough in ultrafast laser technology. The laser source developed by the Xiamen team could be used in applications ranging from advanced materials processing to biomedicine to nonlinear optics.

Specifically, according to the researchers, the laser architecture, with dispersion management capabilities, could serve as a testbed to explore complex, ultrafast soliton dynamics in the visible-wavelength region. It could additionally pave the way for miniaturized visible fiber femtosecond laser sources that have a broad spectral range, narrow pulse width, and high power level.

The visible, mode-locked femtosecond fiber oscillator is based on a high-gain praseodymium (Pr^{3+})-doped fluoride fiber and uses a pair of custom, high-efficiency, high-groove-density diffraction gratings for dispersion management. The oscillator achieves highly stable, self-starting mode locking by building on the PB-NALM. The PB-NALM eliminates the need for long intracavity fibers to accumulate phase shifts. This enables flexible tuning, helps extend the life of the device, and allows intracavity dispersion to be managed in a larger parameter space from normal to anomalous dispersion regimes.

Additionally, the self-starting, mode-locking capability provided by the PB-NALM allows the femtosecond fiber oscillator to yield laser pulses with a central wavelength of 635.5 nm, a widest 3-dB bandwidth of 5.4 nm, a minimum pulse duration of 196 fs, and a repetition rate of 53.96 MHz.

The femtosecond fiber laser uses a figure-nine cavity configuration. By manipulating the intracavity dispersion and polarization, the researchers observed multiple mode-locking states in the oscillator, including conventional solitons, dispersion-managed solitons, dissipative solitons, and bound-state solitons. To further enhance laser performance, the team built a visible chirped-pulse amplification system alongside the oscillator. This enhancement resulted in an average output power of $>$1 W and a pulse energy of 19.55 nJ, while maintaining a compressed pulse duration of 230 fs.

Due to the exceptional heat dissipation of the fibers, the laser system operates with excellent long-time stability, characterized by a low power deviation of $<$0.3% and negligible wavelength drift.

According to professor Zhengqian Luo, the results could support applications in industrial processing, biomedicine, and scientific research.

The researchers said that although visible femtosecond lasers based on the nonlinear frequency conversion of Ti:sapphire femtosecond oscillators, or near-infrared ultrafast lasers, are well developed, they are expensive and limited in footprint and efficiency. The fiber femtosecond mode-locked oscillator used for the infrared wavelengths is now available for the visible spectrum. The researchers expect that their scheme for high-performance, visible femtosecond fiber laser pulse generation will make these lasers suitable for other applications, such as underwater detection and atomic clocks.

The research was published in *Advanced Photonics Nexus* (www.doi.org/10.1117/1.APN.3.2.026004).

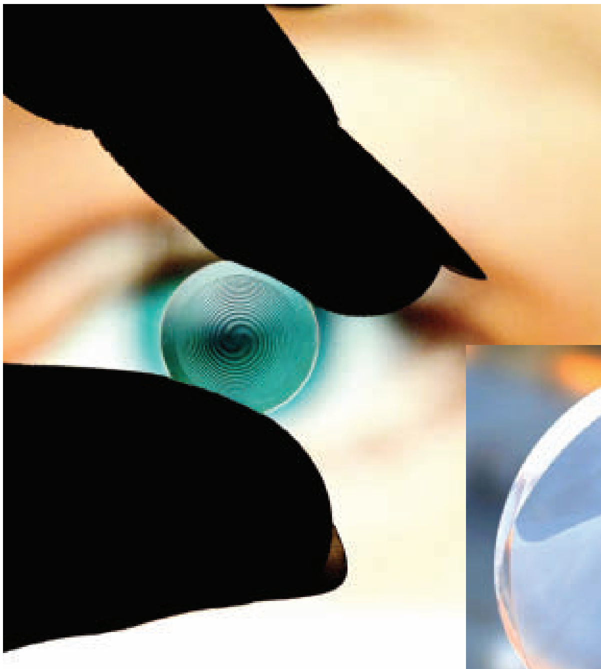
Lens extends focal length, depth of vision as conditions change

BORDEAUX, France — A newly designed spiral-shaped lens could make consistently clear vision possible for people with lens implants or age-related farsightedness. The spiral diopter works similarly to progressive lenses used for vision correction, while foregoing the often-found distortions. Its spiral shape creates many separate points of focus, allowing the user to see clearly at different distances and in various light conditions.

In addition to advancing contact lens technologies and intraocular implants for cataracts, the spiral diopter lens could be used to miniaturize imaging systems while maintaining their optical quality.

According to the researchers, the spiral diopter lenses are superior to conventional trifocal lenses at larger apertures for most focal points, while preserving multifocal behavior even at smaller apertures. They provide wider depth perception while reducing the reliance on larger apertures.

"Unlike existing multifocal lenses, our lens performs well under a wide range of light conditions and maintains multifocality regardless of the size of the pupil,"



Laurent Galinier

Laurent Galinier

The spiral lens could be used on contact lenses **(shown, left)**, in intraocular implants for cataracts, and to create new types of miniaturized imaging systems.

A freeform lens uses a spiral-shaped surface to maintain a clear focus at different distances in varying light conditions.

said Bertrand Simon, a researcher from the Photonics, Numerical, and Nanosciences Laboratory (LP2N), a joint research unit between the Institut d'Optique Graduate School, the University of Bordeaux, and the Centre national de la recherche scientifique. "This new lens could significantly improve people's depth of vision under changing lighting conditions."

The inspiration for the spiral lens design emerged when the paper's first author, Laurent Galinier from SPIRAL SAS in France, was analyzing the optical properties of severe corneal deformations in patients. Galinier conceptualized a lens, with a spiral design, that causes light to spin, like water going down a drain. This phenomenon, known as an optical vortex, creates multiple clear focus points, which allow the lens to provide clear focus at different distances.

Usually, Galinier said, multiple optical components are needed to create an optical vortex. "Our lens, however, incorporates the elements necessary to make an optical vortex directly into its surface," he said.

The lens uses the spiral properties of one of its diopters to create optical vortices. The freeform design of the lens allows its focal points to be shaped from a few simple parameters on the diopter geometry. This enables multifocality, extended depth of field, and depth encoding through the shapes of the focal spots, independent of the aperture.

The researchers used digital machining to precisely mold their spiral design. They tested the lens by using it to image a digital "E," similarly to the letters used on an optometrist's light-up board. They observed that the image quality remained satisfactory regardless of the aperture size. They also discovered that the optical vortices could be modified by adjusting the topological charge, which is essentially the number of windings around the optical axis.

Participants who volunteered to wear the lenses reported improvements in visual acuity at a variety of distances and lighting conditions.

The spiral lens could also lead to new approaches in wearable optics and ultracompact embedded imaging systems.

"In addition to ophthalmology applications, the simple design of this lens could greatly benefit compact imaging systems," Simon said. "It would streamline the design and function of these systems while also offering a way to accomplish imaging at various depths without additional optical elements. These capabilities, coupled with the lens' multifocal properties, offer a powerful tool for depth perception in advanced imaging applications."

To enhance overall performance of the lens, the researchers are investigating the behavior of the optical vortices and the response of the vortices to different aberrations. They plan to perform systematic trials of the lens' ability to correct vision in people to evaluate the performance of the lens in real-world conditions. In addition, they are exploring the possibility of applying the concept of the spiral lens to prescription eyeglasses to enable clear vision across different distances.

The research was published in *Optica* (www.doi.org/10.1364/OPTICA.507066).

Chirality detector improves drug design and efficacy prospects

ORLANDO, Fla. — Researchers at the University of Central Florida (UCF) developed a tunable plasmonic platform for the accurate detection of chiral molecules. The development could help pharmaceutical companies and biomedical labs, for example, classify enantiomers — pairs of chiral molecules — with speed and precision.

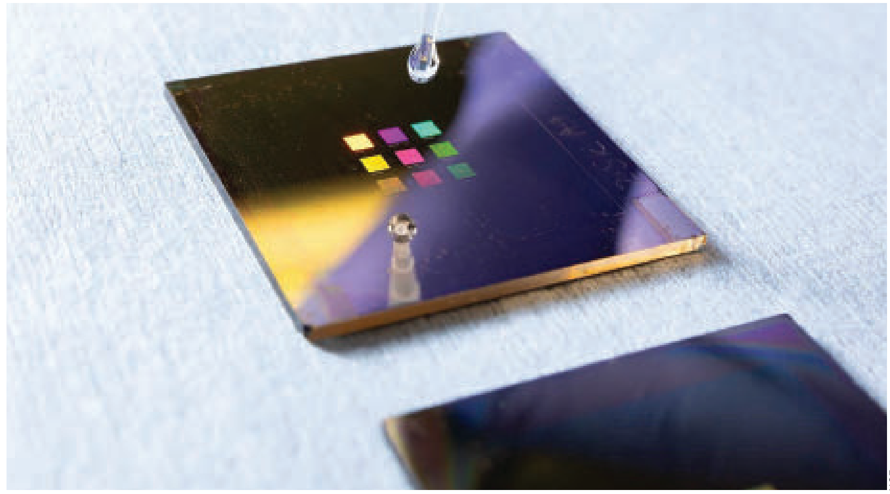
This capability, the researchers said, could be used to support more efficient drug development.

Chiral molecules, known as enantiomers, are mirror image pairs and each enantiomer in a pair can have different effects in the body or during chemical reactions. Some enantiomers have an efficacious effect, while others can cause toxic or severe side effects.

A recurrent challenge in drug development is to synthesize only the desired enantiomer to ensure optimal therapeutic outcomes and minimize adverse effects. More than 50% of all modern drugs and medicine are chiral in nature, and ~90% of these are a mixture containing equal amounts of two enantiomers of a chiral compound. The ability to accurately determine the purity of chiral molecules is therefore imperative to pharmaceutical and drug development.

"In some cases, one enantiomer is the active ingredient while the other is dormant, leading to an overall reduction in the potency of the drug," said Debashis Chanda, a professor at the UCF NanoScience Technology Center. "As a result, the need for enantiomeric identification and purification is in crucial demand in the field of medical and pharmaceutical research."

The UCF platform enabled the researchers to fabricate a sensor using low-cost, high-quality, large-area nanoimprinting techniques and illuminate it with circularly polarized light (CPL) to induce chiral light-matter interactions. The nanostructured sensor comprises a symmetric, achiral nanoscale gold hole-disk pattern, coupled with an asymmetric optical cavity and a back reflector.



UCF

The University of Central Florida (UCF) developed plasmonic technology that significantly improves the detection of molecular chirality, meeting a crucial demand in the fields of medical and pharmaceutical research.

The researchers then used a Fourier transform infrared instrument to illuminate the cavity-coupled, achiral, plasmonic metasurface of the sensor with CPL. The light-matter interaction generated superchiral light on the surface of the sensor, due to the strong coupling between the electron (plasmon) resonances on the gold array and the resonances in the optical cavity.

The superchiral light produced strong chiral near fields on the upper surface exposed to the target analyte, allowing increased interaction with the analyte. When a chiral molecule was added on top of the sensor, it produced differential reflection between a right CPL and a left CPL, enabling the system to detect chirality.

The achiral symmetry of the plasmonic sensor suppressed the circular dichroism of the sensor itself, ensuring almost no background noise and thus allowing the detection of pure chiral signals from the molecule.

By controlling excitation conditions, the researchers reported nearly 100% right-polarized or left-polarized chiral near fields on the same sensor. They used the cavity to tune the chiral plasmonic resonance, which allowed a wide range of chiral molecules with various absorption bands to be probed using the same nanostructure. The system permitted efficient chiral light-matter interactions for the detection of vibrational molecular chirality in the mid-infrared range, which is relevant for drug screening and other applications.

During experiments, the plasmonic platform for identifying chiral molecules demonstrated a 13 orders of magnitude higher detection sensitivity for chiral enantiomers compared to conventional techniques. Moreover, the fabrication of the sensor via nanoimprinting provides lower costs and concentration, and fewer numbers of molecules are needed for accurate detection compared to other methods. The tunable spectral characteristics of the achiral plasmonic system facilitate the detection of a diverse range of chiral compounds.

Further, the ease of fabrication and fast measurement capabilities of the system could make it a suitable platform for an on-chip, surface-enhanced, ultrasensitive chirality detection tool.

The research was published in *Science Advances* (www.doi.org/10.1126/sciadv.adk2560).

Quantum dot sources generate nearly perfect entangled photons

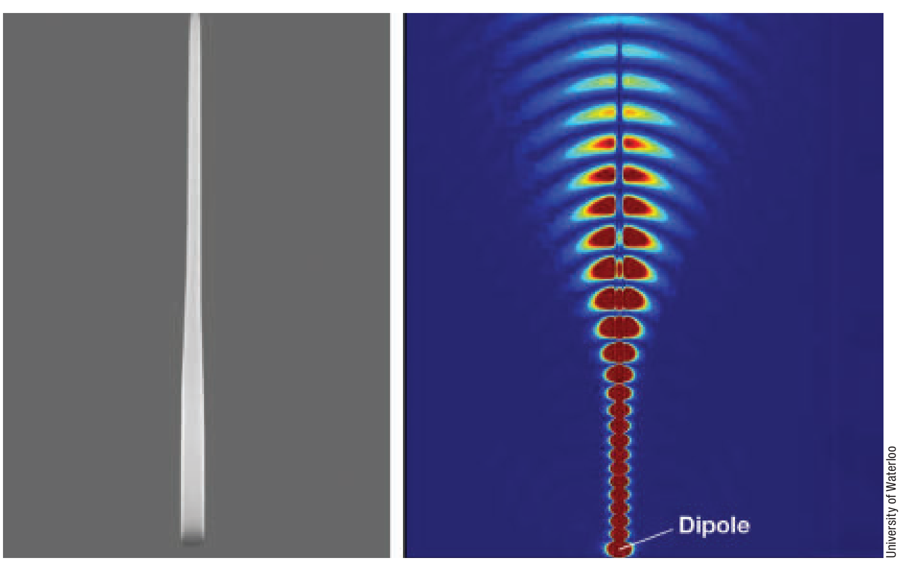
WATERLOO, Ontario — Researchers at the University of Waterloo's Institute for Quantum Computing (IQC) developed a method to efficiently produce nearly perfect entangled photon pairs from quantum dot sources.

According to IQC professor Michael Reimer, the method helps to pave the way for secure quantum communications.

"The combination of a high degree of entanglement and high efficiency is needed for exciting applications, such as quantum key distribution or quantum repeaters, which are envisioned to extend the distance of secure quantum communication to a global scale or link remote quantum computers," Reimer said.

He said that previous related experiments only measured either near-perfect entanglement or high efficiency. The recent work achieves both requirements with a quantum dot.

By embedding semiconductor quantum dots into a nanowire, the researchers created a source that creates near-perfect entangled photons 65× more efficiently than previous work. This new source, developed in collaboration with the National Research Council of Canada, can be excited with lasers to generate entangled pairs on command. Then, the researchers used high-resolution single photon detectors, provided by Single Quantum in the Netherlands, to boost the degree of entanglement.



The entangled photon source, an indium-based quantum dot embedded in a semiconductor nanowire **(left)**, as well as a visualization of how the entangled photons are efficiently extracted from the nanowire.

"Historically, quantum dot systems were plagued with a problem called fine structure splitting, which causes an entangled state to oscillate over time," said Matteo Pennacchietti, a Ph.D. student at IQC and Waterloo's Department of Electrical and Computer Engineering. As a result, slow detection systems could not measure the entanglement.

The researchers overcame this drawback by combining their quantum dots with a fast and precise detection system. "We can basically take a timestamp of what the entangled state looks like at each point during the oscillations, and that's where we have the perfect entanglement," Pennacchietti said.

In subsequent demonstrations, a group used the advancement to simulate quantum key distribution (QKD), by using the generated oscillating two-photon Bell state to establish a secure key.

Now, the researchers believe that their

quantum dot source holds significant promise in the future of secure quantum communications. They expect their findings to lay a foundation for creating large arrays of deterministically positioned quantum dot sources for QKD networks.

The research was published in *Communications Physics* (www.doi.org/10.1038/s42005-024-01547-3).

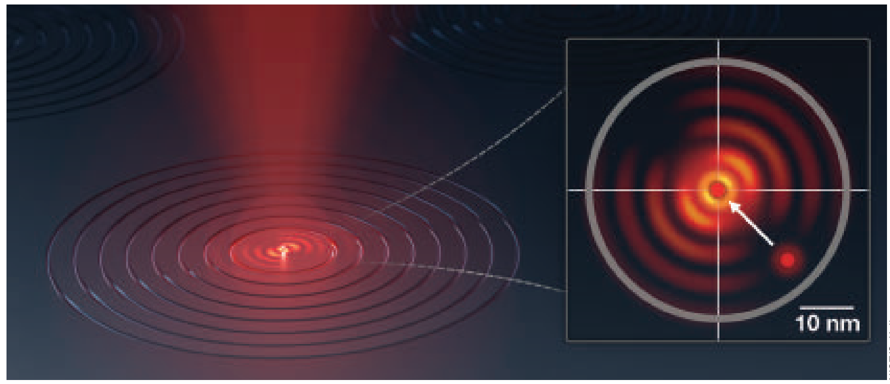
Standards aim to speed market arrival for quantum information tech

GAITHERSBURG, Md. — Devices that capture light from quantum dots, such as chip-scale lasers and optical amplifiers, have made their way from the lab to the commercial market. The transition for newer quantum dot-based devices has been slower, however, due to the extreme level of accuracy needed in the alignment of the individual dots and the optics that extract and guide the emitted radiation.

When localization microscopy of quantum emitters is used to guide lithographic placement of photonic structures, microscopy and lithography measurement errors can easily occur. These errors degrade registration accuracy, limiting device performance and process yield.

To address this bottleneck, researchers at the National Institute of Standards and Technology (NIST) and the University of Maryland developed standards and calibrations for the optical microscopes used to guide the centering of quantum dots within photonic chips. The researchers' method enables precision down to 10 to 20 nm across the entire image from an optical microscope, allowing the correction of many individual quantum dots. The model predicts that if microscopes are calibrated with the new standards, the number of high-performance devices could increase by as much as a hundredfold. The standards and calibrations created by the collaborators are traceable to the International System of Units (SI).

"The seemingly simple idea of finding a quantum dot and placing a photonic component on it turns out to be a tricky measurement problem," said NIST researcher Craig Copeland. In a typical measurement, errors begin to accumulate as researchers use an optical microscope to locate the quantum dots, which reside at random points on the surface of a semiconductor material. If the researchers were to ignore the shrinkage of semiconductor materials at the ultracold temperatures at which quantum dots operate, the errors would grow larger. Further complicating matters, these measurement errors are compounded by inaccuracies in the fabrication process that researchers use to make their calibration standards, which also affects the placement of photonic components.



Accurate alignment of quantum dots with photonic components is critical for extracting the radiation emitted by the dots. In this illustration, a quantum dot centered in the optical "hotspot" of a circular grating **(center dot, inset)** emits more light than a dot that is misaligned **(off-center dot)**.

Addressing these errors, the NIST team created two types of traceable standards to calibrate optical microscopes — first at room temperature to analyze the fabrication process, and then at cryogenic temperatures to measure the location of quantum dots.

Building on previous work, the room temperature standard consisted of an array of nanoscale holes spaced a set distance apart in a metal film. The researchers measured the precise positions of the holes and ensured that the positions were traceable to the SI. They compared the apparent positions of the holes when viewed using the optical microscope with the actual positions of the holes to assess errors caused by magnification calibration and image distortion from the optical microscope.

Following this, the researchers used the calibrated optical microscope to rapidly measure additional standards that they had developed, which enabled them to perform a statistical analysis of the accuracy and variability of the process.

Working at cryogenic temperatures, the researchers calibrated an ultracold optical microscope for imaging quantum dots. To create this standard, they built an array of pillars on a silicon wafer. The researchers chose to work with silicon because the shrinkage of silicon at low temperatures has already been accurately measured.

The cryogenic optical microscopes tended to have worse image distortion than microscopes operating at room temperature. And the optical imperfections in the cryogenic microscopes bent the images of straight lines into curves, which the calibration straightened out. If left uncorrected, this image distortion caused large errors in determining the position of quantum dots and in aligning the dots within targets, waveguides, and other light-controlling devices.

"These errors have likely prevented researchers from fabricating devices that perform as predicted," researcher Marcelo Davanco said.

The researchers believe that their methodology could help enable the lab-to-fab transition for quantum information technologies. Nanoparticle characterization, microsystem tracking, and semiconductor metrology applications could also benefit. The traceable standards could further be used for photonic structures, such as broadband waveguides. These structures require registration errors of <10 nm to achieve high coupling efficiency.

"A researcher might be happy if one out of 100 devices works for their first experiment, but a manufacturer might need 99 out of 100 devices to work," researcher Samuel Stavis said. "Our work is a leap ahead in this lab-to-fab transition."

Beyond quantum dot devices, the traceable standards and calibrations under development at NIST may improve accuracy and reliability in other demanding applications of optical microscopy, such as imaging brain cells and mapping neural connections. Additionally, scientists may need to coordinate position data from different instruments at different temperatures, as is true for quantum-dot devices.

The research was published in *Optica Quantum* (www.doi.org/10.1364/OPTICAQ.502464).

Ultrablack coating overcomes fragility and durability bottlenecks

SHANGHAI — A broadband, ultrablack film from the University of Shanghai for Science and Technology and the Chinese Academy of Sciences could enhance the performance of telescopes and other applications in space exploration and precision optics. During tests, the film achieved an average absorption as high as 99.4%, within a wavelength range of 400 to 1000 nm.

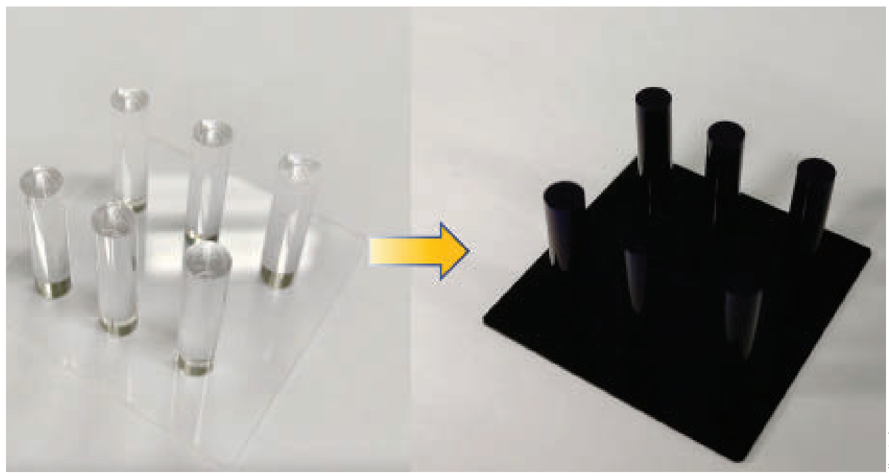
Optical devices that require ultrablack coating for stray light suppression often exhibit significant curvature and intricate shapes, which poses challenges for existing approaches to film preparation. In space exploration applications, for which payload is a critical factor, coating lightweight materials with black films is essential.

In these use cases, the coating must be sufficiently robust to withstand harsh environments.

Today, according to researcher Yunzhen Cao, black coatings, such as vertically aligned carbon nanotubes or black silicon, are limited by fragility. "It is also difficult for many other coating methods to apply coatings inside a tube or on other complicated structures," Cao said.

In response, the researchers designed an ultrablack film using alternating layers of titanium-aluminum-carbon (TiAlC) and silicon dioxide (SiO_2). They deposited the film using atomic layer deposition (ALD) and prepared an interlayer composed of aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2). The interlayer was deposited on magnesium alloys prior to the deposition of the ultrablack film. With the presence of the interlayer, the ultrablack film on the surface of the alloy exhibited favorable adhesion and abrasion resistance.

The use of ALD also enabled the researchers to develop conformal coatings that provide broadband absorption for large-curvature surfaces. "One big advantage of the ALD method lies in its excellent step-coverage ability, which means we can obtain uniform film coverage on very complex surfaces, such as cylinders, pillars, and trenches," Cao said.


Jin et al.

An ultrablack coating can be applied to curved surfaces and magnesium alloys via atomic layer deposition (ALD) to absorb >99% of light.

In a demonstration test, the researchers applied the ultrablack coating to a large-curvature magnesium alloy surface. Magnesium alloys are the lightest structural metal and are widely used for aerospace applications. However, the strong electrochemical activity of magnesium leads to poor corrosion resistance. To prevent corrosion, the researchers created a barrier layer to separate the coating and the surface of the alloy. Together, TiAlC and SiO_2 prevented nearly all light from reflecting off the coated surface of the optical device. "TiAlC acted as an absorbing layer, and SiO_2 was employed to create an antireflection structure," Cao said. "As a result, nearly all of the incident light is trapped in the multilayer film, achieving efficient light absorption."

During experiments, the thin-film coating demonstrated an average absorption of 99.3% across a range of light wavelengths, from violet light at 400 nm to near-infrared at 1000 nm. After undergoing damp heat and thermal cycling tests, the absorptions of the ultrablack film-coated magnesium alloys remained at 99.1% and 99%, respectively, indicating that the film will be durable in harsh environments. The researchers achieved uniform coverage on the complex structure and the coating's performance remained stable.

The researchers anticipate that the coating will be used to enhance space telescopes and optical hardware operating in the most extreme conditions, and they are working to further develop its performance. According to Cao, they aim to expand its absorption range to extend into the ultraviolet and infrared regions. The research was published in the *Journal of Vacuum Science & Technology A* (www.doi.org/10.1116/6.0003305).

“HiFi” project lasers target quantum frequency conversion

FREIBURG IM BREISGAU, Germany — A project funded by the German Federal Ministry of Education and Research is deploying semiconductor lasers to develop technologies to provide quantum frequency converters with high efficiency and low noise for initial test tracks. The Fraunhofer Institute for Applied Solid State Physics IAF (Fraunhofer IAF) has contributed to the project, called HiFi: Highly integrated quantum frequency converter of highest fidelity based on innovative laser, fiber, and production technology.

Fraunhofer IAF developed vertical-external-cavity surface-emitting lasers (VECSELs) based on gallium antimonide. The lasers feature an external resonator and intracavity filter for wavelength selection.

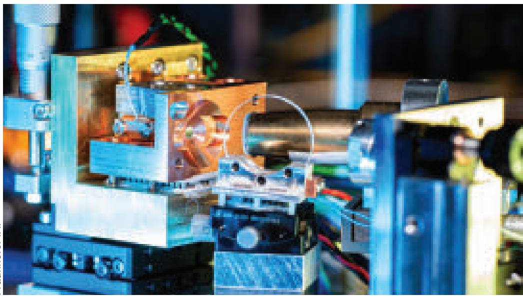
Marcel Rattunde, HiFi subproject coordinator and head of the optoelectronics department at Fraunhofer IAF, said that these VECSELs are spectrally narrow-band pump sources that cover a wavelength between 1.9 and 2.5 µm, depending on the output wavelength of the qubits used. Further, the lasers achieve an output power of up to 2.4 W with an absolute wavelength stability of <2 fm. “This corresponds to a frequency stability of less than 100 kHz and clearly falls below the frequency stability class 1E-9,” Rattunde said.

The result, according to Rattunde, represented an international record for this type of laser, which was achieved through a collaboration with Menlo Systems.

“Together, we locked the disk laser to a frequency comb, which in turn was coupled to a 10-MHz reference,” he said.

In experiments, the researchers set the emission wavelength precisely to the target wavelength (2062.4 nm) for demonstration experiments at the fiber link of Saarland University, to which Fraunhofer IAF has handed over the laser module.

In addition to power scaling, the HiFi project demonstrated the importance of having a precise understanding of the mode behavior of the lasers as well as the identification and elimination of noise

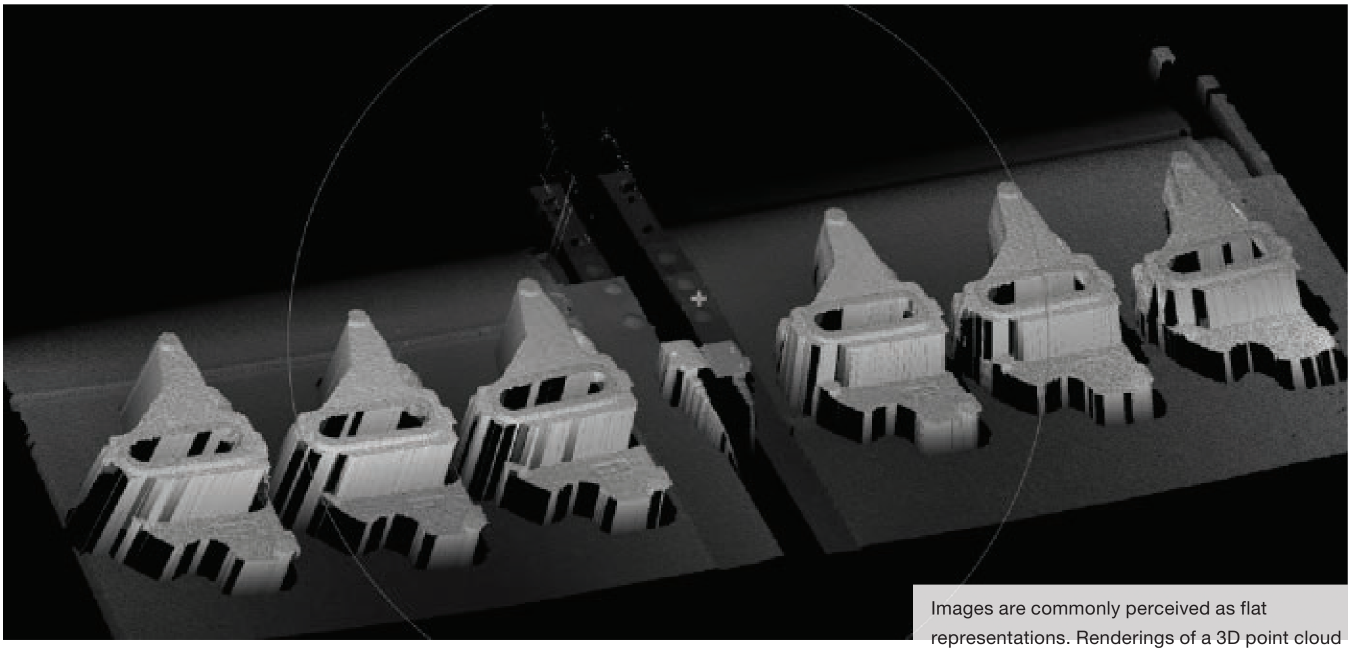


Fraunhofer IAF

A vertical-external-cavity surface-emitting laser (VECSEL) setup.

sources. In quantum frequency conversion, the energy of the pump photon is subtracted from the signal photon by a difference of the frequency process in a nonlinear optical crystal. To ensure a low-noise process, the energy of the pump photons must be below the target wavelength (usually 1550 nm), otherwise the pump laser can generate photons in the output signal due to parasitic effects.

The research was presented at SPIE Photonics Europe.



Images are commonly perceived as flat representations. Renderings of a 3D point cloud offer enhanced information of a scene.

The Evolution of 3D Imaging in Industrial Applications

A growing number of configurable machine vision software platforms on the market support the analysis of 3D data, making processing more accessible without the use of low-level code.

Images courtesy of David Dechow.

BY DAVID DECHOW
MACHINE VISION SOURCE

A wide range of applications in industrial automation require and are enabled by 3D imaging. 3D technologies are in demand in varied industries, including aerospace, automotive, logistics, and more. Components and software that deliver high-quality 3D data have evolved in recent years and the result, in many cases, has been an advancement in image quality, resolution and precision, ease of use, and greatly expanded reliable and robust use cases.

In this context, 3D imaging is a subset of machine vision, which leverages many imaging techniques to perform automated inspection, robotic guidance, online metrology, and other tasks to support and improve a diverse set of processes. While 3D imaging has broad value in other areas, this discussion will focus on how it works and its function in an automation environment.

Background and techniques

Images are commonly thought of as flat or 2D representations of a scene. The features in the image are separated mostly by differences in contrast and brightness, and more specifically by color or texture. Interestingly, the human eye can intuitively perceive or assign depth to things in a 2D representation based on a priori knowledge of the content (although even the human eye can be easily fooled).

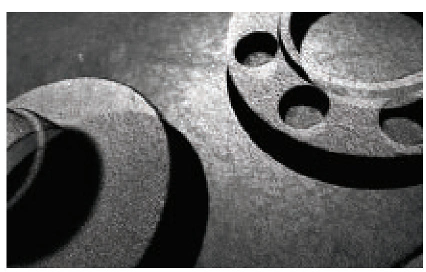
On the other hand, imaging components that capture 3D information provide topographical data representing the surface geometry of the scene in which objects or features are differentiated by changes in relative height. It is important to note, however, that with one key exception, 3D imaging implementations rely on 2D images to construct the 3D data, and in many cases, the extraction of the 3D information is highly dependent on specialized lighting techniques. More specifically, all imaging requires illumination without exception, but with 3D imaging, illumination can be a key part of the overall system or component.

Therefore, the critical characteristic of a 3D image for machine vision is that the image information represents calculated points in real-world space. These points may be relative to the camera orientation, calibrated to a known-world coordinate system — especially when the information is used in guidance, for example — or simply analyzed relative to each other to extract features and defects, and to perform 3D measurements. Note that a 3D image provides a profile of only the surface of the scene as viewed by the camera. A 3D imaging system does not “see” the entire object on all sides, although that can be accomplished using multiple imaging devices or by moving the object in front of the 3D imaging system in a process called 3D reconstruction.

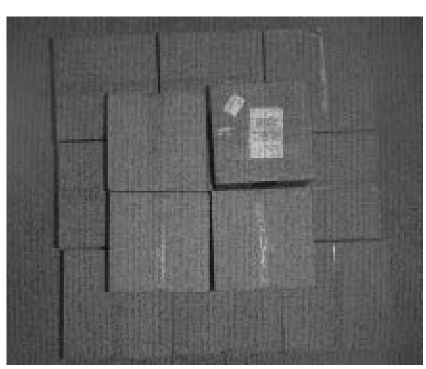
The execution of 3D imaging is by no means new and has been implemented in automated applications for decades. However, technologies and components for 3D imaging have unarguably evolved over the years with notable recent advancements; one outcome is a clear definition of fundamental implementation techniques that differentiate products within the marketplace. These techniques are sometimes described at a very high level in regard to whether the illumination used is active or passive. These terms refer respectively to lighting that contributes directly to the extraction of 3D information or lighting that provides contrast in the 2D scene. Some of the more common methods of acquiring 3D information from images for industrial automation include:

A single camera with passive illumination. This technique uses perspective to calculate the 3D position of a specific object that has rigid features that are known in advance.

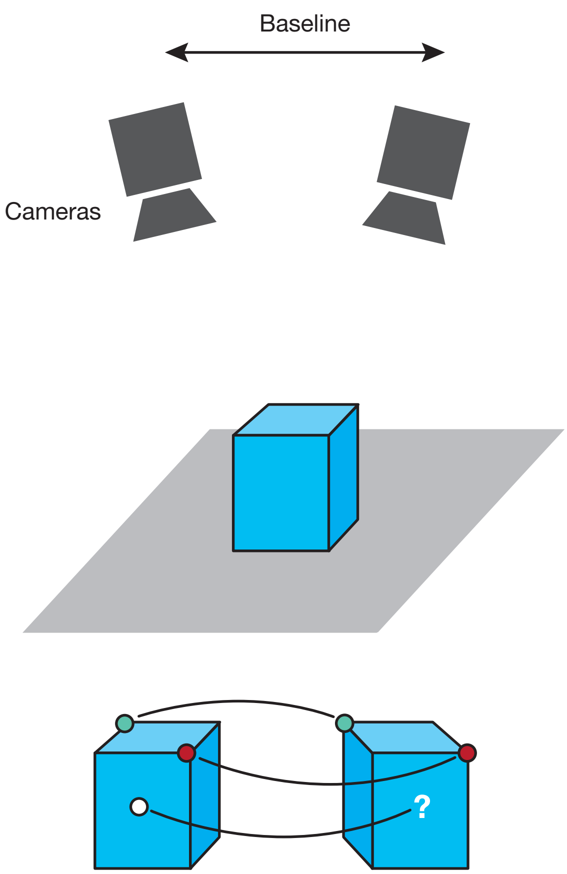
A stereo (binocular) camera pair with passive illumination. Stereo imaging involves the use of two cameras to analyze a single view from different perspectives, much like human eyes. Through proper calibration of the cameras, the geometric relationship of the two different sensors is defined relative to a fixed-world coordinate system. The cameras locate the same (or corresponding) target feature in each field of view and apply transforms to determine the posi-


A typical representation of a 3D point cloud.

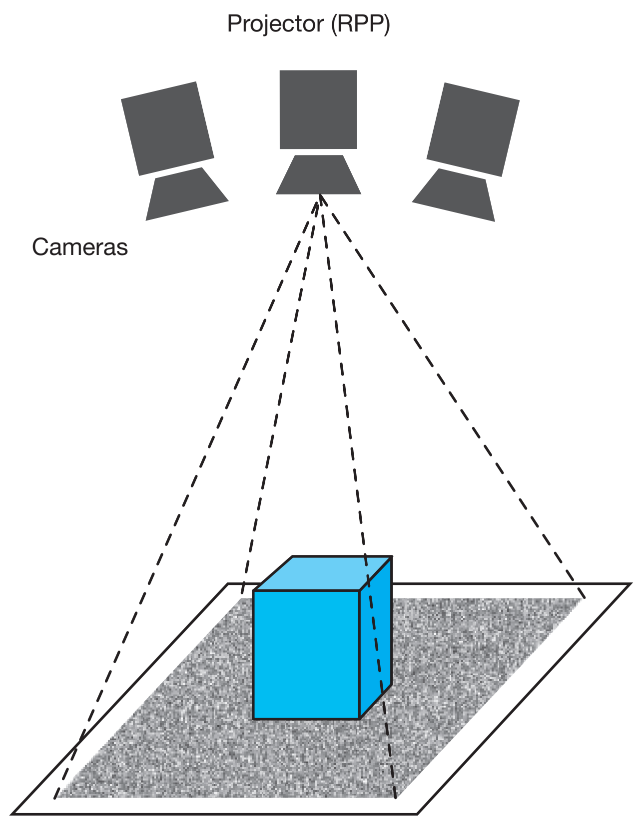

The same point cloud merged with grayscale texture.


An actual view of a structured light pattern for 3D image acquisition.


The same image without the light pattern.



Passive stereo imaging, a 3D-imaging technique.



Active stereo imaging with random structured light, for one or two cameras.

An image showing a defect in 3D using profilometry.

tion of that point in 3D space. However, only features highlighted by the passive illumination can be compared. In this manner, stereo imaging can produce a 3D point cloud of the scene, although the data of the full image might not be valid.

A light line or "sheet of light." These components use a single line of light (active illumination) and triangulation to construct a complete 3D representation of a scene by scanning as the camera or an object is in motion. This imaging technique produces relatively dense 3D information. Commonly called profilometers or depth imagers, these systems are used in a wide variety of applications.

A structured light. This active illumination technique uses a structured light pattern and one or two cameras to image the pattern in the scene and construct the 3D data using varying algorithms. The light patterns range from simple dots to complex dynamic coded patterns to achieve more data points and precision. The calculation of the 3D information may use techniques similar to those found in binocular or line light imaging. In this implementation, the imaging system and part are not moving, and acquisition times are relatively fast.

A single- or multi-camera height from focus, shape, and shading. Using either active or passive illumination, these imaging techniques sometimes require less complex components but often more complex algorithms. In certain implementations, the 3D information might be relative to the features in the scene rather than to a calibrated real-world space.

Time of flight, lidar, ladar. Time of flight is similar to implementations of lidar or ladar (light or laser detection and ranging), and also might be referred to as flash lidar. This imaging is the exception to the use of general 2D sensors for 3D in that it uses specialized imaging sensors and/or camera processing to calculate a distance for each pixel by timing pulsed or phase modulated light reflections (usually infrared or even laser). Imaging speed can be very fast, but the image resolution and distance accuracy might be less than other 3D methods.

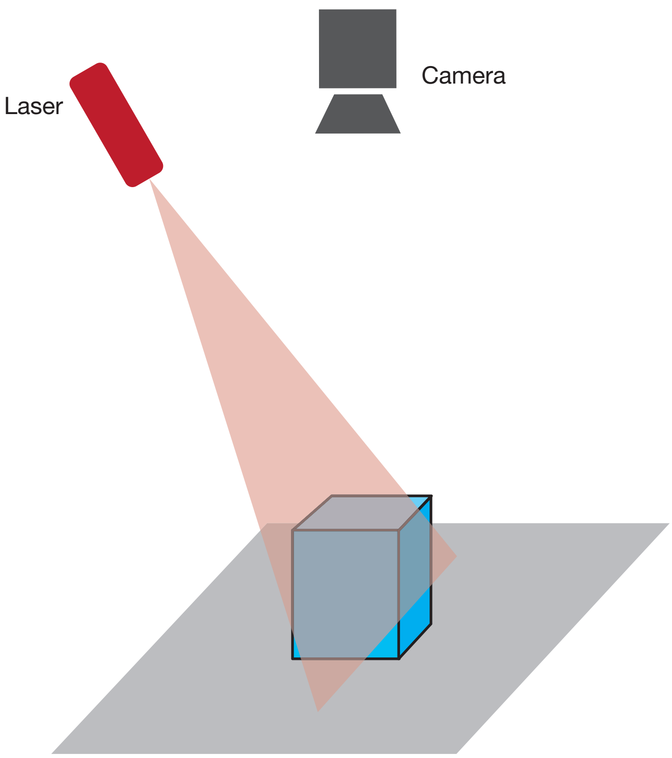
Deciding which technique(s) and components to use requires the understanding of the type of information that is available from a 3D image and what would be most useful for the target application. In general, three types of 3D image data could be available in typical machine vision applications: single point location, depth/range images, and point cloud representation.

For a 3D scene, it is not too difficult to imagine it as a huge collection of individual points, called a point cloud. Each point has an x, y, and z position in space. With a point cloud data representation, further processing is completed, for example, to extract a single point in the scene (such as the highest point above a plane); isolate features or objects based on spatial height relative to a plane for measurement or quality evaluation; or to search for and provide the location of objects in a complex scene based on a stored 3D model of the object's shape, often for the purpose of robotic guidance.

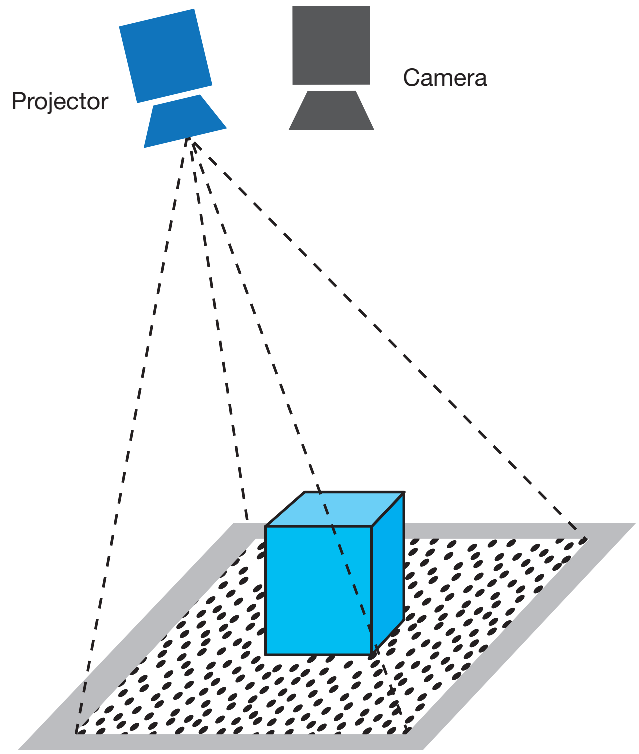
A 3D representation of random objects in a bin for robotic guidance.

Segmenting and analyzing features in a point cloud is performed using specialized algorithms designed specifically to work within the point cloud data representation.

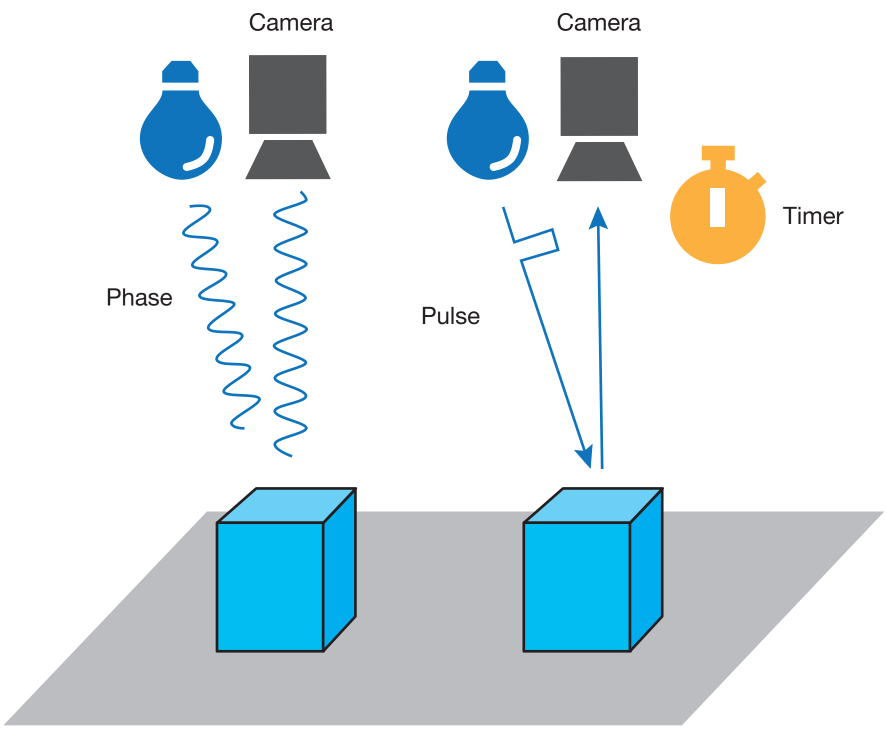
The point cloud can also be represented as a depth or range map, because the z component of each point is usually the



Line or “sheet of light” triangulation using one or two cameras.



A structured light random dot pattern using one or two cameras.



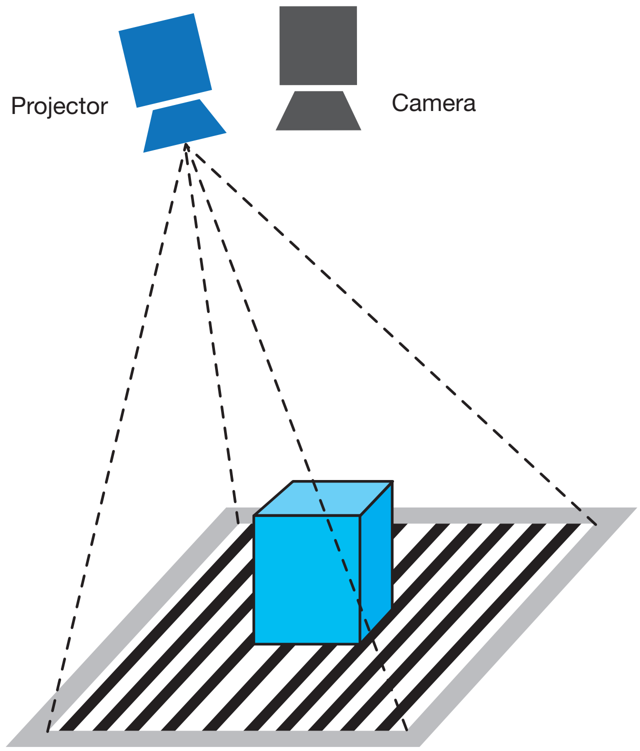
A depiction of time-of-flight imaging.

distance between the feature and a relative or user-defined plane, depending on the imaging technique and components that are used. In some components, only the depth image is processed and 2D algorithms are often used because the pixels have simple single-valued content, except that the pixel intensity is relative to distance, not contrast or color. Even when working a full point cloud, the system might just use the z image and simpler algorithms as part of the overall image analysis.

Single points

The data from a 3D scene comprises only the position of individual points related to specific features or objects. Often, less computational expense is required to extract single point locations, resulting in faster processing. Position and height information from a single point can be used in an application, though multiple individual points are often processed to further define an object’s spatial orientation and size for location and/or quality inspection. This processing might be based on 3D models and, more recently, might even use AI-based deep learning techniques for object segmentation and localization, particularly in the case of robotic guidance in applications such as random bin picking.

How the data are used depends on the application. In any case, a single, unpro-



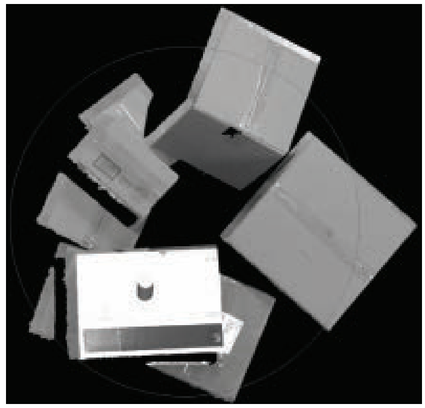
Structured light coded light patterns for one or two cameras.

cessed 3D image point (point cloud or depth image) provides an x, y, and z position relative to a plane. When combined with other related points associated with an object or feature, the data available to the application are a point or points with full 3D planar representation: x, y, and z position, and angles related to the yaw, pitch, and rotation — known as W, P, R: rotations about the x, y, and z axes of an object.

The discussion has so far considered the background and evolution of modern 3D imaging components. These imaging systems have matured significantly in recent years. Some of the advancements that furthered the use of 3D imaging include:

- Improvements in imaging techniques that deliver higher resolution and more precise data in the 3D image, faster acquisition times, and the ability to image moving objects.
- A wider selection of options and features to provide users and integrators with the flexibility needed for varying applications.
- Better standardized interfacing to software and programming libraries.
- Increased control and adjustment of image parameters to tune the response for specific tasks.

However, one of the more compelling trends anecdotally is a subtle movement from sheer do-it-yourself imaging with available components to a focus on application solutions. To be clear, the 3D imaging components in today's marketplace are more powerful and easier to use than ever. The migration toward applications shows promise in expanding 3D imaging's use cases and capabilities to a broader automation audience.



A random box pallet with a 3D view **(above)**.

A 3D representation of a random pallet of boxes for a vision-guided robotics (VGR) pick **(left)**.

On one end of the spectrum, many configurable machine vision software platforms have introduced or significantly increased their offering of basic tools that support the analysis of 3D content. The result is that the processing is accessible without working with low-level code, which had been the case as 3D imaging grew. It also means that engineers who are familiar with standard platforms can reduce the learning curve associated with 3D image processing. In some cases, development platforms are somewhat component agnostic, allowing the end user or integrator to select the imaging component most suited for the target tasks.

In a broader move, certain vendors are focusing on very specific applications and providing off-the-shelf, targeted 3D turnkey solutions, sometimes called application-specific machine vision solutions.

While the applications vary, a noticeable surge in this type of solution can be seen in 3D vision-guided robotics (VGR), and particularly for robotic applications in mixed or homogeneous random part bin picking and palletizing/depalletizing tasks. The promise of application-specific solutions is that the project can be implemented with little or no configuration or programming, and generally supported and maintained without expert technical staff. To be fair, since these systems have only recently emerged, it might be too early to predict their overall performance, but initial observations seem to show good results. Note too that these applications are somewhat tightly constrained to deliver optimal results for a very specific use. A good best practice in considering this type of system is to clearly analyze and document the needs of your application, and then research the system's proven capabilities based on those specific needs.

Key applications

The following are common 3D application areas, along with some implementation notes and best practices:

• *Metrology and defect detection*

3D components that are particularly well suited for 3D measurements and defect detection are available. A key component candidate in these systems is one that uses scanning and laser triangulation (e.g., a depth sensor). They are usually higher-resolution systems in terms of x, y, and z accuracies and have somewhat limited fields of view, which requires the sensor or part to be in motion to capture images. Integration techniques are similar to those used for line-scan cameras (although distance sensors in this context are not line-scan imagers).

The imaging tools and algorithms commonly used may include both standard 2D and targeted 3D tools to provide measurements including depth and sometimes position and detection of defects. Additional 3D components might also be used. It is important in all cases to qualify the required feature size for defect detection and proper resolution for metrology.

• *Robotic guidance and object location*

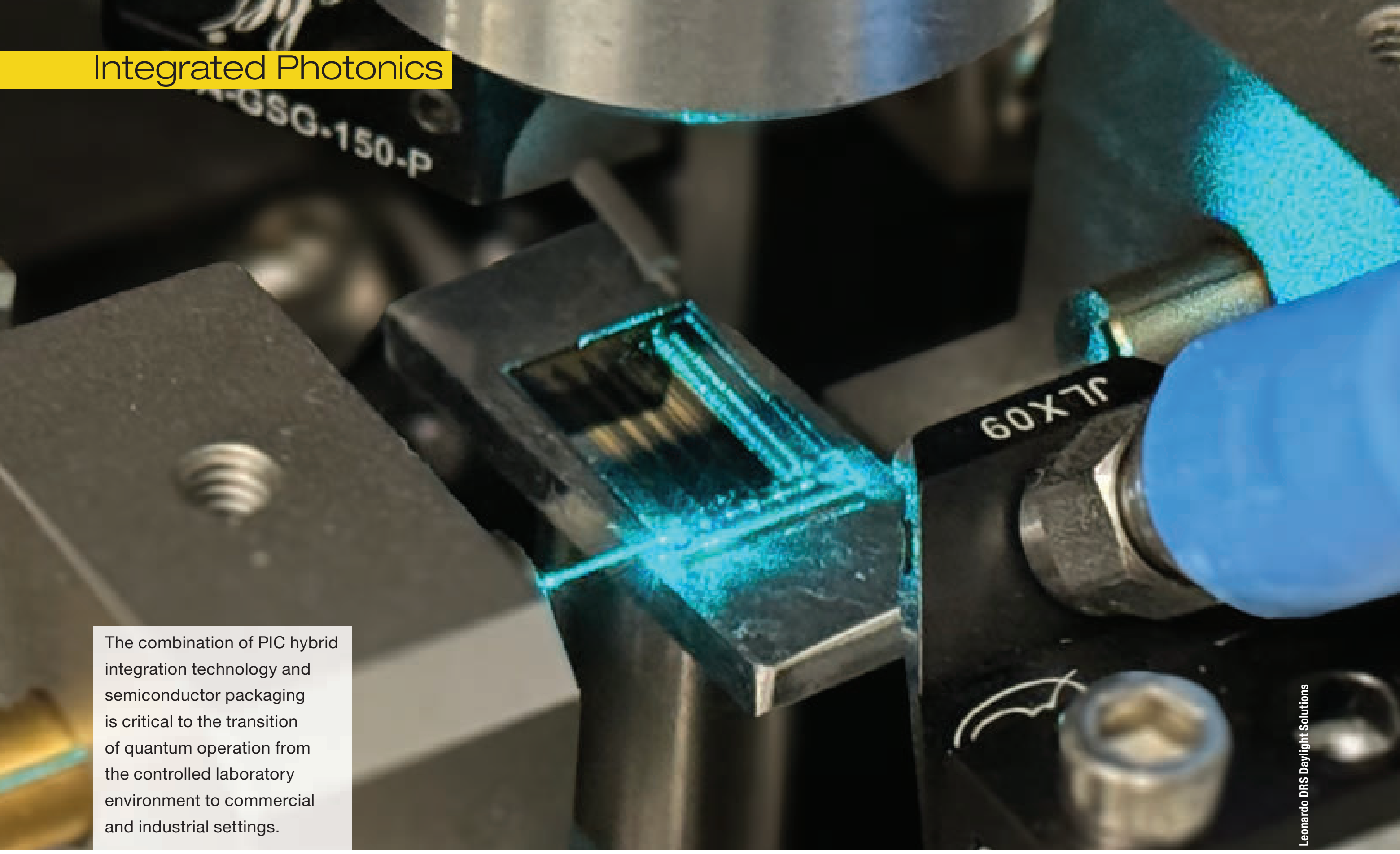
The benefit of using 3D in robotic guidance is the ability to locate an object in any orientation and spatial position. This kind of flexibility provides greater opportunities for VGR in a growing base of applications. Objects that are not resting in a specific plane can be reliably located for picking or processing, potentially even when they are randomly stacked or piled. A broad range of automation applications in assembly, packaging, machine-tending, and many other areas can have greater flexibility with 3D guidance, and most industries, including automotive, metal fabrication, and logistics and distribution, profit from the use of this VGR technology. The technology is indicated in most situations in which an object must be located at different heights and/or in different poses or stable resting states in a view.

Bin picking and palletizing/depalletizing have been mentioned, but the possible use cases are much broader. One important consideration for VGR is to be sure that the application requires 3D imaging. When objects can present and be gripped from just a few stable resting states, it might be less complex and less costly to use 2D guidance with more flexible object detection and grip configurations.

The evolution of 3D imaging in industrial automation opens the door for more flexible automation, which is the cornerstone of the broader offer for machine vision technology. While 3D imaging can require significantly more effort in implementation and integration than 2D imaging, advancements in components and self-contained systems on the market may make the technology easier to use, though certain restrictions may arise in exchange. Examine the possibilities by clearly defining the scope of the project based on the needs of the automation and seek out the best solutions based on the capability of the components and software.

Meet the author

David Dechow is an engineer, programmer, and technologist widely considered to be an expert and thought leader in the integration of machine vision, robotics, and other automation technologies; email: david@daviddechow.com.



The combination of PIC hybrid integration technology and semiconductor packaging is critical to the transition of quantum operation from the controlled laboratory environment to commercial and industrial settings.

Leonardo DRS Daylight Solutions

Chip-Scale Visible Sources

Aim to Release Quantum Technology from the Lab

Advancements in the manufacturing of high-performance visible lasers hold the key to unlocking numerous application opportunities for quantum devices and throughout quantum science.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

The visible range, spanning around 380 to 700 nm, has longstanding use in photonics. Many materials have specific absorption, reflection, and transmission characteristics in this band, which are exploited for applications from optical metrology and biomedicine to quantum and communications.

Increasingly stable and versatile visible lasers are populating the market, and the efficacy of these sources is intersecting with the emergence of chip-scale lasers — a burgeoning innovation area that is poised to benefit a range of disciplines. Chip-scale lasers promise to uniquely address the need for small, low-power, and potentially low-cost sources.

In terms of both applied R&D and productization, quantum devices, in particular, are among the technologies for which chip-scale lasing could serve as the catalyst for a wave of scientific and commercial progress.

Quantum comes calling

Because many of the physical systems used in quantum computing, communications, sensing, and metrology have optical transitions in the visible, as well as the near-infrared, visible sources are integral in quantum information science and technology (QIST). This includes neutral atoms and ions used in optical atomic clocks. With laser sources addressing optical transitions in the visible band, the potential use of neutral atoms and trapped ions spans applications that typically necessitate cooling, initialization, and state readout or the interrogation of specific transitions, said Stephan Ritter, director of quantum technology solutions at TOPTICA Photonics.

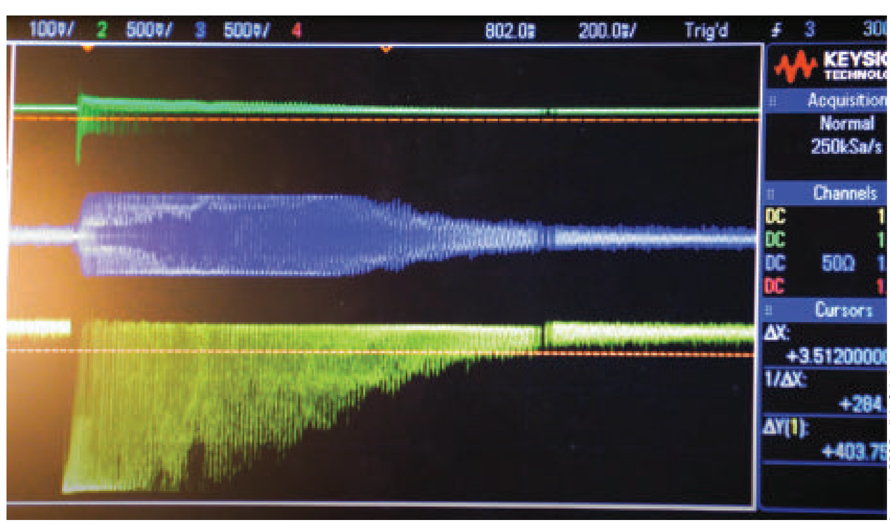
For example, trapped ion and neutral atom arrays are used in color center magnetometers as well as various types of quantum memories that are needed in quantum networks.

“For quantum computers, both neutral atom and ion-trap quantum computers use a number of visible lasers to establish, maintain, and control the qubits that form the base for quantum computation,” said Asger Jensen, senior market development manager and head of quantum photonics at NKT Photonics.

The advancement of on-chip lasing only heightens the application potential for visible sources. Integrating visible lasers in a chip-scale format, and particularly as part of PIC technology, could further enable advancements for quantum sensing, processing, and computing.

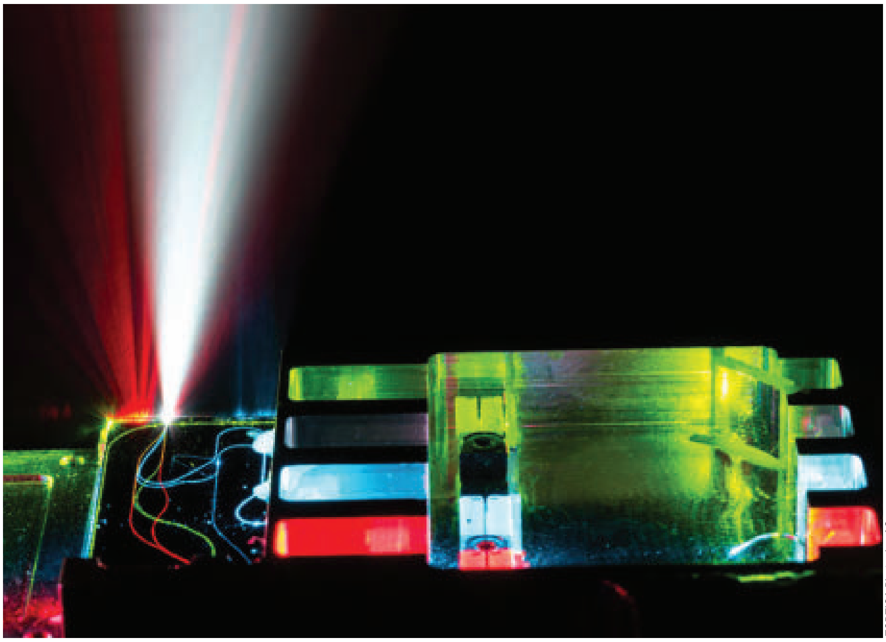
“The size, weight, power consumption, and cost (SWaP-C) scalability of PICs that

Leonardo DRS Daylight Solutions



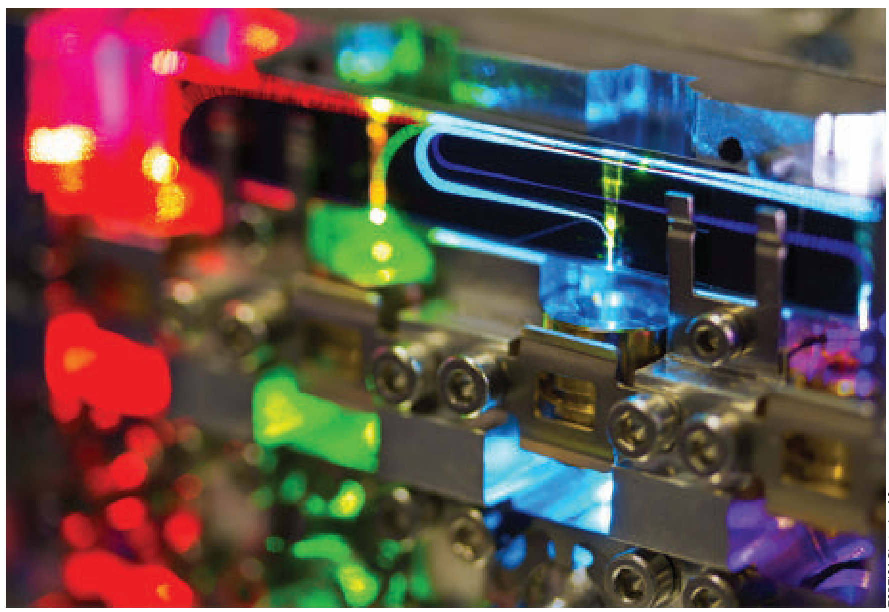
Leonardo DRS Daylight Solutions

The commercial manufacture of visible lasers prioritizes ruggedization, among other qualities. One test involves pounding a table with a hammer **(above)** to ensure that the source stays in lock — indicating that it will maintain performance regardless of temperature or vibration extremes **(right)**.



TOPTICA Photonics AG

Visible light PICs can be used for applications such as spectroscopy, metrology, and sensing. The PIX4life open access pilot line for PICs targets life sciences applications in the visible range.



TOPTICA Photonics AG

operate in the visible are poised to enable what's next in future quantum applications," said Tim Day, senior vice president and general manager of Leonardo DRS Daylight Solutions.

"Along this road map, it is critical that stable, ruggedized lasers are incorporated into systems that are required to operate outside of the lab environment."

Chip-scale visible lasers

The current proportion of the visible laser market pertaining to quantum application end uses is small in comparison to laser-commanding disciplines, such as spectroscopy, biology, and imaging. Dan Blumenthal, head of the Optical Communications and Atomic Quantum Photonic Integration Group at the University of California, Santa Barbara, estimates the market share to be around 10% to 15%.

This value is predicted to rapidly change — and at an uptick — given the pursuit of integrated, chip-scale quantum devices. The maturity of existing visible laser solutions, which are ready to support new-product design, reinforces such a forecast.

"[Laser system developers] are still building tabletop lasers customized to each and every wavelength for quantum, and making money," Blumenthal said. "There are expensive, brute force lasers for quantum, not reliable or inexpensive or compact. There is a realization that this has to change for quantum scale to become reliable."

Blumenthal believes that quantum-focused commercial entities understand the need for chip-scale visible sources and the need to be adaptable to the broad array of unique atomic and quantum wavelengths. For example, leading quantum information company Infleqtion acquired silicon photonics companies SiNoptiq Inc. (for which Blumenthal served as president and CEO) and Morton Photonics earlier this year. The acquisitions are intended to precisely address the emerging market for visible light integrated laser system technologies for quantum applications.

Manufacturers of quantum devices are not the only ones who recognize the current commercial opportunities. Laser manufacturers are increasingly aware of the commercial prospects in the quantum realm that could use integrated visible laser solutions.

"I have seen some laser makers that are putting a lot of resources into serving the quantum community, particularly on topics like clocks and quantum sensors that are a bit further along, though clearly quantum computing and communications are on their radar," said Kartik Srinivasan, project leader and a fellow in the Photonics and Optomechanics Group at the National Institute of Standards and Technology (NIST).

In the commercial sector, NKT's Jensen echoes Srinivasan's observation. He highlights the ongoing priority for laser manufacturers to support the road maps of the laser-heavy quantum applications in platforms that are or will be viable for commercial use.

"These applications in quantum technology have in recent years seen a migration from labs into commercial ventures and a need to scale the systems, and as a consequence, the laser powers," he said. "This has also facilitated a move from lab-appropriate laser technologies, such as titanium sapphire lasers chosen for their versatility, toward industrial laser platforms, such as fiber lasers."

Quantum outside the lab

The challenges in transitioning quantum technologies for use outside of the laboratory are well stated for system developers all the way down the chain to system integrators. The difficulty in maintaining baseline, laboratory-level performance in real-world settings is a bottleneck that exists within this set of challenges.

According to Srinivasan, integrated lasers may unlock quantum applications by helping to make them deployable outside laboratory settings. However, they may not always provide strong benefits in terms of the absolute performance of the quantum technologies that they support. In some cases, he said, real-world performance may be worse than when using the very best laboratory laser technology. In essence, both the integrated laser and the quantum device system, as a result, may face drawbacks in performance when transitioning out of the laboratory.

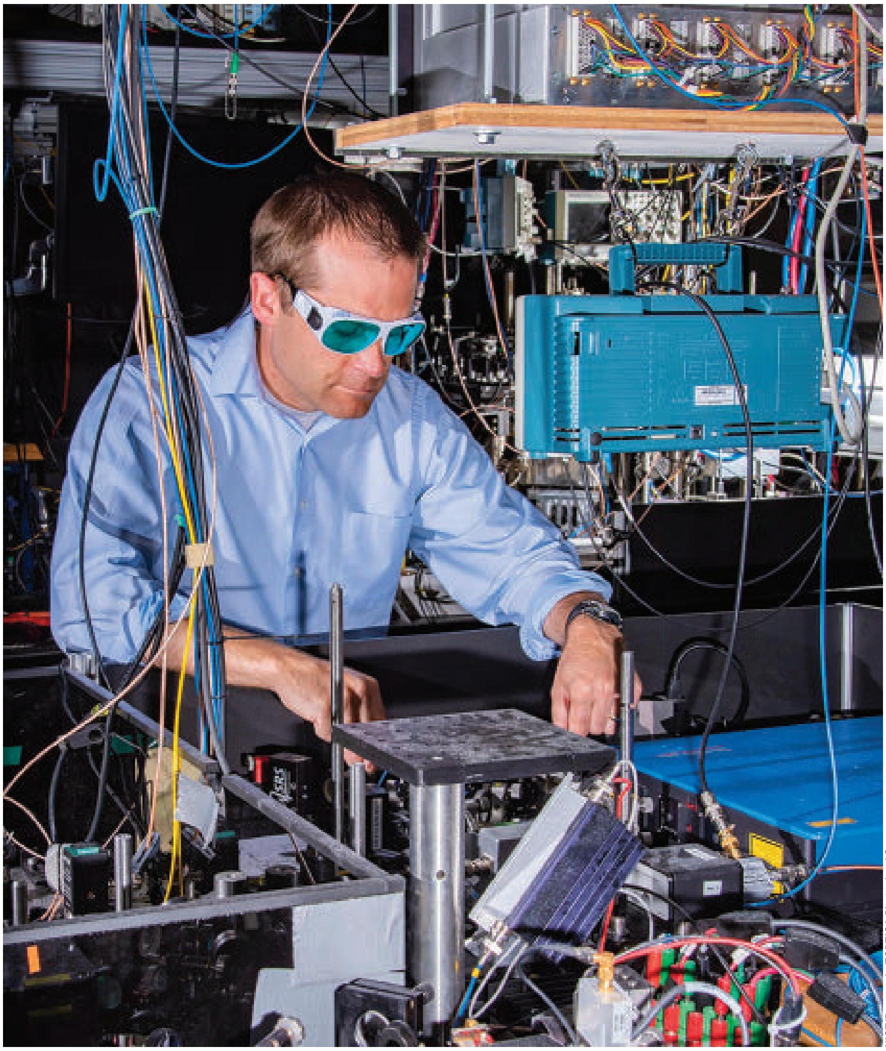
This is not to say the transition is on hold.

"Leveraging the combination of semiconductor and PIC hybrid integration and packaging with product design rules that satisfy military environmental requirements makes a powerful combination when transitioning quantum operation outside of a controlled lab environment," Day said. "Systems integrators across the spectrum of quantum sensors, clocks, computers, and networking will need to consider 'hands-free' operation when deploying systems in real-world environments."

Amid the early stages of the shift to which NKT's Jensen alludes, the majority of quantum applications that use visible lasers are in fundamental physics, quantum science and particle discovery, quantum sensing, optical atomic clocks, precision frequency metrology, and quantum computing. Typically, lasers and other photonic components are used to prepare the laser wavelength, phase noise, stability, amplitude, modulation, and detection for use in a quantum interrogating system in which the laser "touches" the atom, ion, or qubit. A move toward miniaturizing laser systems that are often bulky and expensive could reduce the cost of the quantum device. The likelihood of this cost reduction increases if the lasers are created through scalable fabrication processes.

Of the quantum applications that could be apt to emerge based on chip-scale lasers, Blumenthal puts quantum sensors and timekeeping first on the anticipated rollout timeline. Srinivasan agrees: He predicts that chip-scale lasers will make inroads into quantum sensor systems within a period of five years. Small, compact clusters of quantum processors and networking, followed by quantum computation, are applications that will likely come later, Blumenthal said. Because commercial quantum computers are not yet firmly established in the marketplace, there are other bottlenecks that must be overcome first.

"At the moment, companies are mostly focused on scaling up their processors in terms of the number of logical and physical qubits, and that's what's limiting now," Srinivasan said. "Eventually, the laser size, weight, and power can be expected to be an issue, but advances in laser size, weight, and power must be such that laser quality (e.g., noise) is maintained, or else qubit quality may suffer."



National Institute of Standards and Technology (NIST) physicist Andrew Ludlow and colleagues achieved atomic clock performance records in a comparison of two ytterbium optical lattice clocks. The photo shows the laser systems used in both clocks **(foreground)** and the main apparatus for one of the clocks **(behind)**.

Applications that remain even more distant extend to space-based experiments, space-based quantum gravitational sensors, and global satellite navigation systems.

Integration demands

Without discounting the challenges associated with advancing sophisticated technologies out of the laboratory and into industry, the physical challenge of integrating a visible source onto a chip remains a dynamic bottleneck in the visible sources/on-chip lasing discussion. This barrier is present beyond the realm of QIST.

It also extends beyond the design of the laser system.

"For the chip, you need to choose a material platform that is transparent in the visible wavelength range, like silicon nitride or aluminum oxide," Ritter said. "Unfortunately, this is not the case for indium phosphide, which is well established for applications at telecom wavelengths." The distinct properties of different semiconductors and compounds are fundamental to photonic integration.

As such, this area of materials science is the source of widespread investigation in the R&D community, as well as in industry, given its influence on the development of chip-scale and integrated lasers.

In a 2022 research advancement, the Lipson Nanophotonics Group based at Columbia University demonstrated tunable and narrow linewidth chip-scale lasers for visible wavelengths shorter than red[1]. The group used micrometer-scale silicon nitride resonators and commercial Fabry-Pérot laser diodes in the work.

Critically, the researchers' platform served to simultaneously minimize the material absorption and the surface scattering losses for all visible wavelengths.

Such dual minimization is typically a challenge of these architectures.

"If absorption is not an issue because of the choice of a suitable material, scattering losses due to edge roughness dominate," Ritter said. "These losses increase strongly with the optical frequency and therefore put more stringent requirements on the fabrication process for visible laser sources compared to infrared lasers."

Further, the smaller mode fields that are associated with the shorter wavelengths in the visible range require added precision in alignment and packaging, Ritter said. And, despite the dynamism that the combination of hybrid integration and packing present, hybrid integration of the semiconductor material with the optical chip, via edge coupling or heterogeneous integration, remains a difficult task to solve in systems using visible sources.

"All chip-based laser solutions require packaging techniques, which are less well established in the visible than in the infrared," Ritter said.

"The on-chip integration of optical isolators to prevent reflected light from disturbing single-longitudinal-mode laser operation is an unsolved topic that requires more research."

Though quantum applications are among those poised to benefit from continued progress in this aspect of photonic integration, they are not alone. The depth of applied research into the chip-scale integration of visible laser sources is also tied to end uses in AR/VR and high-performance displays.

Quantum leap

The growing emphasis on commercializing and deploying quantum technologies corresponds to an ongoing shift in emphasis to introduce new laser-specific requirements in SWaP-C. This focus on laser parameters intensifies the focus on

system-level considerations, which are already prevalent.

Reliability, in the sense of where and how the laser can be controlled and coordinated with other lasers in a system, is one concern. An end user must be able to focus on an experiment by automating the application, without always needing "hands on" the lasers.

Another critical consideration is size and scale. Contemporary laser systems and their control mechanisms may occupy as much as 80% to 90% of lab- and rack-scale quantum infrastructure. This makes the current iteration of quantum devices expensive, power consuming, unreliable, costly, and in need of scaling.

Inherently, integrated lasers offer high potential for scalability for high-volume, low-power applications. Commonly, these sources are frequency-converted laser diodes.

But in terms of high powers, there is no way around fiber lasers due to their ability to dissipate excess heat. "When it comes to the most demanding power requirements, diode lasers in combination with fiber amplifiers are the best solution for many quantum technology applications," Ritter said.

This feeds into another consideration: the variety of material systems that might be needed to enable access to optical gain and light emission across a broad range of wavelengths, including through the visible.

"There are so many choices of atomic and molecular species, it is the Wild West of lasers in terms of laser parameters, including wavelength and the coherence properties of the light," Blumenthal said.

In the end, several different semiconductor laser gain media might be needed. How to best integrate those gain media with PICs will need to be determined.

Additional challenges remain. To fully realize the benefits of PICs from a lasers-first perspective, the PICs must be very low loss at the target laser wavelengths — a particular challenge at shorter wavelengths. There can also be more sensitivity to waveguide roughness, and wavelengths that are closer to absorption mechanisms in some PIC waveguide materials can limit the PIC's optical power handling.

"Over the last couple of decades, different integration strategies have emerged at telecom wavelengths, both in order to integrate telecom gain media with PICs and to realize good laser performance, in terms of output power, tuning range, frequency noise, etc.," Srinivasan said. "Some of these strategies are now being applied to visible wavelength lasers, and I expect to continue to see significant improvements in performance and integration in the coming years."

Blumenthal suspects that science is on the verge of a transformation in quantum devices.

"We are on the cusp of transforming lasers, laser systems, and the optics and control needed for quantum to the chip scale, realizing a leap like that of computing in the 1960s," he said.

Scaling up volume and investment

Although advancements in visible laser technology and quantum systems have historically occurred in parallel, certain underlying technical ingredients have influenced both technologies. For example, the demonstration of ultralow-loss PICs in the visible enables the design of very narrow linewidth and low frequency noise lasers. Low noise is critical for clocks and for high-fidelity qubit manipulation. At the same time, ultralow-loss PICs are useful for scaling up photonic quantum computation as well as for applications entirely outside of quantum and laser sources.

But as quantum applications develop a need for laser technology that is currently unavailable, the inverse also appears evident. While the high level of investment in quantum technologies may present an attractive investment — from a commercial perspective — the quantum technologies road map remains unclear.

"Quantum technologies have a place in the future, without a doubt, but for now remain an insignificant part of the overall laser market," Jensen said. "The large number of relevant laser variants combined with no single laser [that has been] used in quantum to reach a significant volume means it is yet to become as attractive from a commercial perspective as other laser applications."

It is therefore important for other areas of the quantum community to continue to show progress in making their technologies more mature, so that laser developers can see that the quantum market is sustainable. Ultimately, sufficiently reliable, scalable, and cost-effective semiconductor laser diodes are compelling for many applications. In particular, the scalability of the underlying manufacturing processes of these lasers, as well as the ability to integrate them with other PICs technologies, makes them a commercially favorable technology.

Additionally, according to TOPTICA's Ritter, the nature of the tie that binds visible sources to quantum technologies is such that a boon to one (quantum science or visible sources) is apt to directly correlate to a boon for the other. Quantum technologies, he said, profit from new visible laser sources, especially when they address commercially relevant aspects, such as SWaP-C, and provide a clear path toward scalability.

"Innovations in visible sources will, in return, find very promising and quickly growing markets in the vast field of quantum technologies," Ritter said.

Also, it is critical to understand that distinct applications present different gauges of the significance and influence of forthcoming innovation.

"For quantum computers, scalability is essential to enable the very ambitious road maps regarding increasing the number of qubits. This requires power and reliability to increase, and size and cost to go down. In sensors, for example, some applications are only enabled by a very small footprint, while still others require stability over a broad range of environmental conditions.

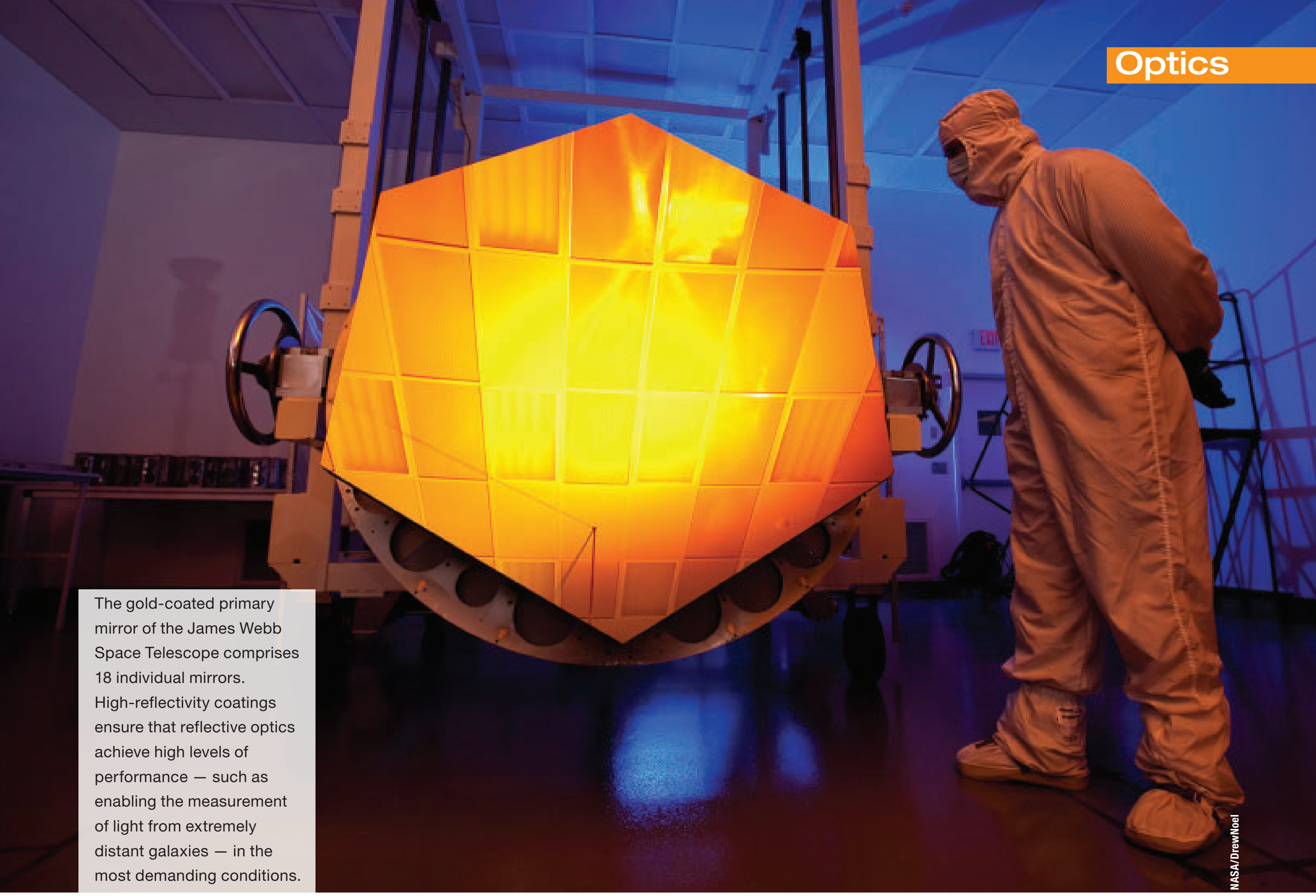
"The interdependence between quantum technologies and laser sources has already proved to be beneficial for both fields, and I expect it to be an even stronger driver of innovation in the future," Ritter said.

For laser manufacturers, the quantum revolution, at least for the moment, could provide fertile ground to finance higher-risk laser developments that may otherwise have decreased in priority.

mariefreebody@physics.org

References

1. M. Corato-Zanarella et al. (2023). Widely tunable and narrow-linewidth chip-scale lasers from near-ultraviolet to near-infrared wavelengths. *Nature Photonics*, Vol. 17, No. 2, pp. 157-164.



NASA/DrewNoel

The gold-coated primary mirror of the James Webb Space Telescope comprises 18 individual mirrors. High-reflectivity coatings ensure that reflective optics achieve high levels of performance — such as enabling the measurement of light from extremely distant galaxies — in the most demanding conditions.

Reflective Optics

Improve in Durability as Applications Increase

Manufacturing trends and product advancements are combined to highlight one of industry's most versatile and widely used optical components.

BY ROBERT BOURDELAIS
MKS/NEWPORT

The range of optical systems in which reflective optics appear is an appropriate indicator of the importance of these components. Mirrors are ubiquitous in the optical bench setups that enable laboratory research across disciplines. Industrial and health and life sciences applications, as well as large-scale optical systems used for astronomy and high-energy physics, also rely on reflective optics. Reflective optics' ability to ensure that a system executes its desired function establishes their role as one of industry's most used optics.

In terms of their parameters, reflective optics are also one of the most critical components to optimize for designers and engineers. Users of systems that include these components must be certain that geometries, as well as the selected materials and substrates, align with the target application. When deployed properly, reflective optics cater to diverse applications — both common and cutting-edge — while delivering high performance.

Currently, mirror technology, much like the applications that it supports, is evolving to meet the increasing needs that industrial, aerospace and defense, and consumer applications place on high-functioning optical systems. In addition to new trends, the ongoing innovation in this technology area extends to capabilities and legacy optical systems that are often overlooked.

What is a mirror?

Simply, mirrors are reflective components. Reflection is broadly defined as the change in direction of a wavefront at an interface between two different media, so that the wavefront returns into the medium from which it originated. According to the law of reflection, when a ray of light hits a surface, it bounces in a predictable way. The incoming angle, called the angle of incidence, is always equal to the angle leaving the surface, or the angle of reflection.

Though all mirrors offer reflective capabilities, the type of reflection in a mirror depends on the mirror's shape and, in some cases, the distance between the mirror and the position of the reflected object. For high-functioning optical systems, the mirrors of choice and those that are used most often, especially for precision optics applications, are "first surface." These components feature a high-reflectance coating that is deposited onto the front surface of a variety of different types of glasses, metals, or semiconductor substrates.

Though second surface mirrors can be manufactured using a similar coating technology, the incident light passes through a transparent substrate material before it is reflected by the coating. This geometry helps protect the coating layer from scratches and oxidization but leads to several issues, such as image distortion, that make this type of mirror unsuitable for most applications in precision optics.

Beyond the shape and surface, configuration is another determining factor of mirror performance. Not all mirrors are flat. Since mirrors can be produced in a variety of configurations, they can be used to provide important reflection characteristics that may benefit certain applications. For example, concave mirrors, commonly found in the largest optical telescopes, are used to collect the faint light signals emitted from very distant parts of the universe. The curved surface concentrates parallel rays from a great distance into a single point, delivering enhanced measurement intensity.

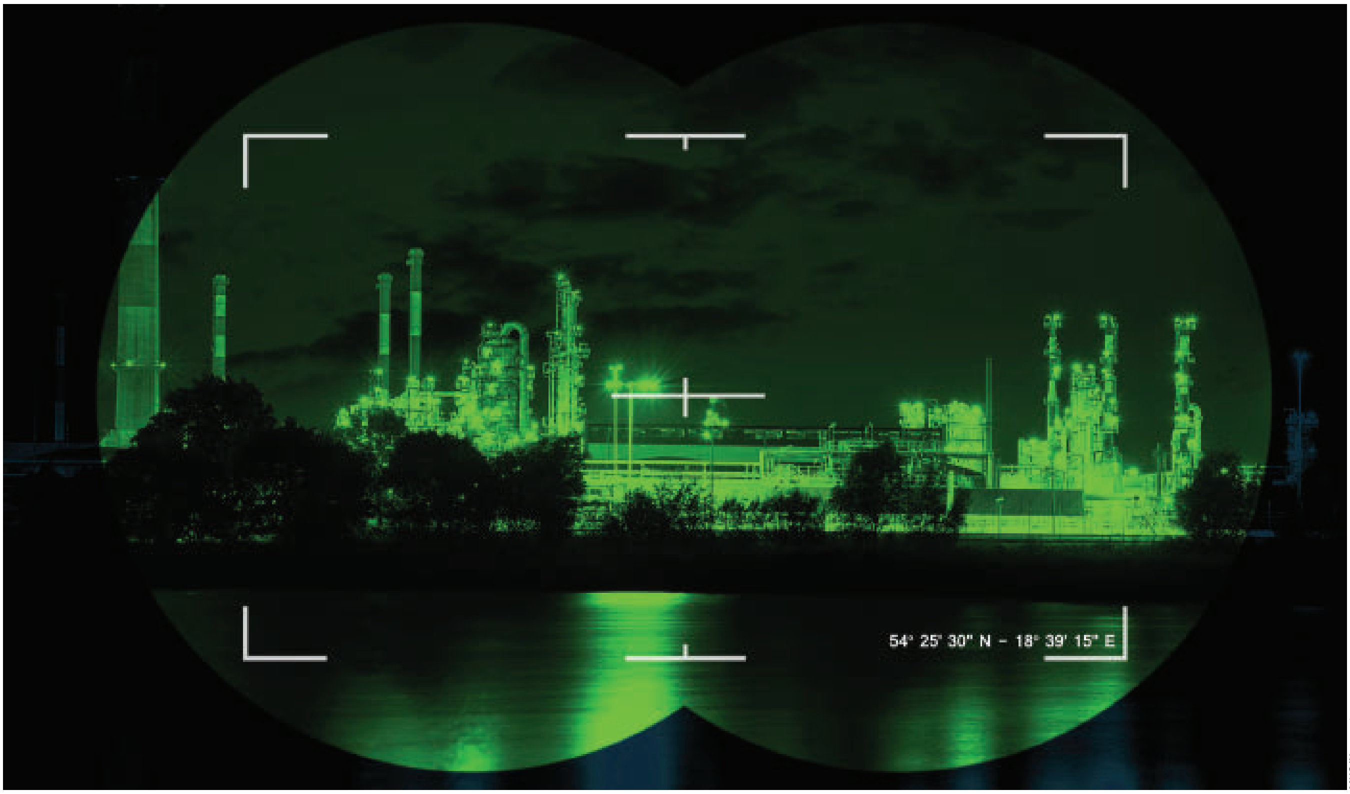
Coating considerations

Several factors must be considered to select the proper mirror for an application, including the application itself. Many characteristics of a mirror, beyond purely physical parameters, depend on the optical coating, substrate, and surface quality. Factors that influence the mirror and system performance are coating durability, thermal expansion of the substrate, wavefront distortion, and scattered light. Measures of reflectivity and laser damage resistance must also be considered.

Because the optical coating dictates reflectivity and durability, it is the most critical element that influences how a mirror performs in application. High-performing mirrors are commonly coated with a thin film. These thin-film coatings are typically comprised of either metallic or dielectric materials, though certain coatings use both types of materials.

Metal coatings consist of thin layers

Optimizing parameters such as materials, substrates, and geometries is critical to ensure the desired performance of a mirror, especially in precision applications.



MKS/Newport

Military and warfighter applications, such as night vision, are among the extreme-environment applications that use mirror and reflective coating technology **(above)**.

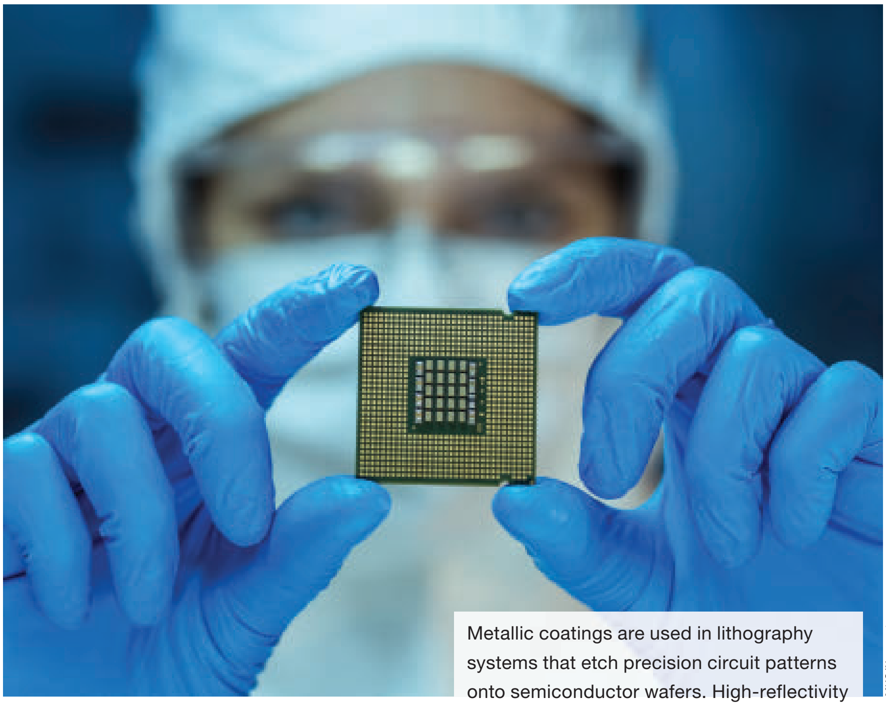
MKS/Newport

Mirrors are used for laser-based satellite-to-satellite communications — one of several aerospace sector trends permeating reflective optics technology **(right)**.

of silver, gold, aluminum, and/or other metals, coated onto the surface of a substrate. The metal layers interact with the incident light, causing it to reflect off the surface. The result is a mirror-like surface that reflects light with high efficiency, which is crucial for applications, such as space communication and semiconductor lithography, that require very precise light control.

In most circumstances, metal coatings are very delicate, especially without the addition of a protective layer. They also require extra care during handling and cleaning; clean, dry air is typically the material that must be used to clean the surface of an unprotected metal coating, though certain contact methods may be acceptable.

Fabricators can overcome this drawback with the application of a dielectric overcoat on a metallic mirror, which allows for improved handling of the component, increases the durability of the coating, and provides protection from oxidation — all without inducing any qualities that could negatively affect the performance of the coating. The dielectric layer(s) can also be designed to enhance the reflectance of the metal coating in



Metallic coatings are used in lithography systems that etch precision circuit patterns onto semiconductor wafers. High-reflectivity coatings are also used in semiconductor manufacturing to increase the efficiency of inspection processes.

MKS/Newport

specific spectral regions. Isopropyl alcohol or acetone can be used to clean the protected metal-coated mirrors.

Dielectric thin-film coatings consist of a stack of numerous thin layers. Often, the thickness of each one is one-quarter of the wavelength of the material in use. Typically, the layers alternate between two or more materials of varying refractive index.

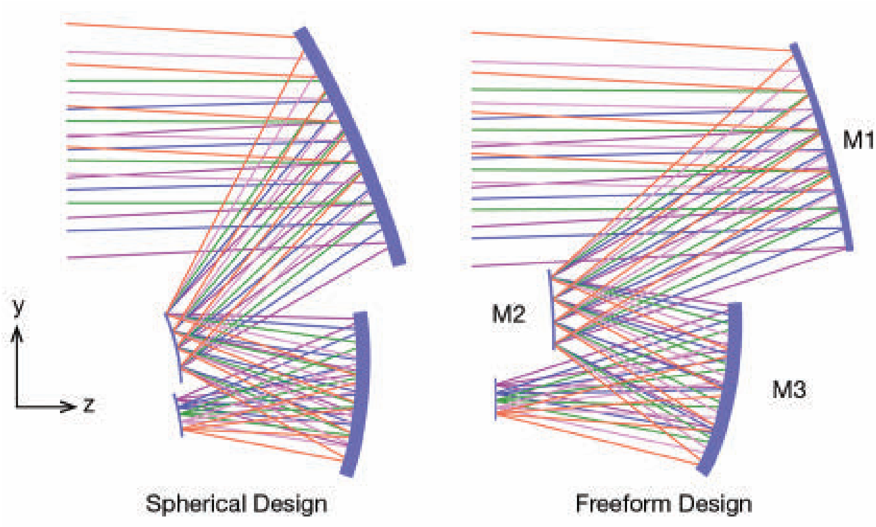
Optical interference is the mechanism by which dielectric thin-film coatings reflect light. Constructive interference of all the reflected light at each material interface combines to yield high reflectance at the desired wavelengths. In fact, the materials themselves may not be reflective at all.

In addition to advantages in durability and accessibility, such as being easier to clean, mirrors with dielectric coatings are also more resistant to laser damage. However, because of their dispersive and predominantly real indices of refraction, dielectric mirrors have a narrower spectral reflectivity and are most often used in the visible and NIR regions. Still, the design of dielectric coatings offers greater flexibility than the design of metallic coatings. Compared with metallic mirrors, a dielectric mirror can offer higher reflectivity relative to certain spectral ranges and can offer a customized, tailored spectral response.

Substrate fabrication

Various techniques are used to apply mirror coatings, and the specific approach is selected based on the required performance of the mirror and the envisioned application. Commonly used techniques include physical vapor deposition, chemical vapor deposition, and sputter deposition. These processes create thin, uniform, defect-free layers of metal on the substrate, enhancing the highly reflective coating on the surface.

Most substrates on which the coatings are deposited are made of dielectric materials, and these substrates control the thermal expansion and transmission properties of mirrors. Certain materials, such as borosilicate glass or fused silica, have lower thermal expansion coefficients than other optical glasses, which, while favorable for certain applications, may not always supersede or outweigh considerations to the cost of the substrate material



The differences in freeform mirror design compared to the conventional spherical design: A freeform surface lacks rotational and translational symmetry **(left)**. In contrast, spherical surfaces are rotationally symmetric in all axes. Aspheric mirror optics typically have a singular axis of rotational symmetry.

Telescopy and space applications are core use cases for reflective optics, such as those used in the James Webb Space Telescope's primary mirror **(below)**.

and ease of polishing, for example. If it is not required to transmit light through the substrate, the back side of the substrate is usually ground to prevent inadvertent transmissions. However, for transmissive mirrors, a substrate material, such as fused silica, with a homogenous index of refraction, becomes an important material.

Reflective optics are typically either directly machined into the substrate using diamond turning or are thin-film coated. Single point diamond turning is the mechanical machining of precision elements using lathes or other machines equipped with diamond-tipped tool bits. Diamond-turned reflective optics may also require post-polishing to achieve the required surface finish. Five-axis diamond turning machines are a relatively recent advancement and have been instrumental in helping to meet customer demand for freeform products.

Surface roughness measuring <100 Å can be achieved for high-precision diamond turning. With a lower surface roughness, an optic will display minimized scatter in the visible spectrum. However, if an application uses light from the lower end of the visible spectrum, 100 Å may be an unacceptable level of scatter. The roughness of the highest precision diamond-turned components can be brought to <50 Å and can be further improved by post-machining plating.

Mirror substrates can also be ground and polished to a desired shape, either planar or curved. The surface quality and flatness determine the fidelity of the mirror performance, and the target application dictates the requirements for these parameters.

Surface flatness is often specified in wavelengths, for example, $\lambda/10$, over the entire usable area of the mirror. In instances in which it is critical to preserve the wavefront, a $\lambda/10$ to $\lambda/20$ mirror should be selected. Less demanding applications can tolerate a $\lambda/2$ to $\lambda/5$ mirror with the associated reduction in cost.

The severity of random localized defects on the surface often dictates overall surface quality, which itself is often quantified in terms of a "scratch and dig" specification. Typically expressed as a numerical set, a lower value — 20-10, for example — indicates improved quality and lower scattering as a result.

For high-precision surfaces, such as those found within the cavity of a laser, a scratch-dig specification of 10-5 may be required. Such a value would yield very little scattered light. Other measurables, such as surface polishing tolerances in terms of irregularity, surface roughness, and cosmetic imperfections, are verified using the latest iterations of advanced metrology equipment. These same parameters and procedures are used to assess the quality and flatness of other optical components, such as lenses or windows.

Driven by application

As much as reflectivity and other design considerations influence mirror technology, the end use or application is typically the core determinant of the type and quality of the mirror found in any system. Several main mirror types, all of which are structured to meet the general yet varying needs of current optical systems, include flat mirrors, off-axis mirrors, Nd:YAG laser mirrors, broadband dielectric mirrors, laser line mirrors, ultrafast laser mirrors, focusing mirrors, infrared mirrors, and hot/cold mirrors. Each option offers distinct advantages for applications spanning industry sectors.

For example, in the health and life sciences market segment, particularly in biomedical technology, metal-coated optical components are found in laser devices used for surgery and diagnostics. For these applications, mirror coatings help to direct laser beams during various surgical procedures. At the same time, high reflectivity coatings enhance the performance of diagnostic equipment, such as microplate readers, Fourier transform instruments, and flow cytometry systems.

In the aerospace/space industry, metal-coated optical components play a similarly vital role. Mirrors are a critical component for laser-based satellite-to-satellite communications. Also, high-reflectivity coatings are used in space telescopes, such as the Hubble, to observe distant astronomical objects. The primary mirror of the James Webb Space Telescope, for example, a collaboration between NASA, the European Space Agency, and the Canadian Space Agency, features an enormous, gold-coated component. The mirror comprises 18 smaller mirrors that allow mission teams to use the scope to measure light from extremely distant galaxies located billions of light-years from Earth.

Reflective components are also embedded in systems that support a range of advanced military technologies in the defense sector. These include tracking and sighting systems as well as other laser systems. Mirror coatings are often used in periscopes, night-vision devices, and laser guidance systems. Such robust metallic coatings can withstand the rigors of battlefield conditions and provide reliable performance.

The extreme environments encountered in defense applications are not the only ones in which metallic coatings deliver the necessary capabilities for demanding applications. In the semiconductor industry, metal-coated components are essential for chip production. Specifically, metallic coatings are used in lithography systems that etch small precision circuit patterns onto semiconductor wafers. High-reflectivity coatings are also used to increase the efficiency of the many inspection processes in semiconductor manufacturing.

Trends and markets

Optimized systems reside at the intersection of optical component design and application knowledge. Working with an experienced and knowledgeable optical component partner often yields outsized results, enabling superior systems-level performance.

This dynamic is critical; often, standard catalog mirrors are not sufficient for meeting the needs of highly functioning optical systems. Proper design and application of individual components in an optical measurement system ensure the highest level of instrument performance.

There are other benefits stemming from this intersection. Currently, for example, freeform mirrors are beginning to find use in commercial and lower-cost optical systems that retain high levels of performance. A freeform is a surface that lacks rotational and translational symmetry. As shown geometrically in the first figure on the previous page, this sharply contrasts most traditional optics that employ spherical surfaces — which are rotationally symmetric in all axes (a sphere has no vertex) — and aspheres, which typically have a single axis of rotational symmetry.

This lack of symmetry in a freeform enables more sophisticated control over ray paths than what would otherwise be achievable. This feature allows freeform surfaces to correct aberrations more effectively than traditional optics, such as the off-axis aberrations that are common in wide-field and high-resolution imaging systems. This capability translates into higher throughput and superior image quality, with increased sharpness and contrast across a wider field of view. Applications from microscopy and spectroscopy to imaging and advanced surveillance are among those that benefit as a result.

The efficacy of freeforms in diverse applications has contributed to a heightened focus on manufacturing, and replication techniques in particular. Newport uses advanced precision replication processes that center on the use of a high-fidelity master from which exact copies are made at high levels of quality and efficiency. In the replication process, the master is produced with a very high degree of fidelity in terms of overall surface accuracy and surface roughness. This replication process serves to erase any tooling marks and midspatial frequency surface errors that may be originally present on the replica substrate surface. Typical specifications for these replica parts are λ/8 surface figure and a scratch-dig of 40-20.

The rise of adaptive optics technology is furthering another trend into the realm of reflective optics. Liquid mirrors, which gained favor for their use in telescope systems, are poised to return to mainstream use due to a series of developments that allow them to act like adaptive optics systems — while bypassing the price tag that is associated with adaptive optics. Using a ferromagnetic liquid, instead of mercury, multiple research groups have demonstrated deformable liquid mirrors. Adaptive optics use state-of-the-art, deformable mirrors that are governed by computers that can adjust, in real time, for the optical distortion caused by turbulence in the atmosphere to create images of celestial objects. These images are almost as sharp as those captured in space. Adaptive optics enable a reflective telescope to see much finer details than what would otherwise be achievable from ground-based telescopes.

Elsewhere, computer superpolishing fabrication and precision ion beam sputtered technology are increasingly enabling the design of high-energy laser mirrors. These components are designed to provide a combination of high laser damage threshold, ultralow scatter, excellent wavefront performance, and rugged mechanical durability.

High-energy laser mirrors are highly reflective and environmentally stable. As a result, they are used in demanding applications, such as military targeting and micromachining, industrial materials processing systems, intracavity lasing, and high-energy research lasing. Mirrors used in the Advanced Photon Source (APS), for example, face the most demanding conditions in the world. To preserve the qualities of the beam, the mirrors must be almost perfectly smooth. This requirement exceeds traditional mechanical chemical polishing and necessitates that atoms are removed from the mirror surfaces one by one.

High-energy laser mirrors are custom fabricated and coated with typical specifications of >99.5% reflectivity, λ/20 flatness (measured at 633 nm), and a scratch-dig of 10-5. In the case of the mirrors used in the APS, only a handful of companies currently manufacture these optics.

One of the most active areas of product development involves multispectral narrowband and broadband (UV through IR) applications, such as fluorescence and spectroscopy. Broadly speaking, markets such as biomedical instrumentation and semiconductor processing are fueling the use of the UV spectrum. The nature of UV applications has changed dramatically during the past decade, primarily due to the availability of higher-power light sources at shorter wavelengths. The result is a wave of product development in UV reflective optics that relies on the latest design, analytical, and production techniques to optimize performance.

Designs for these UV applications can either be refractive (lens-based) or reflective (mirror-based), though reflective systems are drawing more interest. Reflective systems are fully chromatically corrected by nature, making them a cost-effective option for extremely broadband transmission. A drawback is that these systems can correct for only small angular fields.

Meet the author

Robert Bourdelais is senior global business manager for MKS/Newport. He has more than 30 years of industry experience, including in engineering, R&D, operations management, and product management. He is also the author of more than 200 issued patents; email: robert.bourdelais@mksinst.com.

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Photonics Charts Its Course in Helping Athletes Reach Peak Performance

High-speed imaging, lidar, and virtual reality are among the technologies that athletes, coaches, and analysts are using to optimize strength and skill on and off the playing field.

BY MICHAEL EISENSTEIN
CONTRIBUTING EDITOR

Michael Matter's journey into sports technology began with a golf ball. More specifically, a photo of a golf ball that was captured at its precise moment of impact with a club head. The photo — shot by Harold "Doc" Edgerton, the legendary high-speed photography pioneer — showed in detail how the connection flattened the round, rigid surface of the ball.

As a boy, Matter was an enthusiast of both photography and electronics and aimed to replicate Edgerton's stroboscopically achieved imaging feats. "I figured out how to modify a $20 electronic flash to get it from being about a 2-ms flash duration down to about 10 µs," Matter said. In subsequent years, Matter worked with Edgerton at MIT. Eventually, he parlayed his engineering expertise into the Edgertronic series of high-speed cameras.

Decades later, these cameras — produced by Sanstreak, the company that Matter founded in 2012 — are a mainstay of the baseball world. This imaging technology is a leading example of how sophisticated optics and photonics technologies are literal game-changing forces in sports. Fittingly, the post-2015 period in Major League Baseball (MLB) is sometimes referred to as the "Statcast era"; high velocity and precision control are making pitchers increasingly difficult to hit, and, as a result, hitters are inviting nontraditional, technology-based tools to improve their performance. The Statcast name is also an acknowledgment of how this now-ubiquitous platform for camera-based tracking and analysis of gameplay has transformed the game.

Beyond the baseball diamond, athletes in many other sports are enjoying a similar high-tech boost. Basketball, soccer, American football, and gymnastics are among other sports using motion capture, lidar tracking, and VR to optimize performance and develop winning strategies, and team managers, owners, and coaches are scrambling to stay at the leading edge of the technology curve. "There's a huge number of data scientists each year being recruited by [soccer] clubs," said Ian Cowling, CTO of Bicester, England-based Sportlight Technology. "But there are also a lot of problems to solve, and I've not heard of a club who's got enough data scientists yet," Cowling said.

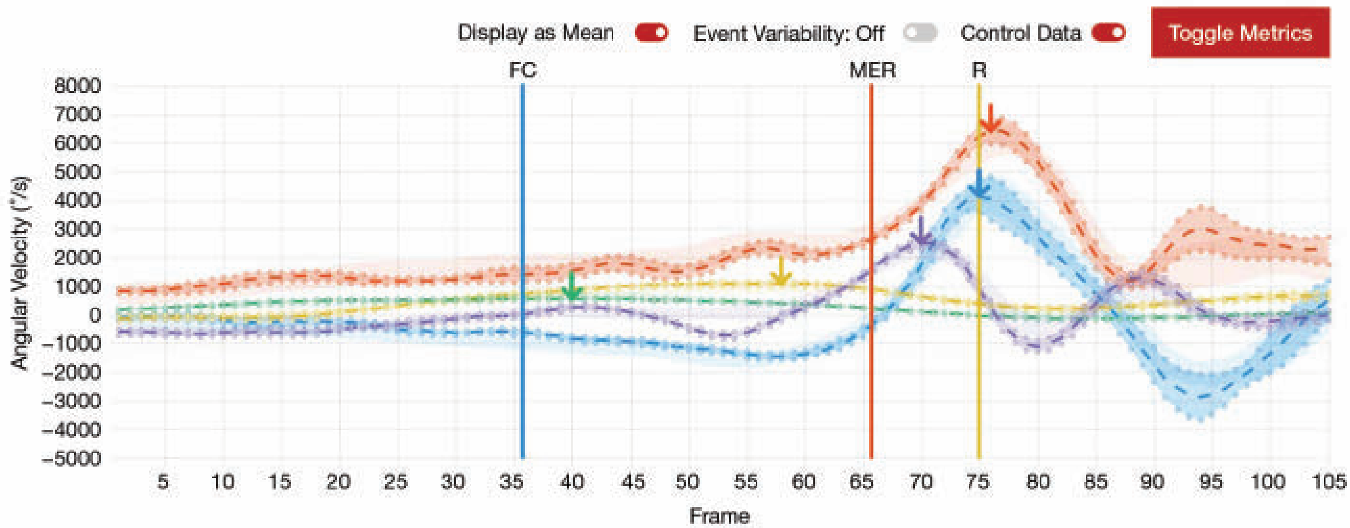
Caught in the act

Perhaps unsurprisingly, Matter's original vision for Edgertronic in the sporting world was for the technology to aid golfers in refining their swing. But the super-slow-motion analysis enabled by his cameras, which can deliver 720p-resolution images at >700 fps, is overkill here. "Ninety-nine percent of golf is like, 'Is your swing good? Keep your head down. Did you follow through?'" Matter said. Indeed, several companies, such as motion capture and 3D visualization technology developer Uplift, now offer software that enables golfers to carefully analyze their swing based on videos captured with a standard iPhone or iPad.

KinaTrax

KinaTrax

KinaTrax's markerless motion capture technology for baseball captures ultrahigh-resolution video at high frame rates to deliver insights on mechanics, movements, and other parameters to pitchers and hitters.



Pelvis		Trunk		Elbow		Shoulder			Hand		
Average Max	Average Timing (FC to Max Pelvis)	Average Max	Average Timing (Max Pelvis to Max Trunk)	Average Max	Average Timing (Max Trunk to Max Elbow)	Average Max	Average Timing (Max Elbow to Max Shoulder)	Average Timing (Max Shoulder to BR)	Average Max	Average Timing (Max Shoulder to Max Hand)	Average Timing (Max Hand to BR)
583°/s	−8 ms	1131°/s	70 ms	2511°/s	51 ms	4403°/s	14 ms	4 ms	6512°/s	5 ms	−2 ms

KinaTrax

Output data from KinaTrax's "kinematic sequence" charts the relationship between frame and angular velocity as it relates to the motion mechanics of a baseball player in action.

Rezzil

VR-based training programs from Rezzil simulate competition scenarios. The technology can artificially augment the capabilities of a user's opponent to improve situational performance.

Edgertronic burst onto the MLB scene in 2015 when a young pitcher started experimenting with Edgertronic, using the ultrahigh-speed images to study his posture, grip, and release. "He said this camera let him invent new pitches," Matter said. Enthusiasm for the technology quickly spread, much to the benefit of the company. "You can pay half a million dollars to a New York ad agency and they wouldn't come up with anything as good," Matter said.

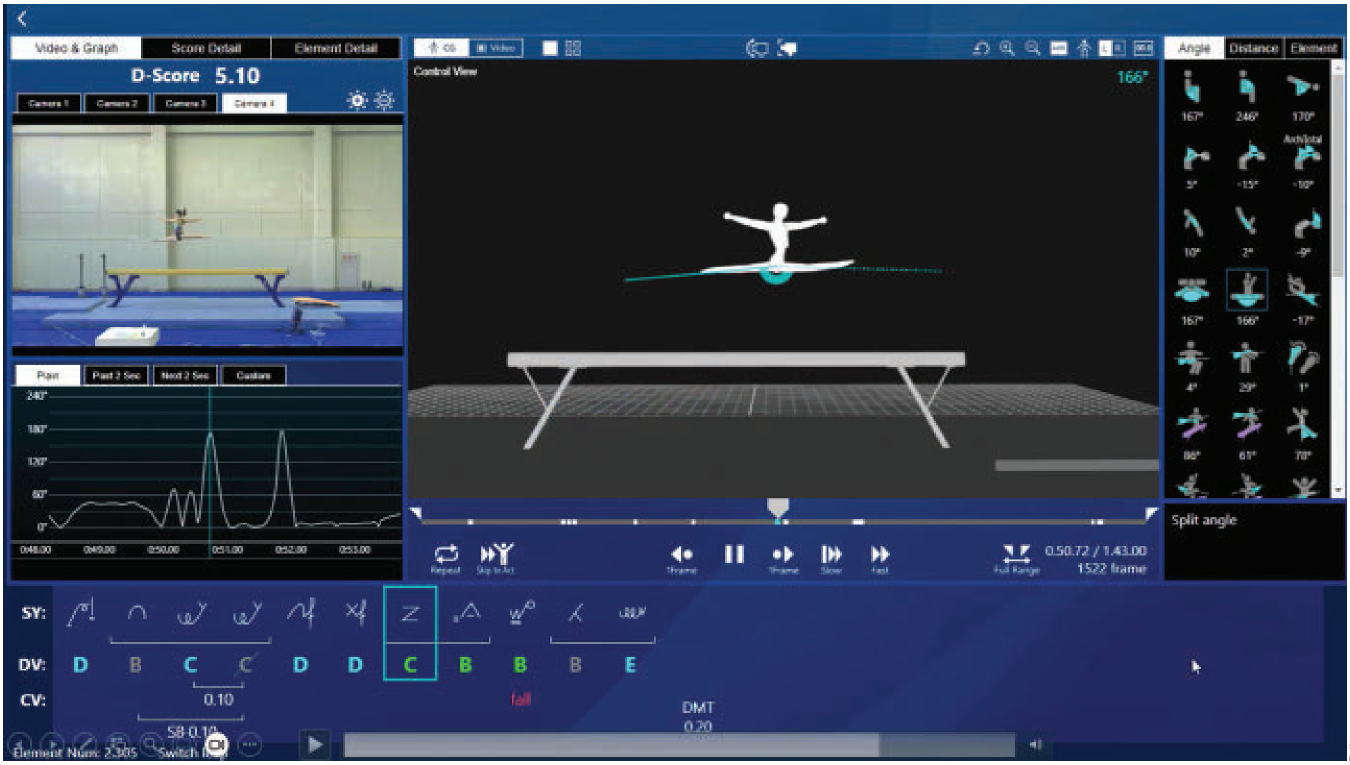
By 2019, the technology had become widespread in the Big Leagues, and MLB published an article calling the cameras one of the technologies that is "changing baseball." According to Matter, most teams have three or four cameras, though he said that one organization uses more than 200, with installations at its training and minor league facilities. The cameras are routinely used in-game to allow players and coaches to carefully review the posture and performance of both pitchers and hitters at every at-bat.

This technology can also be combined with other technologies used in the baseball world, such as the radar-based pitch tracking systems developed by Rapsodo, which MLB uses to measure ball speed and trajectory in-game. This pairing reveals insights into how subtle changes in timing, posture, grip, and/or movement influence the motion of a thrown or hit ball.

Player tracking up to speed

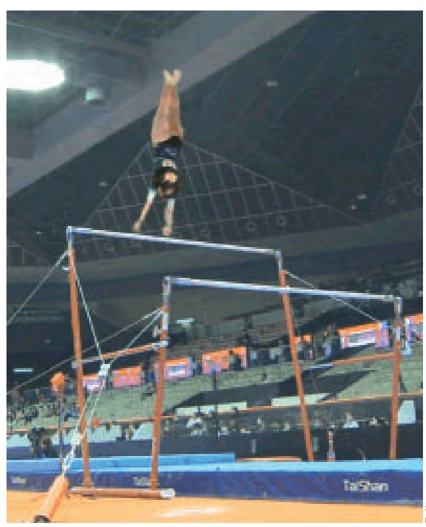
One limitation of Edgertronic technology is that it can only monitor individual players in a relatively fixed position. Though Matter said that the cameras have found situational use in other sports — for example, foul shot and three-point shooting in basketball and placekicking in football — other systems are needed to capture the hectic multiplayer action that is characteristic of most team and individual sports.

Many top leagues currently use large arrays of networked cameras strategically positioned at key sites in stadiums or arenas. These cameras capture complete game action, in high detail, and the resulting data is interpreted algorithmically to identify specific players and reconstruct their movements. Major companies in the

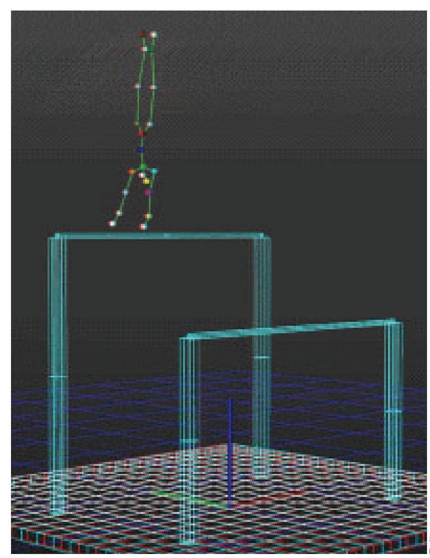


Fujitsu

Information displayed on Fujitsu's Judging Support System (JSS) screen **(above)**. The left side of the image shows the video data and the height and body angle of the elements performed by the athlete in a timeline. The right side displays the athlete's movements in 360°. The lower part of the image displays each element performed and a characterization of its difficulty.



Fujitsu


Fujitsu

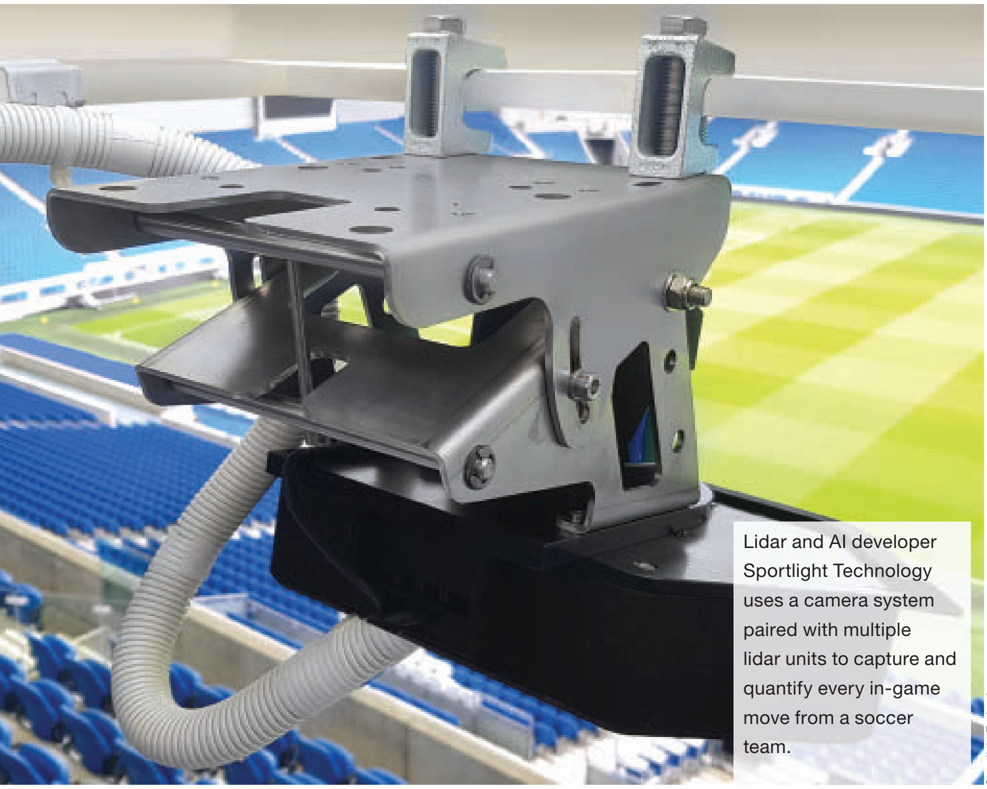
Fujitsu's Judging Support System (JSS) tracks the movement of a gymnast in action **(right)** and precisely captures the position of individual body parts in relation to the uneven bars **(far right)**.

"player tracking" space include Tracab, whose systems are widely used in soccer, and Hawk-Eye Innovations, which is currently employed by the MLB Statcast system and is also a strategic partner of the National Basketball Association (NBA).

Yet while cameras thoroughly document the action of a game, they cannot always precisely quantify the speed and trajectory with which players move and change direction. Cowling and colleagues at Sportlight see lidar as a powerful adjunct for this purpose. The detection and ranging technology delivers accurate measurements of object position and velocity by analyzing the reflection of invisible infrared lasers.

Lidar is widely known and used in the automotive sector, and the rapid growth of lidar in this industry has been a boon to Sportlight's penetration into athletics, resulting in falling costs for sensors that also deliver steadily improving spatial and temporal resolution. Its current lidar units collect >1 million measurements per second, enabling the simultaneous measurement of every player's movement on the field. One peer-reviewed study from 2022 confirmed the precision of its system: The level of error on player velocity readings was on the order of ~10 cm/s, according to the study[1].

Lidar is not the only technology used to provide such analysis. Certain teams use GPS for this task, Cowling said. However, GPS performance can be inconsistent



Lidar and AI developer Sportlight Technology uses a camera system paired with multiple lidar units to capture and quantify every in-game move from a soccer team.

Sportlight Technology

in different areas of the field, leading to incomplete data on player movement. “Sometimes the wide players aren’t tracked for 60% to 70% of the game because GPS signals don’t get through,” Cowling said. In contrast, one or two lidar units combined with a standard camera system can capture and quantify every movement.

“‘What condition are my athletes in, how have they moved over the week, how are they moving at mid-season compared to the start of the season?’ Those are the sorts of questions that we can work on,” Cowling said. According to Cowling, 19 of the 20 English Premier League soccer teams currently use Sportlight, and the company recently began working with the NBA to assess the technology’s applicability to basketball.

Picking up the pieces

To obtain the most accurate performance analysis of an elite athlete, one must carefully analyze each component piece of the athlete’s body as it moves through space and rotates while pitching, catching, kicking, or leaping. Motion capture technologies, which algorithmically analyze video footage and reconstruct a virtual “skeleton” that mimics the anatomy of an athlete in action, have immensely benefited this sort of biomechanical analysis. The resulting insights can help players hone their performance and track progress in recovering from injury and reduce the risk of future traumas.

Many biomechanics labs and training facilities use marker-based systems that require athletes to undergo precise tagging with labels, which the analytical software can use to recognize and track individual body parts for subsequent reconstruction. Marker-based methods are well established and can be powerful tools, but they also require expert supervision and may not capture real-world performance. These require athletes to undergo precise tagging with labels that the analytical software can use to recognize and track individual body parts for subsequent reconstruction. “It’s unnatural,” said Scott Coleman, director of sales and marketing at KinaTrax. “They’re in their underwear, they have all this stuff on, and then it takes hours and hours.”

KinaTrax is one of several companies offering markerless motion capture, with a primary focus on baseball. According to Coleman, approaches such as those developed by KinaTrax have been enabled by the development of sophisticated digital cameras that capture ultrahigh-resolution video at high frame rates; KinaTrax's current systems operate at 600 fps. The systems analyze the acquired data via an AI algorithm that has been trained to recognize key landmarks on the players' bodies and convert them into a 19-segment biomechanical model. These systems can analyze player performance in actual games without disrupting the athletes' routines.

A typical KinaTrax system setup for baseball involves positioning eight to 16 cameras between the left field and right field foul poles and home plate. The technology generates complete biomechanical profiles for every pitch and at-bat in a game. Among the measurables that the system gauges, Coleman said, are player kinematics and kinetics, temporal and spatial values, step width, step length, and stride.

KinaTrax is currently used by 20 MLB teams, along with numerous minor league teams and training facilities, Coleman said. The company aims to extend motion capture to every single baseball player on the field during the next several years. It is also looking into extending its offerings into other sports, with preliminary work underway in the NBA and National Hockey League. These sports will pose a thornier challenge than baseball, however, with more movement and opportunities for occlusion of the camera's view by other players, officials, and fans.

AI assists gymnastics judging

Athletes and coaches are not the only ones benefiting from markerless motion capture. Japanese technology company Fujitsu is demonstrating how this technology can turn the art of judging gymnastics into more of a precise science.

According to Shoichi Masui, a senior research expert at Fujitsu, the company first launched a project to optimize athletics judging following a remark made by the head of the International Gymnastics Federation (FIG) during a meeting in 2015 with Hidenori Fujiwara, head of Fujitsu's sports business division. "He jokingly said, 'In the future, maybe robots will be doing the scoring,'" Masui said. "[But] Fujiwara took the joke seriously and built a prototype."

Fujitsu debuted its first-generation Judging Support System (JSS) a year after the meeting. The system used lidar to scan gymnasts' bodies and generate a 3D contour map, which was then computationally converted to a simplified skeleton that can be analyzed to assess posture and form. During the next few years, the then-high costs of lidar drove the company to transition to a multicamera-based system, coupled with a more sophisticated AI-based algorithmic platform.

According to Masui, Fujitsu also grappled with significant imaging challenges that confounded analysis in earlier iterations of JSSs. These included the blurring of joint positions as estimated by the AI-assisted skeleton recognition algorithm, and the preparation of the training data for the AI system. The Fujitsu team ultimately resolved these bottlenecks with algorithmic tools for error-correction and the production of computationally generated synthetic — though highly photorealistic — training data.

Fujitsu first deployed JSS for pommel horse competitions. The concept was that this event would provide a viable testbed because of the relatively limited performance area compared to other gymnastics events. "We later realized that we had actually started the development with the most difficult apparatus even for gymnastics judges," Masui said.

But the system proved to be a success nonetheless, and Fujitsu has been a partner with the FIG since the start of its development in 2016. In 2019, Fujitsu provided its first official showcase of the JSS at the Artistic Gymnastics World Championship in Stuttgart, Germany. At the time, the platform was limited to only four events — pommel horse, still rings, and men's and women's vault. Fujitsu has subsequently expanded JSS to enable judging support for all 10 standard gymnastics apparatuses, and Masui said that the FIG has expressed its intent to continue to use this platform to assist its human judges in future events.

The implementation of the technology, Masui said, shows a combination of technological and practical innovation. For judges at major competitions, he said, "long hours spent deliberating are the norm, but a technology that offers objective information to help support scoring could help streamline that process."

Getting into the game

Finding better and smarter ways to train is a universal goal for athletes and coaches. The challenge is to find regimens that realistically test and bolster the skills that players need on game day.

"Players don't generally feel the pressure when they're training," said Andy Etches, cofounder and sports director of Manchester, England-based Rezzil. The company is developing VR-based training programs that simulate real competitions, or even crank up the difficulty by artificially augmenting the performance of a user's opponents. "If they're playing in a friendly game, they know they're playing in a friendly game, and so getting them to react in a natural way is really difficult," Etches said.

It takes a lot of refinement to make VR training appealing for athletes. Etches said that some simulators focus purely on what the players see but do not incorporate their physical movements. This level of artificiality takes them out of the experience and can also contribute to unwanted side effects such as motion sickness, which could deter many new users from embracing the simulator.

"We use devices that are capable of six degrees of freedom and that have high refresh rates and enough computing power behind them to give realistic responses," Etches said. Since the VR setup is designed to respond to actual player movement, it can be combined with biomechanical analysis to provide additional layers of insight into player performance.

The company's current focus is on soccer, and Etches said that every team in the English Premier League is currently using Rezzil as a part of their training regimen. The company has even designed drills tailored to build essential skills such as scanning — the rapid visual information-gathering process that players perform before making a play. VR also offers a safer way to practice skills that are essential in-game but potentially harmful if practiced repeatedly off-field, such as heading a ball. Rezzil has also paired with the NBA and at least one football team in the U.S. to build specialized regimens ftor basketball and football, respectively.

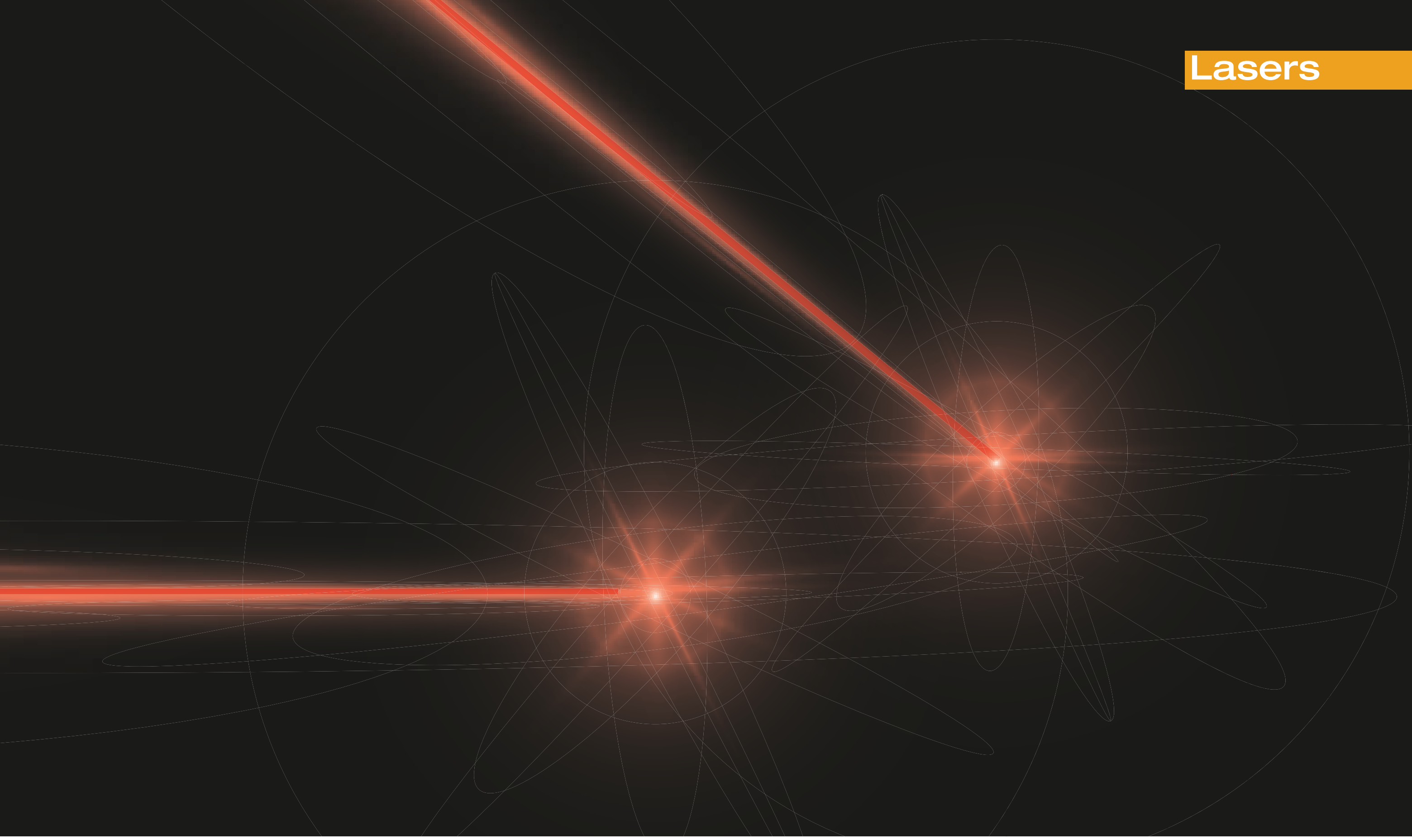
Etches is excited about how the platform might bring fans closer to the game, too. The company recently signed a deal that will allow them to pull the data from future matches into their VR platform, allowing both professionals and amateurs to relive those games firsthand.

"A lot of fans sit at home and go, 'Oh, I could have scored that,' and we'll go, 'OK then, here's the ball coming at you at 80 mph,'" Etches said. "I think it will bring people closer to the game."

michael@eisensteinium.com

References

1. T. Bampouras and N.M. Thomas (May 2022). Validation of a LiDAR-based player tracking system during football-specific tasks. *Sports Engineering*, Vol. 25, No. 8.



Waveform Dynamics Sharpen Laser Scanners for Imaging Applications

Selecting the proper waveform and scan pattern are core considerations for imaging applications to ensure that the laser scanner performs its target function at high levels of accuracy.

Image on this page, courtesy of iStock.com/Dmytro Naumov.

BY WILLIAM R. BENNER JR.
SCANNERMAX

Many photonics systems and methods require projecting lasers over an area of interest so that the reflected light can be sensed and interpreted. Among the most prominent examples are in the realms of imaging and ranging. These include confocal microscopy, lidar, and optical coherence tomography.

Techniques such as these support a range of industrial and biomedical applications. For each, the use of laser scanners is imperative to achieve system functionality.

Depending on the application, different waveforms can be used with laser scanners. The selection of the proper waveform to drive the scanner is vital to achieving the widest scan angle and the best possible image quality.

Laser-scanning fundamentals

There are three ways to move a laser beam to scan a pattern over an area of interest. The beam can be diffracted, which is achieved using acousto-optic (AO) beam deflectors; it can be refracted, using electro-optical (EO) scanners, such as Pockels cells; and it can be reflected, usually off a mirror mounted on a motor. Each method scans a line in 1D. Two scanners can be coupled to complete a scan of a 2D area.

Although AO and EO devices reach favorable scan speeds up to ~100 kHz, both mechanisms present drawbacks. Notably, the scan angles that the devices offer are only a few degrees or less; beam size is limited to a few millimeters; and, for AO devices specifically, they cannot scan multiple wavelengths simultaneously. AO devices also fail to deliver desirable levels of optical throughput.

Reflection scanning is performed by mechanical scanners rotating a physical mirror. This allows a wide scan angle that can exceed 90°, with beam diameters of up to 50 mm. Optical throughput is typically very high, and multiple wavelengths can be deflected simultaneously.

However, because a physical mirror is being moved during these scans, mechanical scanning is slow relative to the AO and EO methods.

Galvanometer scanners

Three forms of scanning exist under the umbrella of mechanical scanning: polygon, resonant, and galvanometer. Polygon and resonant scanning use mirrors to scan the same area repeatedly, typically at fixed angular amplitude(s). In contrast, galvanometer scanning systems can position a beam anywhere within the scan area at any time — making them the most versatile type of mechanical scanner.

Galvanometer scanners are widely used in imaging applications due to their high flexibility. Commonly, end users deploy

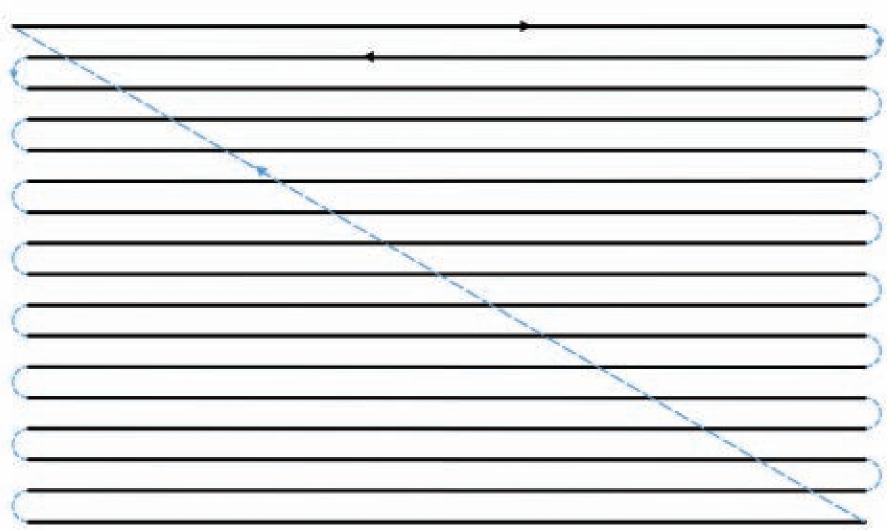


Figure 1. In this raster scanning system, a triangle wave is used on the x-axis with a stepped sawtooth on the y-axis **(above)**. The dark lines represent a constant velocity triangle wave. The dashed blue lines at the edges represent the y-axis scanner stepping downward while the x-axis scanner turns around, amid the final retrace of the y-axis **(dashed blue line)**.

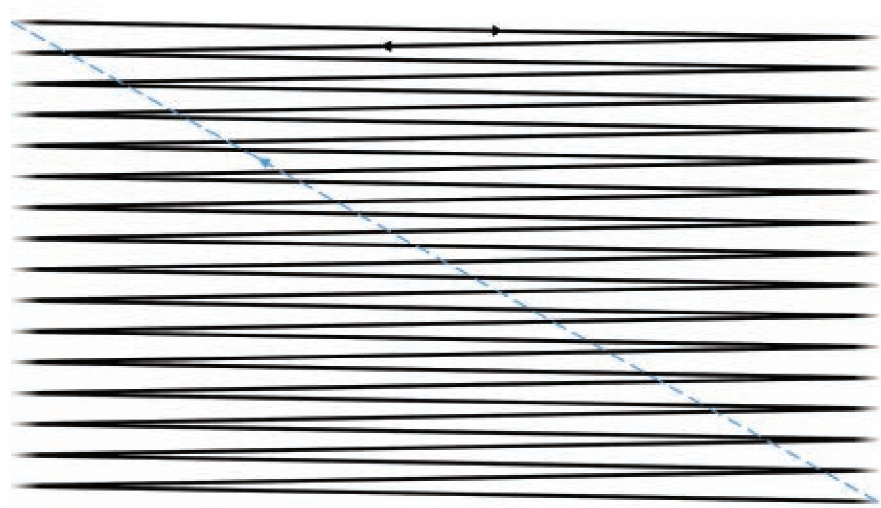


Figure 2. The scan sequence from Figure 1 with the use of a conventional sawtooth instead of a stepped sawtooth **(right)**. The lines in the sequence are diagonal, with the beam direction constantly traveling downward.

Images on this and the following pages courtesy of ScannerMAX via William Benner Jr.

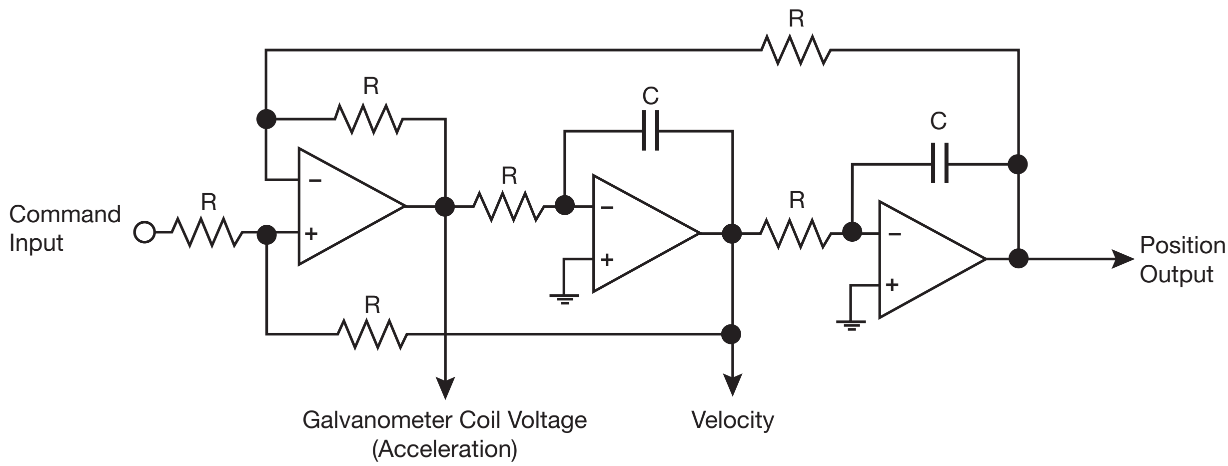


Figure 3. A two-pole low-pass filter model illustrating how the mirror position tracks the command signal, while driving coil voltage in a galvanometer scanning system.

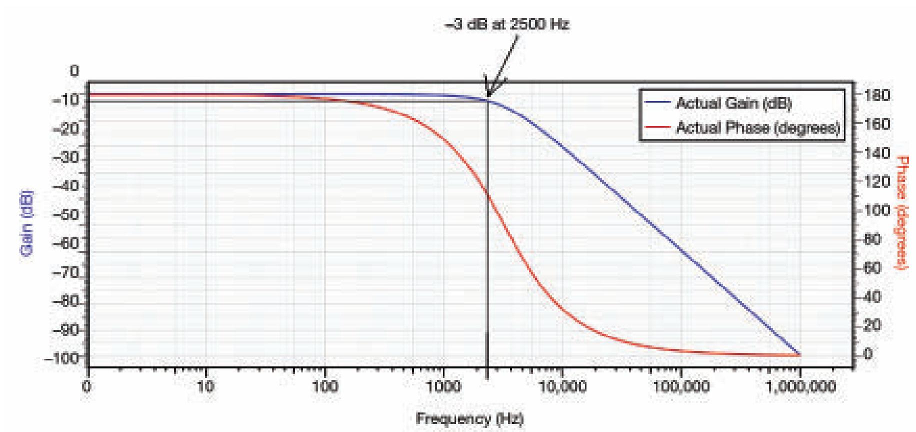


Figure 4. A –3-dB bandwidth of 2.5 kHz is shown as the amplitude of the position signal "rolls off" as frequency is increased. Due to the low-pass filter action, the higher the scan frequency, the greater the roll-off of the real position.

two galvanometers with mirrors on their shafts in combination. In such an architecture, the laser beam is reflected off one mirror, which is scanned horizontally onto a second mirror, which scans vertically. This combination allows the beam to be placed anywhere in a rectangular scan field and allows pairs of galvanometers to draw complex patterns. Supported applications span optical layout templates, or ply alignment, as well as laser projection of vector graphics.

In many cases, end users are unaware of the simple scanning patterns and optimizations that can be used to repetitively scan a beam over an area of interest. With source signals obtained from computer output, a user can easily maintain full control over the waveshape and the relative timing of the x and y signals.

Covering the area of interest

The most common scan pattern for systems and applications is a raster. This pattern features an x-axis scanner, which is responsible for scanning horizontal lines, and a y-axis scanner, which steps the lines vertically down the area of interest. The x-axis moves faster, sweeping the beam back and forth hundreds or even thousands of times per second. The y-axis moves the horizontal lines downward and may be operated in the range of 1 to 100 Hz, depending on the desired number of lines of horizontal sweep.

To generate a raster, the x-axis scanner can be fed with a sine wave, triangle wave, or sawtooth wave as well as by feeding the y-axis scanner with a stepped waveform that positions the y-axis on each next line.

Figure 1 shows a triangle wave driving the x-axis scanner, and a stepped sawtooth on the y-axis. The black lines represent a constant velocity triangle wave and the dashed blue semicircles moving at the edges represent the y-axis scanner stepping downward as the x-axis scanner turns around. The diagonal blue line represents the final retrace of the y-axis.

In this sequence, all the lines remain completely horizontal since a stepped sawtooth is used on the y-axis. Whereas, if a regular sawtooth was used on the y-axis, the beam direction would always be downward, even on the horizontally scanning lines. As a result, the lines would be diagonal using a conventional sawtooth (Figure 2).

Though a galvanometer is not the only option for such a system, an x-y galvanometer scanning system is very useful. For example, it can scan each waveform type and can jump from point to point and hold a position indefinitely if desired for the application. Moreover, galvanometers can change their scan extent to "zoom" into a particular area and can change the offset to "pan" around a prospective image.

Telling the scanner where to go

Galvanometer scanning systems accept an input referred to as the "command" input. The scanning waveforms sine, triangle,

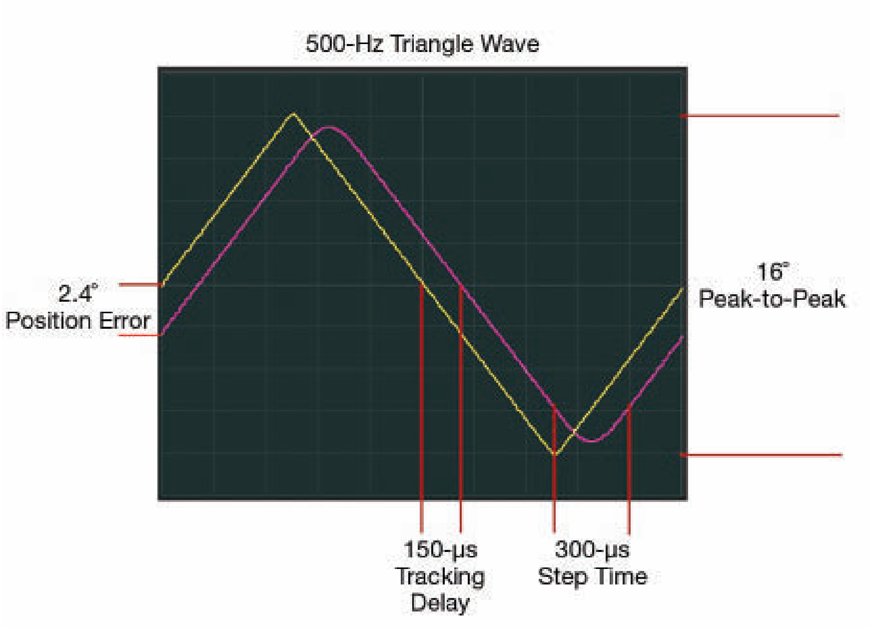


Figure 5. This oscilloscope screenshot shows a 500-Hz triangle wave fed to the command input **(yellow)**, with the mirror position **(pink)** and the delay between command and position.

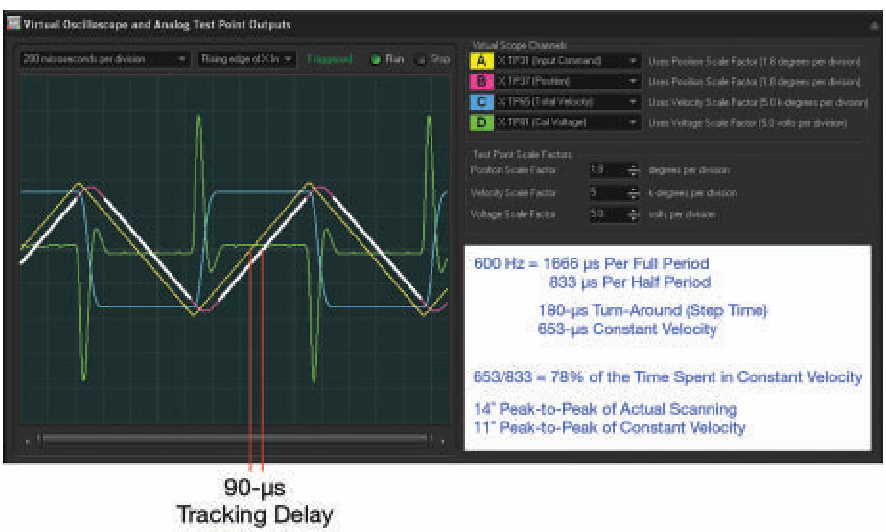


Figure 6. When the beam is traveling at constant velocity **(blue)**, the position is highlighted **(white)**. The velocity is constant, but there are short periods of time when the mirror must slow down, turn around, and speed up again. These areas **(pink)** are not highlighted and correspond with the scanner's step time.

and sawtooth are fed to the command input of the servo system as a periodic series of samples.

The mirror angle that is achieved during scanning is referred to as the position. Since galvanometers are electromechanical systems, the mirror angle (position) cannot instantly achieve the angle requested by the command input. This causes a delay in time between the command and the actual mirror position during operation. For the same reason, the mirror position is unable to completely track the incoming command signal through all amplitudes and frequencies, which are other highly important values influencing the scan system sequence.

In many cases, end users are unaware of the simple scanning patterns and optimizations that can be used to repetitively scan a beam over an area of interest.

Although this dynamic can be easily understood for galvanometer scanners, and indeed all laser scanners, the subject of laser scanning can present challenges. This is especially true for electrical engineers — who are most commonly tasked with integrating these scanners into a product. As a result, conceptual models tailored for these engineers aid greatly in their understanding and quick implementation.

Consider, for example, a properly tuned galvanometer scanning system — galvanometer scanner motor plus servo driver. This system behaves much like a low-pass filter used in electronics. The circuit in Figure 3 is a simplified model that shows the behavior of the scanning system and how the mirror position tracks the command signal, while also driving the galvanometer coil. The corresponding frequency response graph in Figure 4 shows how the amplitude of the position signal "rolls off" as frequency increases. The diagram specifically shows a −3-dB bandwidth of 2.5 kHz.

In Figure 3, a command input (waveform) is sent to the servo driver, which sends voltage to the coil so that the motor accelerates. This acceleration establishes velocity, which in turn affects the position of the motor and mirror.

Per this multistep sequence, the mirror's actual position will always lag behind the command input. Insofar as it relates to low-pass filtering, low-pass filter action dictates that a higher scan frequency corresponds to a greater roll-off, or rounding, of the actual position.

Delay, step time, and position error

Detecting and understanding errors that may arise during the scan process is necessary to realize the simplicity that a properly functioning system delivers to an application. In Figure 5, for example, a triangle wave is fed to the command input (yellow) with the mirror position (pink). This oscilloscope image shows an obvious delay between command and position. It also shows that the position waveform does not quite achieve the same amplitude as the command. Further, the position has a rounded top and bottom, which is caused by the low-pass filter action of the servo/scanning system.

The delay between the command and position is called a tracking delay. As long as the operational amplifiers, as shown in Figure 3, do not saturate, this tracking delay will remain consistent regardless of the amplitude or slope of the command signal.

However, if the slope of the command input changes direction — which it does twice per cycle in a triangle wave — it will take the position some time to change direction and start traveling at the new slope rate. This amount of time is referred to as the step time or settling time.

This delay between command input and position also means that the command arrives to request a position before it is achieved. Therefore, if the command is changing, this time delay causes a difference in the angle between command and position. This difference in angle is referred to as position error (Figure 5).

Constant velocity

For most imaging applications, it is desirable to maintain constant velocity during the entire length of each scan line. However, some portions of the waveform must be dedicated to slowing and reversing the scanning direction in preparation for the arrival of the next scan line or scan field. Scanning efficiency is the ratio of time spent in constant velocity to the total amount of time in one cycle.

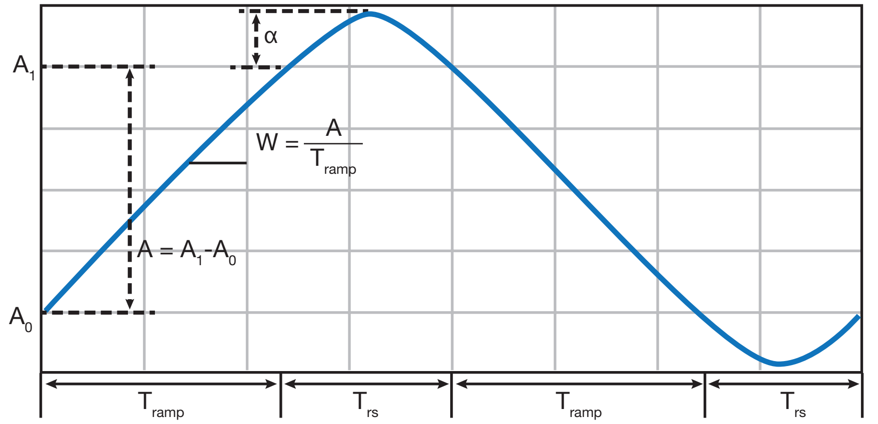


Figure 7. The cycloid approach replaces the tips of the triangle wave with half of a sine wave. T_{ramp} represents the amount of time allotted for each ramp portion; T_{rs} represents the amount of time allotted for each half sine wave. Letter A represents the amplitude of the ramp portion; A_0 and A_1 represent the start and finish, respectively. Alpha represents the amplitude of the sine wave portion.

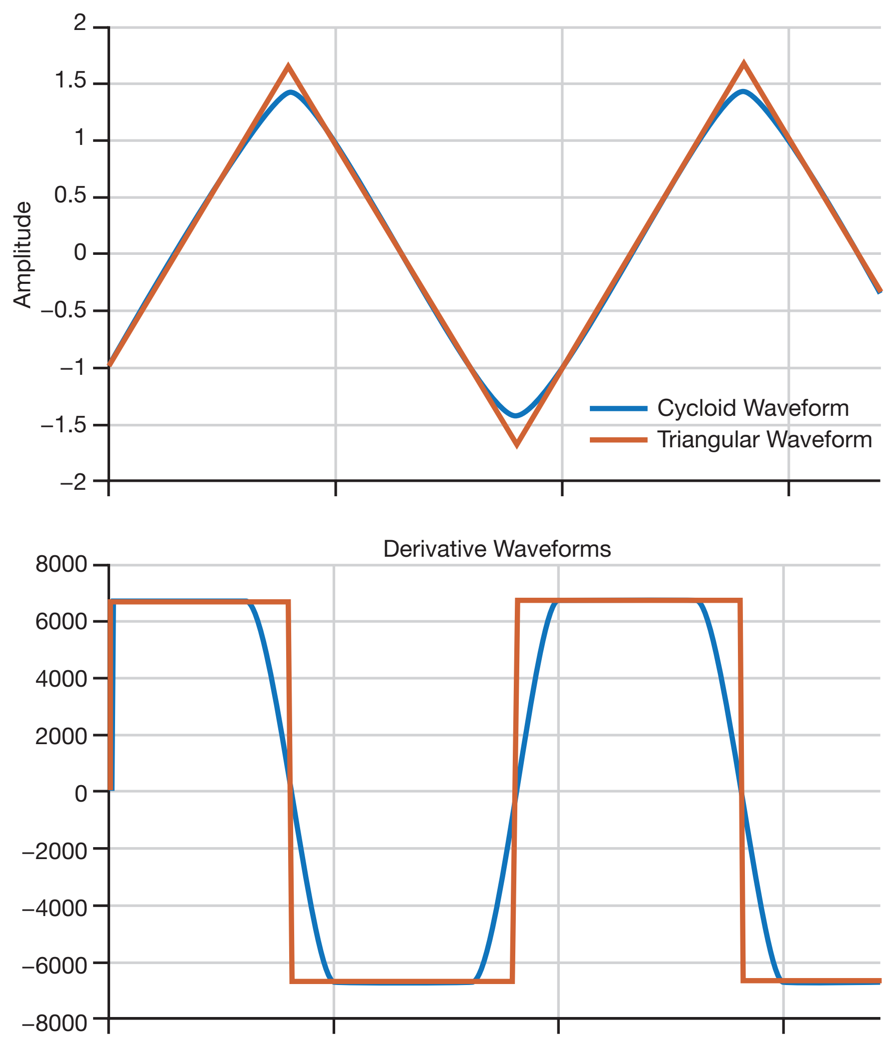


Figure 8. The triangle wave compared with the cycloid. The derivative waveforms are also shown, to indicate velocity.

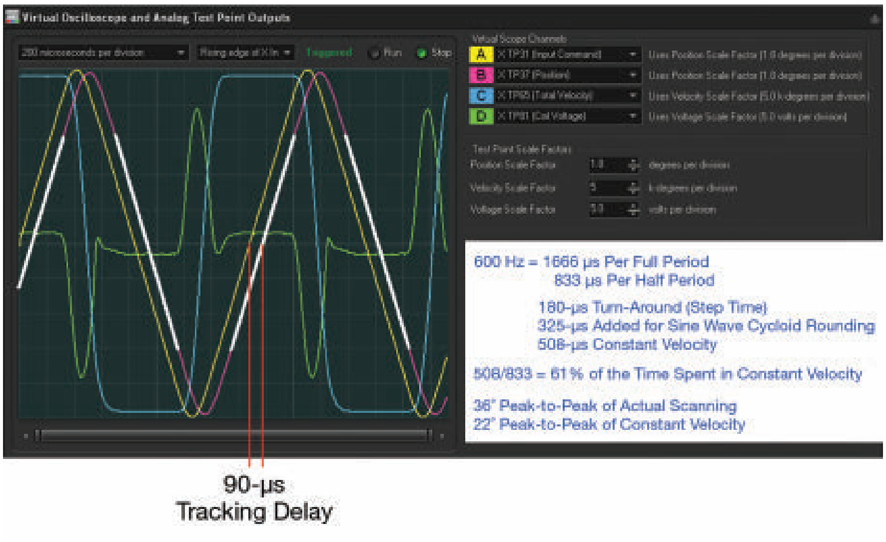


Figure 9. A triangle wave modified using the cycloid approach shows the benefit of cycloids for triangle-wave scanning.

Figure 6 shows a 600-Hz triangle wave, with servo gains set such that the tracking delay is 90 µs. The total scan angle is 14°, of which 11° are in constant velocity. This is the maximum scan angle possible for this frequency, with this servo tuning, and using a standard triangle-wave input since the coil voltage parameter is nearly touching +/−20 V.

A white trace shows the position during the times when the beam is traveling at constant velocity in Figure 6 (blue). For this scanning scenario, the velocity is constant at 16,800°/s for 78% of the time. However, there are short periods when the mirror must slow down, turn around, and speed up again. These areas (pink) correspond with the step time of the scanner, which is 180 µs for the servo tuning shown.

Because the beam must be turned off during the period when the scanner is turning around, less than the full 14° would be usable for an imaging application that requires constant velocity. At 16,800°/s, the position error for this tuning is 0.75 mechanical degrees, or 1.5 optical degrees, which must be subtracted from both peaks of the triangle wave, giving a useful scan angle of 11 optical degrees peak-to-peak. With the traveling in constant velocity for 78% of the time, the overall scanning efficiency is 78%.

Avoiding saturation: cycloid approach

The scan angle in Figure 6 could not be increased because the coil voltage was already at the maximum recommended +/−20 V: As shown, the coil voltage peaks occur at the "tips" of the triangle wave, where the command input is changing the slope. Any increase in scan angle would result in exceeding this voltage limit, which would cause overshoots and distortion in the actual scanning.

However, it is possible to reduce the rate of change of the slope at the tips of the triangle wave, which would enable operation at a larger scan angle. This is performed by "rounding" the tips of the triangle wave. The optimal way to achieve this is to replace the tips of the triangle wave with half of a sine wave.

To replace the tips of the triangle wave with half of a sine wave — completed via the cycloid approach — the triangle wave is broken into two separate ramp portions. One ramp portion is ascending and one is descending. A small amount of time is allotted between each ramp portion for the half sine wave to be inserted. Also, the amplitude of the half sine wave is adjusted so that the position, velocity, and acceleration all match. This provides a smooth transition between the ramp and sine wave portion.

In Figure 7, T_{ramp} represents the amount of time allotted for each ramp portion and T_{rs} represents the amount of time allotted for each half sine wave. Letter A represents the amplitude of the ramp portion, with A_0 and A_1 representing the start and finish of the sequence, respectively. Alpha represents the amplitude of the sine wave portion.

Figure 8 shows this same principle, where the triangle wave can be compared with the cycloid wave. The derivative waveforms are also shown to indicate velocity, which is constant during the ramp portions and changing smoothly and symmetrically between the ramp portions.

Figure 9 incorporates a triangle wave modified using the cycloid approach shown in Figures 6 and 7. Specifically, half sine waves lasting 325 µs are inserted to enable an increase of the total scan angle to 36°, of which 22° is in constant velocity. The usefulness of cycloids for triangle-wave scanning is evident, since the coil voltage is no greater than in Figure 6, but the usable scan angle with constant velocity has doubled, with no additional change to oscilloscope scale factors in Figure 6.

The velocity in the scanning scenario shown in Figure 8 is constant at 48,292°/s for 61% of the time (white portions of the position trace). The time periods dedicated to slowing the mirror and turning around are the pink portions of the position trace and correspond to the 180 µs step time of the scanner. An additional 325 µs is also added for the half sine waves that make up the cycloid portion of the waveform.

At 48,292°/s, the position error for this tuning is 2.18 mechanical degrees, or 4.36 optical degrees, which must be subtracted from both peaks of the ramp portions of the triangle wave to accurately gauge the scan system performance and influencing values. The amplitude of each half sine wave is 2.62°, giving a useful scan angle of 22 optical degrees peak-to-peak. Since the beam is traveling at constant velocity for 61% of the time, the overall scanning efficiency is 61%.

Meet the author

William R. Benner Jr. is president and CTO of Pangolin Laser Systems and project leader for the ScannerMAX division. He holds more than 50 patents spanning actuators, position sensors, and lenses used for laser projection applications; email: contact@scannermax.com.

Product News

Small Beamsplitter Detector

The LIM-082 from **InfraTec** is a small beamsplitter detector in current mode that can be used in gas measurement technology. With its integrated operational amplifier, the detector provides a large, low-impedance output signal that makes it insensitive to interference coupling. The LIM-082 is suitable for direct connection to an analog-to-digital converter of a microcontroller and uses gold-coated microstructures to split incoming radiation into several radiation beams in different directions with equal intensity.
sensor@infratec.de

16-Wavelength Light Source

The SuperNova from **Ayar Labs** is a 16-wavelength light source designed for AI and optical I/O applications. Compliant with CW-WDM MSA specifications, the light source offers compact packaging, operates at wide temperature ranges, and can supply light for 256 data channels. The SuperNova enables 16 Tb/s of bidirectional bandwidth and 64× the wavelengths compared with CWDM4 multiwavelength pluggable optics.
info@ayarlabs.com

Compact ROADM

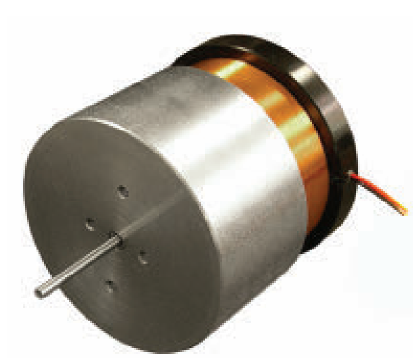
The DCP-R-34D-CS from **Smartoptics** is a compact reconfigurable optical add/drop multiplexer (ROADM) for larger fiber optic networks. Taking up a single rack unit and consuming <100 W of power per direction, the ROADM provides broad interoperability and wavelength selective switch technology for flexibly managing next generation disaggregated networks. The DCP-R-34D-CS's ports are equipped with flex grid support and enable cross-connect and add/drop functionality in the local node.
info@smartoptics.com

Fiber Metalization System

The MIDAS Metalization System from **Intlvac** is designed to produce a single or multilayer symmetrical metal coating on ends, mid spans, or windows of optical fibers for use in a hermetically sealed opto-electric package. It can also create radially symmetrical material stacks on cylindrical rod or tube components. Intended for a small cleanroom footprint, the system is load-lock-based and uses a low energy plasma pre-clean to ensure adhesion by removing residual hydrocarbon and water vapor contamination. The MIDAS also features a coating chamber that contains an array of sputter cathodes allowing for the uniform distribution of different metal and multilayer coatings.
sales@intlvac.com

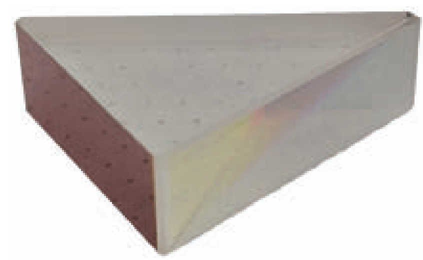
Electro-Optical Modulators

The 65-GHz and 20-GHz Ultra Low Vπ Intensity Modulators from **HyperLight** are electro-optical modulators based on high-bandwidth and low-voltage thin-film lithium niobate PIC technology for datacom, telecom, test and measurement, and radio-over-fiber applications. The 65-GHz Intensity Modulator has a Vπ of 1.4 V, uses a V-type (1.85-mm) radio frequency connector, and has a wavelength coverage across O, C, and L bands. The 20-GHz Ultra Low Vπ Intensity Modulator features a Vπ of <1 V while maintaining low insertion loss and the ability to reduce the noise figure in radio-over-fiber links.
sales@hyperlightcorp.com



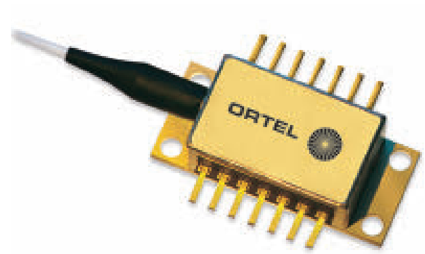
Moving Coil Motor

The GVM-095-051-01 from **Moticont** is a linear voice coil servo motor that can be used in applications such as wafer handling and optical focusing. The brushless servo has a 1-in. (25.4-mm) stroke with 23.5 lbs. (104.6 N) of continuous force for a high force-to-size ratio and 74 lbs. (329.3 N) of peak force at a 10% duty cycle. The GVM-095-051-01's motor is compact with a diameter of 3.75 in. (95.3 mm) and a length of 2 in. (63.5 mm) and features the ability to quickly accelerate and decelerate and smooth motion at low speeds. It operates with accuracy and repeatability in a closed servo loop.
moticont@moticont.com



Extended C+L-Band Grisms

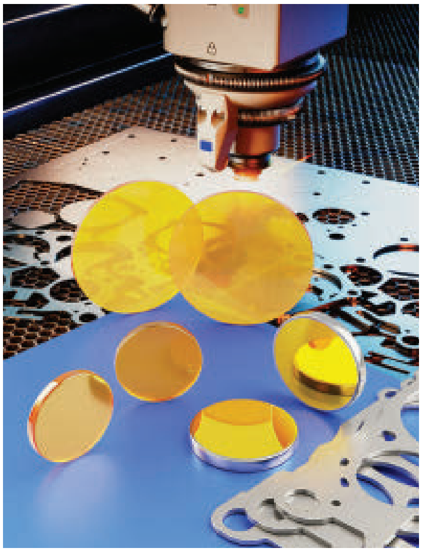
Coherent's family of aberration-correcting, high-efficiency grisms and transmission gratings encompass the entire extended C+L band in a single optic for the construction of compact network components that support wavelength selective switches and optical channel monitors. Using multilayer dielectric diffraction, the diffraction gratings enable the curvature and spacing of every individual grating line to be separately controlled. The grisms and gratings feature expanded functionality past dispersion to include aberration correction and wavefront transformation, efficiency up to 97%, and a design that provides for higher dispersion.
info@coherent.com



Distance Sensing Laser Module

The Model 1786 from **Ortel** is a 1550-nm laser module made for use as a continuous wavelength coherent optical source for optical sensing and lidar systems. A narrow linewidth source, the laser can achieve a maximum of

300 KHz of linewidth and is offered in 40-mW, 50-mW, and 63-mW variants. The laser is packaged in a 14-pin butterfly package and comes coupled to an internal thermo-electric cooler for applications that are exposed to wide temperature ranges and humidity. The 1786 laser is also qualified to Telcordia GR-468 standards.
info@ortel.com



CO_2 Optics

CO_2 Laser Lenses from **Laser Research Optics** are designed for use in the production of precision gaskets manufactured from stainless steel, phenolic, and other hard materials. The lenses can be finished with dual-band antireflective coatings and come in 0.5- to 1-in. optical density sizes with focal lengths between 1 and 2 in. The CO_2 Laser Lenses conform to ISO-10111 specifications, can be replaced in the field, and are compatible with many CO_2 laser producers.
sales@laserresearch.net

Wafer Inspection System

The LS9300AD from **Hitachi** is a system for inspecting the front and back sides of nonpatterned wafer surfaces for particles and defects. In addition to the conventional dark-field laser scattering detection of foreign material and defects, the system is equipped with a differential interference contrast inspection function that enables detection of irregular defects and shallow, low aspect microscopic defects. The LS9300AD also uses the wafer edge grip method, and the rotating stage can be used in conventional products to enable front- and back-side wafer inspection.
contact@hitachi-hightech.com

Intra-Data Center Optics

The ICE-D series from **Infinera** are a line of high-speed intra-data center optics based on monolithic indium phosphide PIC technology.

The optics provide intra-data center connectivity at speeds of 1.6 Tb/s and faster and enable highly integrated solutions to combine multiple optical functions onto a single monolithic chip. The ICE-D chips have demonstrated a reduction in power per bit by as much as 75% while simultaneously increasing connectivity speed.
techsupport@infinera.com

Optical Transport Solutions

Optical transport solutions from **Nokia** are meant for optical transport, internet protocol (IP) routing, and passive optical network applications and include coherent optical transceivers, a photonic engine, and a multihaul transceiver. The coherent optical transceivers are available in 100 Gb/s, 400 Gb/s, and 800 Gb/s along with 100G pluggable coherent transceivers to bring the performance of coherent optics to the metro edge into existing 100-GigE ports. The PSE-6 photonic service engine can power 800-Gb/s (ZR/ZR+) coherent transceivers. The 400G multihaul transceiver (shown) is in a QSFP-DD format and has a high optical launch power for 400ZR/ZR+ applications.
press.services@nokia.com

Linewidth Laser Module

The LXM from **TeraXion** is a narrow linewidth laser module for coherent applications including wind sensing, distributed acoustic sensing, frequency-modulated continuous wave lidar, optical network monitoring, and quantum communications. With parameters including ultralow phase noise and frequency modulation capabilities, the module is compact and rugged and comes in two different configurations. The LXM features a distributed feedback laser semiconductor design for stability and scalability, high frequency modulation capabilities, and a narrow linewidth for increased accuracy and resolution.
info@teraxion.com

High-Resolution SWIR Cameras

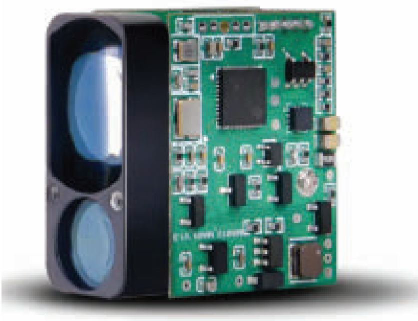
The fxo992 and fxo993 from **SVS-Vistek** are high-resolution SWIR cameras for use in industrial automation applications, such as semiconductor, battery, glass, laser, and gemstone inspection. Equipped with Sony's high-resolution IMX992 and IMX993 indium gallium arsenide sensors, respectively, the cameras offer 5.2 MP at 132.6 fps and 3.1 MP at 173.4 fps and a thermo-mechanically optimized design measuring 50 × 50 mm with a maximum length of 82.8 mm. The fxo992 and fxo993 also feature firmware that includes image optimization functions, such as defect pixel correction or two-point nonuniformity correction, an integrated multichannel strobe controller, the GenICam interface for camera configuration, and an associated transport layer for image capture.
info@svs-vistek.com

Zoom 3D Scanner

The SmartScan VR800 from **Hexagon AB** is an optical 3D scanner with a motorized zoom lens that enables users to adjust data resolution and measurement volume entirely through software settings. The scanner combines dual stereo cameras and optical zoom-enabled projection, which allows users to define the form in which they collect data. It comes with smart resolution, smart zoom, and smart snap software functions that enable customization of inspection resolution and measurement volume without mechanical alterations. The SmartScan VR800 can be used in a range of measurement applications for parts made through additive manufacturing, tool and die, and casting and molding.
media@hexagon.com

Laser Ranging Modules

The LSP-LRS-1200 and LSP-LRS-1000 (shown) from **Lumispot Tech** are 905-nm laser ranging



modules that can be used in laser range finding, distance sensing, and consumer applications. The LSP-LRS-1200 can measure distances from 5 to 1200 m away with 0.1-m measurement resolution at a weight of 19 g. The LSP-LRS-1000 uses a 905-nm laser diode to measure up to 1000 m and is coin-sized at a weight of 10 g. Both modules feature ±1-m accuracy, ≥3-Hz measuring frequency, a maximum operating consumption of 500 mW, and an operating temperature range from −20 °C to 55 °C.
sales@lumispot.cn

Compact Smart Camera

The Vision Cam XM2 from **IMAGO Technologies** is a compact smart camera powered by the NVIDIA Jetson Orin module. The embedded vision system is equipped with a high-resolution sensor that captures up to 5 MP per image and 165 fps at full resolution and can capture up to 1400 fps at video graphics array resolution. The Vision Cam XM2 also features an integrated processor with 6× Arm Cortex-A78 CPUs, 1024 GPU cores, and 32 tensor cores. It can be used for AI-based applications, intricate pattern recognition processes, automation and quality assurance, and the combination of numerous operators.
marketing@imago-technologies.com

Active Aligner

The MRSI-A-L from **MRSI Systems** is an active aligner for optical packing solutions including fiber and lens attachments for transceivers, silicon photonics, arrayed waveguide gratings, lidar, and integrated optics. The attachment machine is modular and uses up to 12 axes for versatility and offers precise control over reflective surface angles, laser beam profile measurement and processing, 1-µm accuracy laser height detection functions, and software empowering for altering process capabilities. The MRSI-A-L also features integrated pick and

place capabilities, dot or pattern dispensing functionalities, machine vision technology, and active alignment capabilities for single and/or dual optical components.
sales.mrsi@mycronic.com

Sensor System

The AugaOne sensor system from **ArgusEye** accelerates downstream monoclonal antibody process development by providing specific real-time and automated in-line data with high sensitivity, without requiring sample pretreatment. Using a nanoplasmonic sensing technology platform, the system supports biopharmaceutical scientists and can handle complex samples, such as cell culture and plasma, to deliver data independent of matrix effects, cells, and temperatures. The AugaOne features a modular design as well as capabilities for in-line monitoring.
info@arguseye.se

OSP Terminals

Go!Foton's expanded line of outside plant (OSP) terminals are made for bandwidth applications in data centers and for extending fiber-to-home in rural areas. The small tube terminals use 6F one-side and 12F duo-side micro-tube-based interface supports with up to 12 fusion splices of local connector form factors. The Multi-Port Midspan Terminal (MMT)-midsize, a compact version of Go!Foton's MMT, has 12 ports and can be equipped with planar lightwave circuit splitters or cascaded tap/splitters. The Microtube M-CHT (midspan clamshell hardened terminal) provides IP68-rated drop ports compatible with flat and round drop cables and supports both field-installable connectors and field splicing.
generalinfo@gofoton.com

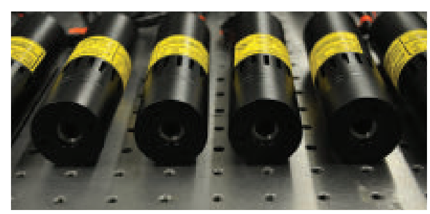
O-Band Transceiver

The QSFP28 from **Approved Networks** is an O-band transceiver for high-speed data transmission for distances up to 25 km. Able to upgrade bandwidth to 100G, when paired with

a 16-channel wavelength division multiplexing mux/demux it does not require power outside of the user's switch and eliminates the need for additional components, such as amplifiers. The QSFP28 allows for potential growth up to 1.6 TB/s.
sales@approvednetworks.com

Single-Slot Card

The FSP 3000 M-Flex800 from **Adtran** is a multirate line card for ZR and ZR+ optics in internet protocol (IP) over dense wavelength division multiplexing solutions. Designed to meet the connectivity needs of telecom operators, cloud providers, and enterprises, the card supports a range of gray and coherent interfaces, including 100 Gbit/s, 400 Gbit/s, 800 Gbit/s, ZR, ZR+, OpenROADM, and other types of coherent optics. The FSP 3000 M-Flex800 is designed for tasks such as IP and optical demarcation, ZR-to-ZR interconnects, and edge optical transport networking applications.
info@adtran.com



380-nm Laser Module

The IQ1C195(380-210) from **Power Technology** is a continuous wave high-power 380-nm laser diode module for high-end analytical and scientific applications, such as bioanalysis, fluorescence, and Raman spectroscopy. The laser features a collimated or focused beam with diffraction-limited performance and operates from eight volts of direct current with a compact design. The IQ1C195(380-210) is available with digital or analog modulation.
sales@powertechnology.com

PIC with Equalizer

The NPG102 from **NewPhotonics** is a PIC with an integrated optical equalizer for linear receive optics and linear drive pluggable optics applications in the data center. An octal and quad parallel single-mode transmitter for 8× and 4× 200G PAM4 transceivers, the PIC's optical signal processing enables >1000× lower latency resulting in lower system pJ/bit.
sales@newphotonics.com

Industry Events

JUNE

⭘ SENSOR + TEST
(June 11-13) Nuremberg, Germany.
Contact AMA, +49 (0)5033-9639-0, **info@ama-service.com**; www.sensor-test.de/en/conference-2/.

⭘ EMVA Business Conference
(June 13-15) Gdańsk, Poland.
Contact European Machine Vision Association, +34 93-220-7201, **info@emva.org**; https://bc-2024.emva.b2match.io/.

⭘ SPIE Astronomical Telescopes + Instrumentation
(June 16-21) Yokohama, Japan.
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/astronomical-telescopes-and-instrumentation?utm_id.

⭘ UKIVA Machine Vision Conference
(June 18-19) Coventry, England.
Contact PPMA, +44 (0)20-8773-8111, **mvcbookings@ppma.co.uk**; www.machinevisionconference.co.uk/.

⭘ Optica Quantum 2.0 Conference and Exhibition
(June 23-27) Rotterdam, Netherlands.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/topical_meetings/quantum/.

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

JULY

⭘ SEMICON West & FLEX
(July 9-11) San Francisco.
Contact Semi Global Headquarters, +1 408-943-6900, **semiconwest@semi.org**; www.semiconwest.org/about/welcome.

⭘ Laser Additive Manufacturing (LAM) Workshop
(July 15-17) Dayton, Ohio.
Contact the Laser Institute, +1 407-380-1553, **info@lam.ngo**; www.lam.ngo/.

Optica Sensing Congress
(July 15-19) Toulouse, France.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/optical_sensors_and_sensing_congress/.

Vision Spectra Conference 2024
(July 16-18) Virtual.
Contact Photonics Media, +1 413-499-0514, **conference@photonics.com**; www.photonics.com/vsc2024.

⭘ Microscopy & Microanalysis
(July 28-Aug. 1) Cleveland.
Contact the Microscopy Society of America, +1 703-234-4115, **associationmanagement@microscopy.org**; https://mmconference.microscopy.org/.

Optica Advanced Photonics Congress
(July 28-Aug. 1) Québec City.
Contact Optica, +1 202-223-8130, **info@optica.org**; www.optica.org/events/congress/advanced_photonics_congress/.

AUGUST

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

SEPTEMBER

⭘ 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.

⭘ 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/.

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

OCTOBER

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

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

PAPERS

Single-Molecule Sensors and Nanosystems International Conference — S3IC 2024
(Oct. 28-30) Paris.
Deadline: Abstracts, July 5
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 Photonics West 2025
(Jan. 25-30) San Francisco.
Deadline: Abstracts, July 17
Contact SPIE, +1 360-676-3290, **customerservice@spie.org**; www.spie.org/conferences-and-exhibitions/photonics-west/presenters/abstract-submission-guidelines.

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

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

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/.

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/.

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

PHOTONICS SHOWCASE

4 & 5 mm Single-Axis Galvo Scanners

Introducing our newest and smallest galvanometer offering. Our single-axis galvo scanners with 4 and 5 mm beam diameters are optimized for low inertia and high torque, resulting in faster small step response and higher closed-loop bandwidth. These galvos are ideal for high-speed scan and imaging applications. The 4 mm and 5 mm galvos offer a step response of 200 µs and 250 µs, respectively. They offer 99.8% linearity and <20 µrad repeatability.

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www.thorlabs.com

Tiny Picomotor™ Actuators

These piezo linear actuators are a smaller-sized version of our standard Picomotor™ actuators. They offer the same exceptional precision, small step sizes, and set-and-forget stability as the standard Picomotor™ actuators but in an ultra-compact package.

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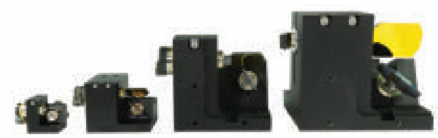
ScannerMAX Optical Scanning Systems



ScannerMAX provides a wide range of optical scanning systems with apertures that range from 3mm to 50mm and wavelengths ranging from 260nm to 10.6µm. Offering tailored solutions for various applications, including microscopy, LiDAR, template projection, material processing, and more. Our systems, designed and manufactured in the United States, ensure quality, precision, and reliability in the field of optical scanning technology.

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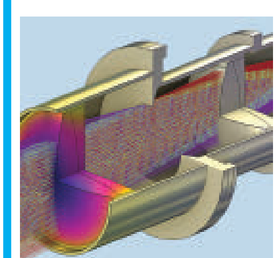

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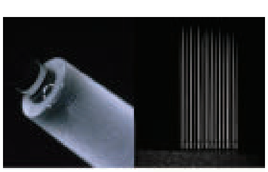
The NYFORS SMARTSPLICER



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

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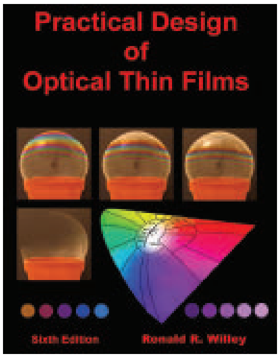

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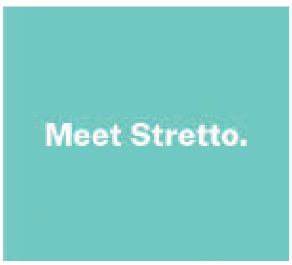

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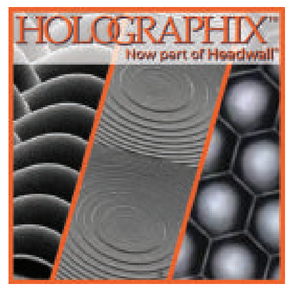
Spectrum of Optical Solutions



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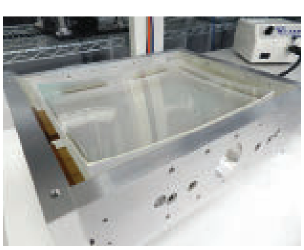

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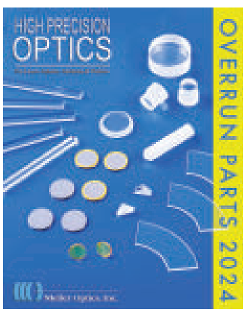

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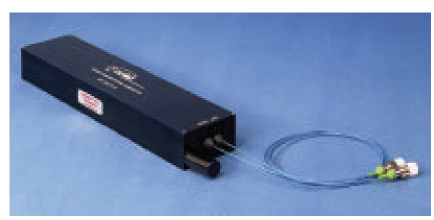
Fiber Optic Delay Lines



Fiber Optic Delay Lines (ODL) are offered in manual or electrically controlled versions, allowing the variable air gap spacing to be accurately controlled. ODLs are offered with variable ranges starting from 13 ps (4 mm) to 1200 ps (400 mm). Devices come with fine delay resolution, low insertion loss & variation, low return loss, and a wide operating wavelength in a compact design, ideal for interferometry setups for Quantum and OCT applications.

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matt.beebe@photonics.com

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

South Central U.S., Southeastern U.S., Midwest, CT, ME, NH, NJ, NY, PA, RI, & VT
José D. Amor
Account Executive
Voice: +1 413-499-0514, Ext. 108
Fax: +1 413-443-0472
jose.amor@photonics.com

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

Reprint Services
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Invisibility: Not a bug, but a feature … from a bug

University researchers estimated that ~25% of Americans suffer from some form of entomophobia, or a fear of insects. But amid the tendency for these creatures to frighten mammals, our six-legged frenemies do, in fact, play an important role in balancing the ecosystem. Pollination and pest control are among their essential jobs.

Pioneering next-generation technology, though, is not typically considered a demand that humankind places on insects.

Perhaps it is time to start.

Taking inspiration from a common backyard insect, researchers at Penn State made a breakthrough that might unlock the ability to create devices that provide a form of invisibility.

Leafhoppers, the insects of the researchers' inspiration, naturally secrete and coat themselves in tiny particles with a cavity-ridden, soccer ball-esque geometry called brochosomes. Scientists have known about this phenomenon since the 1950s, although they have yet to decipher what exactly the bugs are *doing* with it.

In 2017, the same research team behind the current advancement successfully replicated brochosomes in a lab, aiming to better understand their properties. This entailed reducing the light that is directly reflected on the particle by 94%, which marked the first time that the researchers had ever witnessed a naturally produced hollow particle control light in such a way.

Like a flurry of hornets escaping a nest-turned-piñata, team members pondered theory after theory that used the new-found data to explain why leafhoppers were able to create and then cover themselves in brochosomes.

Sheer survival instincts, they determined, were at the root of this mystery.

Specifically, the researchers found that the natural light-reflecting powers of the brochosomes held two advantages. Firstly, the size of the cavities in each particle cause the brochosomes to be efficient absorbers of UV light. This reduces their visibility to birds and reptiles that use the UV spectrum to see. Secondly, the antireflective property of the brochosomes scatters visible light, which creates a matte-colored bug.

The researchers have since identified several proposed applications for this discovery, ranging from the milder and more responsible to the more futuristic and, objectively, more awesome. These include more efficient solar energy harvesting systems, coatings that protect pharmaceuticals from light-induced damage, and advanced sunscreens for improved protection against sun damage.

The application that really ought to bug us out involves the potential for cloaking technology. One day, we all might be able to wear the humble leafhopper's armor to hide among the metaphorical leaves.

That is, if we overcome our fears.

The research was published in the *Proceedings of the National Academy of Sciences* (*PNAS*) (www.doi.org/10.1073/pnas.2312700121).

Image courtesy of iStock.com/Heather Broccard-Bell.