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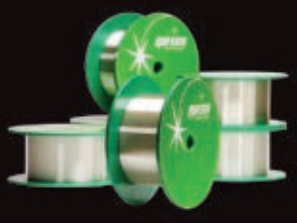

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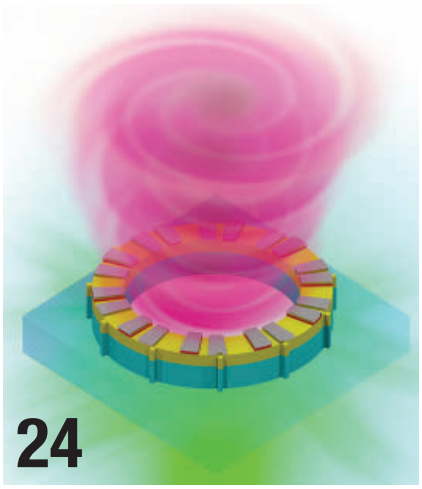

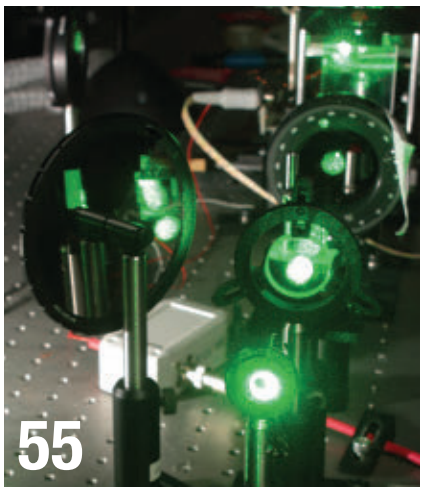

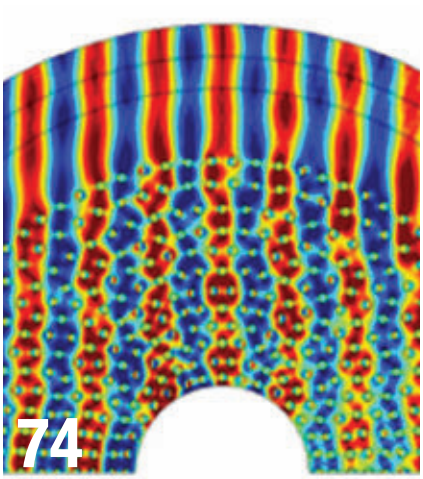

Departments & Columns

THE COVER
Lasers stimulate neurons and map activity via fluorescent probes. Image courtesy of Lloyd Russell, University College London. Cover design by Senior Art Director Lisa N. Comstock.

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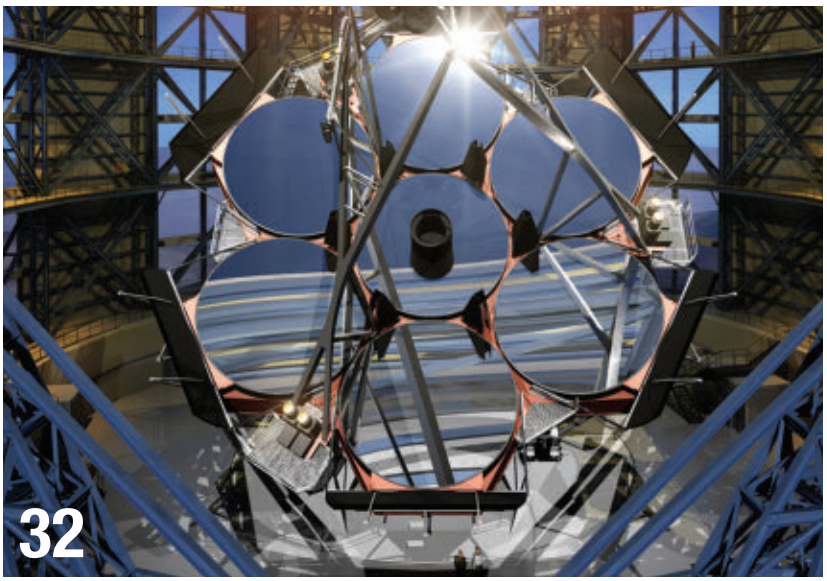
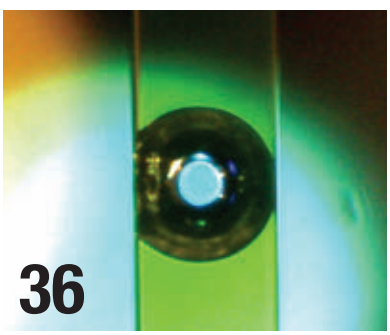
PHOTONICS: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing.





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editorial COMMENT

Optimal conditions, great viewing

Nestled in the Andes mountain range in the Atacama Desert in Chile sits the Las Campanas Observatory. At an elevation of almost 8,000 feet, the remote location is prized for its dark skies, excellent weather and superior visibility. Soon it will be home to the Giant Magellan Telescope (GMT) now under construction.

The GMT promises researchers an unprecedented view into the cosmos — peering back to a time not long after the Big Bang when the first stars, galaxies and black holes were formed. In addition to some of the most advanced optics ever produced, the telescope features a revolutionary adaptive optics system with six sodium laser beacons that, when used in conjunction with natural stars, will produce diffraction-limited images in the near- and mid-IR of never-before-seen resolution. For details, read Antonin Bouchez's "A High-Resolution View of the Universe" on page 32.

From the mysteries of the universe, we turn to secrets of the brain. While filtered lamps and LEDs have their place in the burgeoning field of optogenetics, lasers — specifically femtosecond lasers — offer the rare combination of spatial selectivity, high brightness and the capability of exciting multiphoton processes. Don't miss, "Femtosecond Lasers Power New Approaches in Optogenetics," by Coherent's Darryl McCoy and Marco Arrigoni, page 42.

From new frontiers in medicine and astronomy, we also examine the innovative optical materials set to displace existing technologies in the years ahead. Learn more about the latest advances in nanotubes, metamaterials and super-black coating in Marie Freebody's "Optical Materials of Tomorrow," page 50.

Also in this issue:

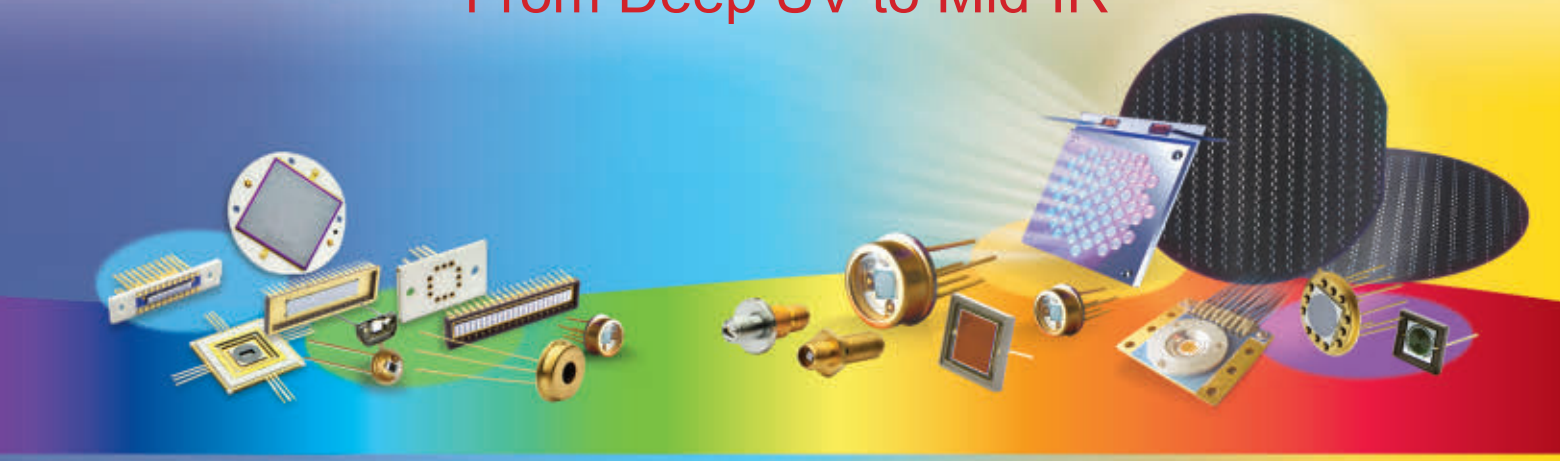
- Manijeh Razeghi and colleagues from the Center for Quantum Devices at Northwestern University share specifics of a widely tunable, monolithically integrated mid-IR semiconductor laser operating at room temperature in "Quantum Cascade Laser Breakthrough for Advanced Remote Detection," page 47.
- Clever innovation and disciplined engineering are helping create better, smaller and less expensive flow cytometers. See Giacomo Vacca's "In Vitro Diagnostics, Immunology Spurring Advances in Flow Cytometry," page 36.
- In "From Masers to Lasers in Space — and at the Cinema!," Senior Editor Justine Murphy surveys the laser's use in consumer electronics, telecommunications, industry and science, page 57.

We hope you enjoy the issue!

Michael D. Wheeler
michael.wheeler@photonics.com

Spanning the Spectrum

From Deep UV to Mid-IR



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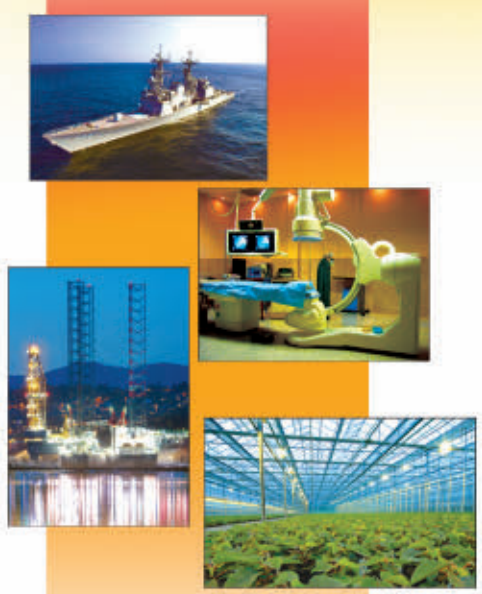

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In the December issue of
Photonics Spectra...

- **Optical Coatings**
- **Terahertz Imaging**
- **Test & Measurement**
- **OLEDs**
- **Lasers in Medicine**

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What's Online:

Laser Additive Manufacturing

Thursday, January 12, 2017, 1 p.m. EST

Wayne Penn, applied physics consultant for Alabama Specialty Products Inc., will provide an in-depth introduction to laser additive manufacturing (LAM) in this webinar for engineers, managers and system integrators.

Penn will cover the open source world of 3D printing, describing ways that it is being used and what some manufacturers have been able to achieve through its use. He will discuss the challenges of additive manufacturing (AM), including quality control, and the role of laser welding and cladding technology in AM. He will present examples of industrial applications showing the use of additive manufacturing and conclude with a look at future initiatives in the area of LAM. More information about this webinar will be available soon at **www.photonics.com/webinars**.

Available on Demand

For additional on-demand webinars covering the application of photonics and optics in a range of industries, visit **www.photonics.com/webinars**.

Vision Guided Robotics

David Bruce discusses the two subsets of VGR, 2D and 3D, and reviews the proper techniques for selecting and implementing vision guidance systems. He covers the steps required to set up and execute 2D and 3D VGR, the advantages of using virtual VGR, and the trade-offs to consider when selecting a VGR system.

Bruce is an engineering manager at FANUC America Corp. (FAC). He has an M.S. from Oakland University and a B.A.Sc. from the University of Windsor.

Visit **www.photonics.com/W97**.

Laser Measurement Best Practices: How to Avoid Choosing the Wrong Power/Energy Sensor

Presented by Ophir-Spiricon

Ophir-Spiricon sales engineer Dick Rieley discusses laser measurement best practices and guides you through the factors to consider when selecting a sensor. The focus of the webinar is on key factors in the sensor selection process, including beam diameter, beam density values, cooling requirements and exposure duration.

Choosing the wrong laser sensor can result in a damaged sensor requiring premature replacement, which in turn can lead to additional costs, unexpected downtime and invalid measurements. This informative presentation on sensor selection will help ensure that you make the right choice for your laser.

Visit **www.photonics.com/W98**.

Breaking Through

This podcast series, hosted by Photonics Media Senior Editor Justine Murphy, focuses on women working in photonics — in academia, research and industry — about challenges they face, and how to rise above those challenges to help future generations succeed.

To listen to this free podcast, visit **www.photonics.com/V280**.

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Navitar wins legal battle against Chinese counterfeiters

Optics manufacturer Navitar Inc. has won a legal battle against Chinese metrology machine makers over income tax evasion, smuggling crimes of evading import duties and value-added tax, along with false advertising, to combat the counterfeiting of their video microscope.

"Instead of hitting them head on with counterfeiting claims, we used a tactic I call the 'Five Fires Method,'" said Julian Goldstein, CEO of Navitar, "We uncovered every illegal activity these companies were engaging in, setting small fires from every direction. We alerted and provided evidence to the Chinese government resulting in numerous fines and penalties for income tax evasion, import duty and value-added tax smuggling, and false advertising. As a result of our victories, I am pleased to say that the doors are open once again for our legitimate Chinese dealers and OEM customers to compete and prosper in this marketplace."

Navitar won its case with the help of Rep. Louise Slaughter, the International Trade Administration and the U.S. Embassy in China.

"Navitar was targeted because of our global success in the automated inspection industry," said Goldstein. "Our video microscope lenses are sold to multinational technology companies like Apple Inc. and used to ensure the quality of their components, sub-assemblies and finished products, which are made at Foxconn manufacturing factories in China."

Navitar Inc.

Rep. Louise Slaughter with Navitar CEO Julian Goldstein.

Navitar exports optical components from its Rochester, N.Y., manufacturing facility to over 45 countries. Exports to China have doubled this year. In addition to their New York headquarters, the company has manufacturing facilities in California, Massachusetts and New Jersey.

"We have a long history of doing business in China," Goldstein said. "I knew it would be too difficult to win a counterfeiting lawsuit against these Chinese companies, so we needed another way to expose their unlawful actions."

Molex fiber used on NASA climate monitoring satellite

Molex LLC has announced that its Polymicro Technologies optical fiber is being used to build NASA's Ice, Cloud and Land Elevation Satellite-2 (ICESat-2) for climate monitoring.

The satellite, slated to be launched in 2017 from Vandenberg Air Force Base in California, will measure changes in Earth features such as melting ice sheets, thinning sea ice and growing trees. The Molex optical fiber will be used onboard ICESat-2 and in ground support equipment assemblies that enable integration and testing. The custom fibers are composed of high OH glass/glass fiber, including a glass core, glass cladding layer, acrylate buffer and a protective nylon outer jacket.

"We are extremely proud to be a part of this vital NASA project and look forward to continued collaboration on future projects," said Gary MacDonald, technical sales supervisor of Molex. "Molex has an ongoing relationship with NASA Goddard, and our optical fiber is currently in use on the Mars Rover Curiosity as well. We consider it an honor and a privilege to have been chosen to supply our custom fiber on such a remarkable venture."

The Mars Rover Curiosity includes an armor jacketed fiber optic assembly built with Molex Polymicro Technologies FVA300330500 fiber. The assembly connects to the body-mast unit on the vehicle's ChemCam active remote sensing instrument.

ICESat-2's photon-counting laser altimeter will measure the round-trip time of individual laser photons reflecting off the ground and returning to the satellite's receiver telescopes at a rate of 10,000 laser pulses/s. By matching those times with the satellite's precise location in space, the mission will determine the elevation of features on Earth and provide a continuous record of feature changes occurring in the 21st century. The 3,483-lb ICESat-2 will have a design life of three years and enough fuel to operate for seven years.

• Mitutoyo acquires majority stake in Tag Optics • Framos selected as Ximea distributor •

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Specialised Imaging awarded Queen's Award

Imaging system developer Specialised Imaging Ltd. has been awarded the 2016 Queen's Awards for Enterprise: Innovation for its Kirana camera and its growth in export sales.

The camera uses a custom image sensor developed with assistance from the Science and Technologies Facilities Council at Rutherford Appleton Laboratories, and is used in scientific, industrial and defense applications.

This is Specialised Imaging's second Queen's Award in five years. The company is a supplier of ultrahigh-speed imaging systems for research establishments and universities covering diverse fields such as space research, mechanical and electrical engineering, medicine and defense.

The Queen's Awards for Enterprise is an awards program for British businesses and other organizations that excel at international trade, innovation or sustainable development. They are the highest official U.K. awards for British businesses.

Pyreos secures £1.8M in funding

Sensor developer Pyreos Ltd. has secured £1.8 million ($2.4 million) of funding from new and existing shareholders as it continues to expand its business.

The company, which was spun out from German industrial firm Siemens in 2007, will use the cash to accelerate development and marketing of its products and sensor components, including the ezPyro sensor, launched in May. With a built-in digital interface, ezPyro has a broad range of applications including the detection of flames in the oil and gas and petrochemical industries, the analysis of gases by industrial laboratories or universities and in smart watches, fitness trackers and other wearable technology.

Existing investors taking part in the latest funding round include Robert Bosch Venture Capital GmbH, the Scottish Investment Bank, Seraphim Capital and Siemens Technology Accelerator. They were joined by new investor London Business Angels, a private investment group.

"We are delighted to have secured this level of investment at such an exciting time for the business," said Andy Laing, chief financial officer of Pyreos. "The continued support of major shareholders and the introduction of a knowledgeable new investor both validate the huge opportunities available to Pyreos. Their confidence in this business, and their cash from this funding round, will help us to accelerate the development and commercialization of a number of strategically important innovations."

The investment comes on top of a £2.5 million ($3.3 million) funding package that Pyreos secured from investors in March of 2015.

Eagleyard lasers used on ESA Gaia star surveyor

Two laser diodes from Eagleyard Photonics GmbH are being used on board the European Space Agency's Gaia star surveyor.

The single frequency DFB-852 laser diodes in a 14-pin butterfly housing are responsible for keeping the two telescopes in the right position, helping achieve Gaia's mission to create the most accurate 3D map of the Milky Way. They were shipped in 2010, with Gaia beginning its work in July of 2014.

On its way to meeting its goal, Gaia has pinned down the precise position and brightness of more than 1 billion stars. It also features the distances and motions across the sky for more than 2 million stars.

Eagleyard is a developer of high-power laser diodes based on gallium arsenide.

Luxtera ships one-millionth transceiver product

Semiconductor provider Luxtera Inc. has announced the shipment of its one-millionth silicon photonic parallel single-mode fiber four-lane transceiver product.

The patented technology blends the long reach capabilities of single-mode fibers with low-cost transceivers. This combination is critical for the cost-effective scaling of cloud computing data centers, according to the company.

Luxtera was a founding member and drafter of the 100G-PSM4 Multi Supplier Agreement (MSA) in 2014, the first standard to enable silicon photonics interoperability with legacy DML Optical modules for PSM4 fiber without compromising the cost benefits of silicon photonics. This widely accepted MSA has the support of dozens of companies with PSM4 product offerings and is being deployed at scale by the major cloud computing operators.

Carbon nanotube market poised for growth

According to a report by Lux Research, the carbon nanotube market will grow to 560 million in 2025, driven by faster development of commercial applications, while the market for graphene will lag at $305 million, due to slower adoption in energy storage.

The success of carbon nanotubes (CNTs) comes mainly from the use of multiwalled nanotubes as a superior replacement for carbon black, rather than as a super-strong material or for ultrafast electronics.

"The CNT market can now support a

few pure-play materials suppliers, but the overall state of the market remains oversupplied," said Anthony Schiavo, an analyst from Lux. "Developers finding ways to ease adoption with more convenient form factors and intermediates has been key. The less a product resembles a nanomaterial, the more likely it is to succeed."

Composites, Lux says, are key for graphene as new applications are tested. Composite applications will be the largest user of graphene through 2025, as the market grows to 7,500 metric tons amid a slowdown in energy storage. Emerging areas of growth include sensors and water, where companies such as G2O Water have used graphene derivatives.

New form factors such as sheet, tape and yarn are leading to easier product integration, raising chances of success. CNT yarns and sheets producer Nanocomp Technologies was the sole company to be ranked as "dominant" on the Lux Innovation Grid. N12 Technologies, which develops vertically aligned CNT sheets, was rated "high potential."

Lux provides research and strategic advice for emerging technologies.

Phoenix Software joins AIM

With the support of the SUNY Polytechnic Institute, photonic design automation (PDA) software developer Phoenix Software BV is now a member of the American Institute for Manufacturing Integrated Photonics (AIM), an industry-driven public-private partnership that fosters the nation's photonics manufacturing capabilities.

"AIM Photonics is building a membership that includes some of the country's most innovative technology companies that each provide critical elements to the success of the institute," said Robert Duffy, chairman of the AIM Photonics Leadership Council.

Phoenix Software is a developer of a photonics design automation platform that uses a hierarchical building block-based paradigm to enable photonic designers to capture and verify photonic integrated circuits (PICs) at a higher level of abstraction that is agnostic to any given physical fabrication process.

"We are extremely happy to be working with AIM and SUNY Polytechnic Institute in the United States," said Twan Korthorst, CEO of Phoenix Software. "We have many customers in the United States who have been wanting a U.S.-based fabrication site for their PICs and we were pleased to be able to inform them that photonic design kits and high-level photonic libraries will soon be available from AIM for the Phoenix Software platform."

AIM Photonics supports small- and medium-sized enterprises, providing practical access and technology on-ramps for U.S. industry, government and academic communities.

"Phoenix Software brings over 20 years of commercial photonic design automation experience with extensive work in the creation and use of PDKs [processs design kits]," said Michael Liehr, CEO of AIM and executive vice president of innovation and technology for the SUNY Polytechnic Institute. "We are excited to leverage their help in building the PDKs necessary to enable photonic designers to bring designs into our facilities. Phoenix and other PDA companies are key to scaling photonic design into commercial applications, and we look forward to working with Phoenix Software to help us work on next-generation electronic-photonic design automation platforms."

$724B

— value that the photonics market is estimated to reach by 2021, according to a report by MarketsandMarkets

Leica expands in southeastern US

Microscope developer Leica Microsystems Inc. has announced an expansion in the southeastern United States.

Associated Microscope Co. Inc. of Elon, N.C., will represent Leica's educational microscopy solutions exclusively in the states of Florida, Georgia, Alabama, Mississippi, Tennessee, North Carolina and South Carolina, and nonexclusively in the state of Virginia.

Associated Microscope currently provides Leica microscopes, accessories and service for education markets.

"We are very excited to expand our relationship with Associated Microscope into an exclusive partnership," said Lon Nelson, director of microscopy sales at Leica. "Associated's Service and Sales organization has worked tirelessly over their past 39 years in the classroom educational market, establishing a long list of satisfied and loyal customers. Associated will expand our presence in the southeast U.S. market and allow us to provide an even higher level of service and support to our educational customers."

Leica Microsystems develops and manufactures microscopes and scientific instruments for the analysis of micro- and nanostructures.

PEOPLE IN THE NEWS

Semiconductor equipment developer Suss Microtec AG has appointed **Franz Richter** as its president and CEO. Richter previously spent 14 years with the company, spending six as its CEO until 2004.

Ilsaraisaferrari.com

The European Photonics Industry Consortium (EPIC) has hired **Carmen Ferrari** as its events and marketing manager. Ferrari will manage events and online/offline interaction among experts and leaders of the international photonics community. "The timing for Carmen to join the EPIC team is perfect as it allows us to extend our offering of member services from technology workshops to now also include a series of international business delegations," said Carlos Lee, director general of EPIC.

The University of Arizona College of Optical Sciences (OSC) has announced that **Robert R. Boye**, manager of the physics-based microsystems department at Sandia National Laboratories, has been selected as the college's 2016 Alumnus of the Year. The award recognizes Boye's numerous contributions to the field of optics, both in research and in management. As part of the Sandia's Microsystems Engineering Sciences and Applications (MESA) facility in Albuquerque, N.M., Boye and his group have worked to advance the state-of-the-art in quantum sensing.

Professor John Bowers at the University of California, Santa Barbara, (UCSB) has been selected to receive the 2017 Institute of Electrical and Electronics Engineers (IEEE) Photonics Award. Bowers is the first faculty member from UCSB to receive the honor, which recognizes his pioneering research in silicon photonics, including hybrid silicon lasers, photonic integrated circuits and ultralow-loss waveguides.

Sandia National Laboratories

The Eta Kappa Nu honor society of the Institute of Electrical and Electronics Engineers (IEEE) has awarded researcher **Salvatore Campione** at Sandia National Laboratories its 2016 Outstanding Young Professional Award. A researcher of nanophotonics and metamaterials, with special expertise in periodic structures, leaky-wave antennas and electromagnetic theory, Campione was recognized by the society "for his contributions to the electromagnetic modeling of complex systems and structures from microwave to optical frequencies." The Outstanding Young Professional Award is presented to exceptional young engineering professionals for meritorious service in the interests of humankind, as well as for outstanding achievements in their career. Campione, who received his doctorate degree in electrical and computer engineering from the University of California, Irvine, in December 2013, is listed as author or co-author in more than 50 peer-reviewed journal articles, two book chapters and 80 conference contributions, along with three provisional patents.

The International Society for Optics and Photonics (SPIE) has awarded **Jennifer Barton** the SPIE President's Award, and **Majid Rabbani** the SPIE Directors' Award. Barton is interim director of the BIO5 Institute at the University of Arizona, which works to solve complex biology-based problems affecting humanity. Barton is known for her innovative use of optical techniques in the detection and treatment of cancer and other diseases including the development of miniature endoscopes that combine two imaging techniques, optical coherence tomography and fluorescence spectroscopy. Barton is leading a two-year, $1 million project funded by the National Cancer Institute to identify imaging biomarkers of ovarian cancer, the deadliest gynecological cancer in the United States, to enable the first effective screening system for the cancer.

Rabbani's research interests span various aspects of digital image and video processing and analysis. Rabbani is symposium chair for SPIE Commercial and Scientific Sensing and Imaging 2017 at SPIE Defense and Commercial Sensing, has served on symposium and conference committees for other events, is the chair of the SPIE Fellows Committee and was a longtime course instructor for SPIE.

Business Wire

Interconnect data solutions provider Mellanox Technologies Ltd. has appointed **Alinka Flaminia** as its senior vice president and general counsel, assuming responsibility for the company's global legal affairs, public policy interests and compliance operations. Gideon Rosenberg, vice president of legal affairs, will take on the additional role of deputy general counsel.

Laser Guide Star Alliance wins Leibinger Innovation Prize

The Laser Guide Star Alliance, the development team led by Domenico Bonaccini Calia, Wilhelm Kaenders and Wallace Clements at the European Southern Observatory in Garching, Germany, along with Toptica Photonics AG in Gräfelfing, Germany, and MPB Communications Inc. in Montreal, received third prize in the 2016 Berthold Leibinger Innovation Prize.

The team developed and patented an essential foundation of a new beam source technology for the Very Large Telescope based in the Chilean Atacama Desert. Using Raman amplification, they generated the required wavelength with diode and fiber lasers, providing performance significantly higher than 20 W. The technology took eight years to develop.

In April, four of the radiation sources were mounted and used on the telescope. Uses for the technology also include the tracking of satellites, atomic spectroscopy and photonic imaging.

The Berthold Leibinger Innovation Prize honors scientists and developers who make advancements in the field of laser technology. Since 2000, the Berthold Leibinger Stiftung has given the award every two years for excellent research and development work on the application or generation of laser light.

ESO

The Berthold Leibinger innovation award ceremony was held Sept. 9.

RPO awarded small business grant for chalcogenide glass IR development

Rochester Precision Optics (RPO) LLC has been awarded a grant from the Small Business Technology Transfer (STTR) government program to pursue chalcogenide glass IR optic development for quantum cascade lasers.

RPO, after successful completion of Phase 1 STTR, seeks to develop a fast axis collimating lens for quantum cascade lasers (QCL), which are tunable to emit in the full IR range. Because primary applications are wide, the lenses must withstand the stress of both continuous wave and pulsed laser emission. Lenses for this application are not known to currently exist, making RPO first in the industry to achieve a working prototype. “Our work in developing chalcogenide

IR lenses for QCL is just one example of RPO's commitment to innovation," said Dane Hileman, president of RPO.

RPO has successfully designed the lens, as well as test materials and coatings for damage threshold. By the end of Phase 1, a working prototype was produced and provided to the U.S. Air Force for testing.

"We had great results with the prototype," said George Lindberg, RPO's glass materials manager and principal investigator on the project.

Potential applications range from military systems to spectroscopy, including medical, scientific, research, security and pollution monitoring.

The STTR program expands funding opportunities in the federal innovation R&D arena. The program is focused on the expansion of the public/private sector partnership to include the joint venture opportunities for small businesses and nonprofit research institutions.

RPO is a developer of glass, plastic, crystal and IR optics for customers in defense, commercial and industrial markets.

Lighting Science signs patent agreement with Osram-Sylvania, Hubbell

LED solutions provider Lighting Science has announced the signing of a perpetual patent license agreement with Osram-Sylvania Inc. and Hubbell Lighting, a division of Hubbell Inc.

The license agreement covers Lighting Science's 968 patent family and applies to Osram-Sylvania's and Hubbell's respective low-profile retrofit downlight products. This technology was first introduced in Lighting Science's Glimpse flush mount retrofit downlight.

"As a leading provider of innovative lighting products, Hubbell is pleased to be able to license Lighting Science's innovative downlight technology, which will bring significant value to our customers," said Kevin Poyck, group president for Hubbell Lighting.

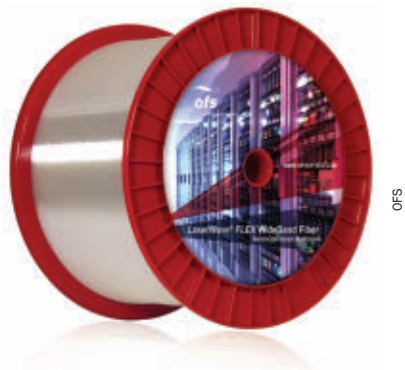
Osram-Sylvania and Hubbell are the latest companies to join Lighting Science's patent licensing program. Others include Cree, Cooper, USA Light and Electric, Green Creative, Cordelia Lighting and Hyperikon. Lighting Science holds nearly 400 U.S. and foreign patents covering the fields of biologically adjusted and corrected lighting, light spectrum control, micro-electric optics, advances in roadway infrastructure and various other lighting form factors.

Lighting Science provides LED lighting solutions, designing and manufacturing products for consumer and commercial applications.

• Elbit receives $90M+ contract • PI Alignment System named R&D 100 finalist •

OFS Cable wins innovation award

The LaserWave FLEX WideBand Multimode Optical Fiber from OFS Fitel LLC has won a silver award from the 2016 Cabling Installation and Maintenance Innovators Awards Program.



OFS

Presented annually, the awards recognize the most innovative applications of cabling and communications technology products and systems in the structured cabling industry.

"OFS appreciates this recognition of our product by the 2016 Innovators Awards Program," said Timothy F. Murray, CEO and chairman of OFS. "The LaserWave FLEX WideBand Multimode Fiber reflects our company's ongoing commitment to developing industry-leading fiber optic innovations that exceed the needs and expectations of our customers while also positively affecting the lives of end users around the globe."

Designed to meet the demands of today's OM4 networks, the LaserWave FLEX WideBand Multimode Fiber uses short-wavelength division multiplexing to allow multiple lanes of traffic over the same strand of optical fiber. With this ability, this new fiber may increase transmission capacity by up to 400 percent, helping service providers gain greater capacity and faster speeds using less fiber, time and money.

OFS is a designer, manufacturer and provider of optical fiber, fiber optic cable, connectivity, fiber-to-the-subscriber and specialty photonics products.

Hyperspectral imaging poised for growth

The global hyperspectral imaging market is projected to reach $90 million by 2021 with a compound annual growth rate of 9.8 percent, according to a report by Mordor Intelligence.

Hyperspectral imaging is a part of many medical procedures such as gastrointestinal tract, mucosal membrane, ophthalmology, vascular systems and surface tissue applications. The market has been segmented into agriculture, surveillance, life sciences, environmental testing, food industry, mining and mineralogy, machine control, physics and astronomy and others.

Use in military surveillance contributed to the largest market share of nearly 21 percent in 2015. Mining, mineralogy and meteorological applications have contributed greatly toward a high market share. Healthcare applications, especially in diagnostics, are increasing rapidly, and the hyperspectral imaging market for life sciences is expected to grow at the highest compound annual growth rate. Untapped markets in emerging economies, elucidation of newer application areas of hyperspectral imaging and increasing adoption in the health-care industry are expected to bring other market opportunities.

CSA laser launches aboard NASA OSIRIS-REx

A laser altimeter from the Canadian Space Agency (CSA) has been launched on board NASA's OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) spacecraft, en route to the Bennu asteroid.

The instrument was built for CSA by MacDonald, Dettwiler and Associates Ltd., and Optech. In exchange for providing the laser altimeter, CSA will receive a portion of the returned asteroid sample for study.

The OSIRIS-REx Laser Altimeter (OLA) is the most sophisticated lidar system ever launched to an asteroid, containing approximately 4,000 mechanical parts and 3,000 electrical parts, and using less power than a 75-W light bulb.

The device will create 3D maps of the near-Earth asteroid Bennu, aiding in the selection of a sample collection site. The advanced lidar system will provide mission scientists with fundamental data on the asteroid's shape, topography, surface processes and evolution. An accurate shape model will also be an important tool for navigators as they maneuver the spacecraft around the 500-m-wide asteroid. Canada will own 4 percent of the returned sample, which will be curated and studied.

Trumpf creates venture capital firm

Manufacturing solutions provider Trumpf GmbH & Co. KG has founded Trumpf Venture GmbH, a venture capital company to fund technology startups.

The company aims to fund promising young companies that want to play a major role in shaping the future of industry. Over the coming five years, Trumpf Venture GmbH will establish an investment portfolio of around 40 million euros.

"Once we get into our stride, we plan to participate in around five startups per year," said Christof Siebert, head of technology management at Trumpf. "As a strategic investor, we want to use our network, our industrial production expertise and our technological know-how to assist startups with market launch and successful growth.

Trumpf says it is especially interested in the fields of photonics and digitally connected production as well as in new manufacturing processes, smart components and high-tech materials.

"We're already having discussions with first startups and assuming that we'll be able to make investments relatively soon," Siebert said.

Trumpf provides manufacturing solutions for machine tool, laser and electronics markets.

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Hyperspectral imaging shines light on ancient Mexican text

Journal of Archaeological Sciences: Reports, 2016 Elsevier

Pages 10 and 11 of the back of Codex Selden. The top image shows the pages as they appear to the naked eye. These pages were scraped in the 1950s during a series of invasive tests which uncovered this vague impression, hinting at the possibility that an earlier Mexican codex lay hidden beneath. The lower image has been created using hyperspectral imaging to show the hidden pictographic scenes that lie underneath a layer of plaster and chalk on the back of Codex Selden.

Journal of Archaeological Sciences: Reports, 2016 Elsevier

An image created using hyperspectral imaging, which shows the hidden pictographic scenes on pages 10 and 11 of the back of Codex Selden. These images lie underneath a layer of plaster and chalk and are not visible to the naked eye. The Bodleian Libraries' hyperspectral imaging scanner shines white light at an object and for each pixel, it captures all the light that the object reflects back — not just the visible light that the human eye can see, but 900 different wavelengths in the electromagnetic spectrum. Different pigments or paints have different 'spectral signatures' or 'fingerprints' which allow them to be identified by the scanner. Through high-level computer processing, reconstructed images like this one can be created.

OXFORD, England — Researchers at the Bodleian Libraries have used hyperspectral imaging to reveal never-before-seen pictographic scenes from a rare precolonial Mexican codex that has been hidden underneath a layer of gypsum and chalk for 500 years.

Until now, no other technique has been able to unveil the concealed pictorial narrative in a noninvasive manner. The organic paints that were used to partially create the vibrant images on early Mexican codices do not absorb x-rays, which ruled out x-ray analysis, a technique that is commonly used to study works of art.

"Hyperspectral imaging has shown great promise in helping us to begin to reconstruct the story of the hidden codex and ultimately to recover new information about Mixtec history and archaeology," said David Howell, head of Heritage Science at the Bodleian Libraries. "This is very much a new technique, and we've learned valuable lessons about how to use hyperspectral imaging in the future both for this very fragile manuscript and for countless others like it."

The researchers analyzed seven pages of the codex for this study. The results thus far indicate that the covered text and pictorials contain unique genealogic information that may prove invaluable for the interpretation of archaeological remains from southern Mexico.

"After four or five years of trying different techniques, we've been able to reveal an abundance of images without damaging this extremely vulnerable item. We can confirm that Codex Selden is indeed a palimpsest," said Ludo Snijders from Leiden University.

A palimpsest is a document that has been covered up and reused to make the manuscript that is currently visible. The newly revealed manuscript was hidden on the back of Codex Selden, which dates from around 1560 and is one of fewer than 20 known Mexican codices to have survived from precolonial and early colonial Mexico.

The researchers continue to analyze the remainder of the document with the aim of reconstructing the entire hidden imagery, which will allow the text to be interpreted more fully.

Working with the Humanities Division in the University of Oxford, Bodleian Libraries acquired the hyperspectral scanner in 2014 with the support of the University's Fell Fund. Hyperspectral imaging is now used by Bodleian researchers to reveal hidden text and images and identify unknown substances and pigments with a high degree of accuracy. Researchers have recently used the scanner to clarify the text of the famous Bakhshali manuscript from India, which includes the first use of zero; to analyze the medieval Gough Map, the earliest road map of Great Britain; and to reveal a hidden devil in a centuries-old Armenian gospel-book.

The research was published in the *Journal of Archeological Science* (doi: 10.1016/j.jasrep.2016.07.019).

Vortex laser may help shape the future of data transfer

BUFFALO, N.Y. — A light-based communications tool that is structured to carry data in a helical path may enable fast transfer of large amounts of data, resolving potential bottlenecks in data transfer as the demand for information sharing grows. The novel technique uses a vortex beam that travels in a corkscrew pattern, encoding data into the vortex twists. The shape of the beam enables it to encode data for optical communications with greater freedom than a conventional laser, giving it the potential to carry 10 times or more information than lasers that move in a linear direction.

Although the size of today's computers has been scaled down as increasing capability is packed into silicon chips, creating light beams with the desired amount of twist has typically been achieved with bulk optic devices.

A possible approach would be to use a twisted-light source with a controlled amount of optical angular momentum that would be generated internally to the designed device structure.

To make a vortex laser useful for practical applications, researchers at the University at Buffalo, the State University of New York, reduced a vortex laser to a size compatible with the computer chips used in today's computers. They used orbital angular momentum (OAM) to distribute the laser in a corkscrew pattern, and demonstrated that a microring laser could produce a single-mode OAM vortex lasing with the ability to precisely define the topological charge of the OAM mode.

The research team also showed that the polarization associated with OAM lasing could be further manipulated on demand to create a radially polarized vortex emission.

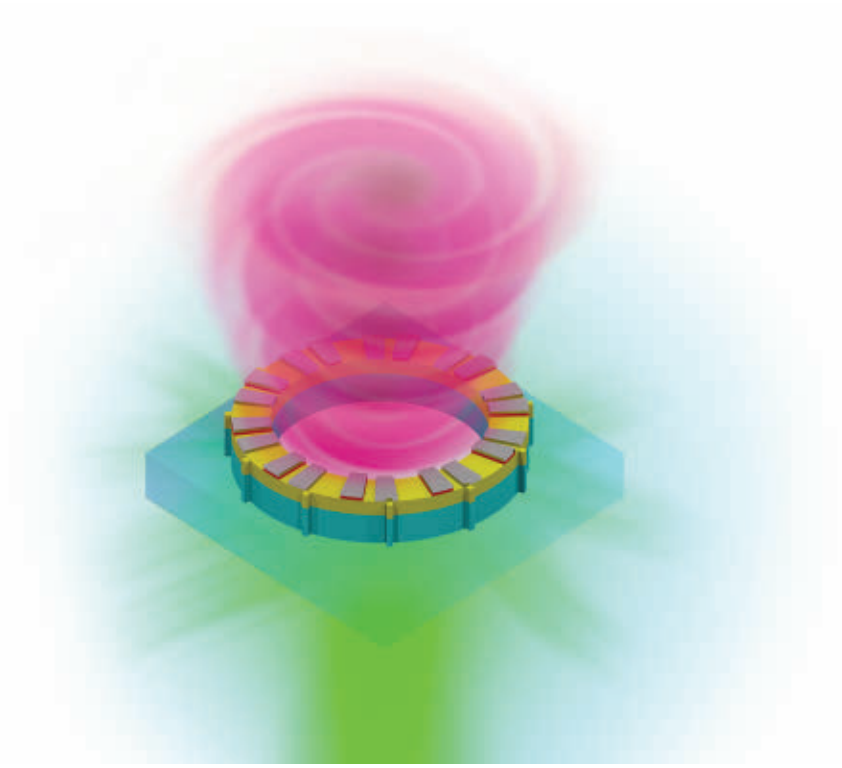
"To transfer more data while using less energy, we need to rethink what's inside these machines," said professor Liang Feng.

Use of OAM lasing, especially at a micro- and nanoscale, could address the growing demand for information capacity. The research team's OAM microlaser could find applications in the next generation of integrated optoelectronic devices for optical communications in both quantum and classical regimes. As techniques like wavelength-division multiplexing and time-division multiplexing near their data transfer limits, microlasers could find application in telecommunication and information technologies to increase the rate of information transmission.

The research was published in *Science* (doi: 10.1126/science.aaf8533).

University at Buffalo, SUNY

A close-up look at the vortex laser beam.



University at Buffalo, SUNY

A vortex laser on a chip. Because the laser beam travels in a corkscrew pattern, encoding information into different vortex twists, it's able to carry 10 times or more the amount of information than that of conventional lasers.

Solid-state photodetector may speed switching of optoelectronic devices

NAGAKUTE, Japan — An all-solid-state wavelength-dependent bipolar photodetector (WBPD), composed of a single semiconductor, has demonstrated a faster response time than existing WBPDs that are comprised of hetero-nanostructures. The novel WBPD has also demonstrated tunable switching wavelengths.

To speed response time in the novel photodetector, researchers at Toyota Central R&D Labs used a tungsten disulphide film with front and rear ends modified by oxidation and sulpherization. The band structure of the semiconductor film had the ability to increase or decrease at both the rear and front surfaces, which allowed it to form a U (or upside down U) shape, making the film capable of carrying photocurrents with wavelength-dependent switching.

The researchers also exploited the dependency between wavelength and depth of photon penetration in semiconductor material. Because shorter wavelengths are more readily absorbed than long, shorter wavelengths have a higher distribution of excited electrons near the front surface; whereas longer wavelengths have greater distribution at a deeper level of penetration into the material. When drift and diffusion processes are taken into account, this phenomenon causes photocurrents in opposite directions, for short- and long-wavelength incident light.

The researchers showed that the threshold wavelength at which the photocurrent polarity changed could be tuned by choosing a suitable thickness for the device. The device thickness affected the distribution of photoexcited carriers as a result of the wavelength-dependent absorption, allowing tunable switching wavelengths.

In existing WBPD devices, the switchable photocurrent polarity behaviors are caused by differences in the optical properties of the two materials that comprise the device; and the transition wavelengths of the output polarity are limited by the optical properties of the two types of materials. The low carrier mobility in liquid electrolytes, which are used in many current WBPD devices, can slow switching response time.

For current and future optoelectronic devices such as logic gates, extremely high response times will be required. An all-solid-state WBPD (i.e., a WBPD without any electrolytes) may have significant advantages over WBPDs using molecules and electrolytes.

"Optoelectronic sensors that can switch their photocurrent direction based on the wavelength of incident light are an important building block in novel optical logic gates, color sensors and photocatalysts," said Takashi Ikuno and Masaki Hasegawa, researchers at the Toyota Central R&D Labs.

The research was published in *Applied Physics Express* (doi:10.7567/APEX.9.062201).

Direct-drive laser fusion experiments move toward target ignition

ROCHESTER, N.Y. — Conditions capable of producing a direct-drive laser fusion yield that is five times higher than the current record for laser fusion energy yield have been demonstrated. The work, which shows the use of direct-drive laser fusion to compress fuel to about half the pressure required to ignite it, represents an advance in a national research initiative to develop fusion as an energy source. In a direct-drive approach to inertial confinement fusion (ICF), researchers at the University of Rochester's Laboratory of Laser Energetics (LLE) targeted 60 laser beams to strike a millimeter-sized pellet of fuel. At the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, researchers are using 192 laser beams in an indirect-drive approach to achieving laser fusion, in which the laser light is first converted into x-rays in a hohlraum.

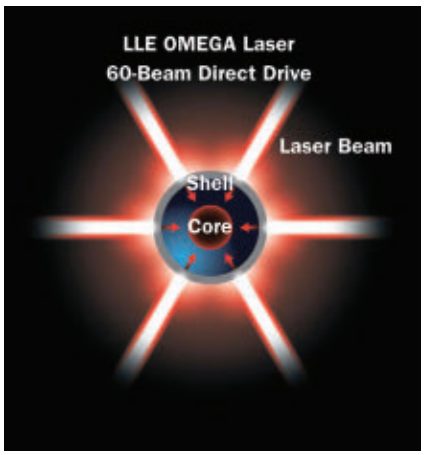
LLE researchers reported that direct-drive implosions on the LLE's OMEGA laser achieved core conditions that could lead to significant alpha heating at incident energies available on the NIF scale. The extrapolation of the experimental results from OMEGA to NIF energy assumes that the relative conditions produced at LLE are reproduced and scaled up at the NIF.

The LLE results indicate that the direct-drive approach may be a potential alternative to other fusion methods.

"We've shown that the direct-drive method is on par with other work being done in advancing nuclear fusion research," said LLE researcher Arijit Bose.

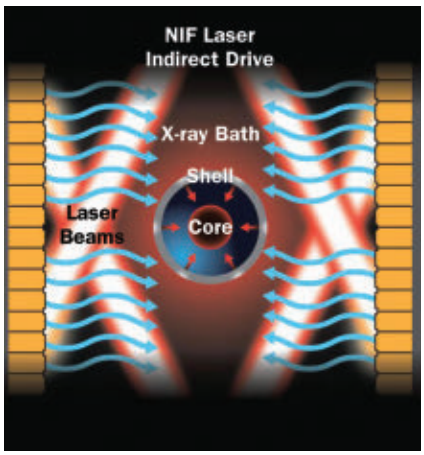
Researchers estimated that the current best-performing OMEGA implosion could produce approximately 125 kilojoules (kJ) of fusion energy. Similar levels of alpha heating have been observed in current highest performing indirect-drive NIF implosions.

One hundred kJ is roughly equivalent to 20 minutes' output of a 100-watt light; but in a fusion experiment at NIF, that energy would be released in less than a billionth of a second, and would be enough to bring the fuel a step closer to conditions required for ignition. If ignited, thermonuclear fuel would unleash an amount of fusion energy much greater than the amount of input energy.



Michael Osadciw/University of Rochester

In the direct-drive method of inertial confinement fusion, laser beams directly strike the fuel pellet.



Michael Osadwic/University of Rochester

In the indirect-drive method of inertial confinement fusion, laser beams are converted to x-rays.

"In laser fusion, an ignited target is like a miniature star of about a 10th of a millimeter, which produces the energy equivalent of a few gallons of gasoline over a fraction of a billionth of a second. We are not there yet, but we are making progress" said professor Riccardo Betti.

E. Michael Campbell, deputy director of LLE, said the results were made possible because of a number of improvements in the direct method approach. One improvement involved the aiming of

the 60 laser beams, which now strike the target more uniformly.

"It's like squeezing a balloon with your hands; there are always parts that pop out where your hands aren't," said Campbell. "If it were possible to squeeze a balloon from every spot on the surface, there would be a great deal more pressure inside. And that's what happens when the lasers strike a target more symmetrically."

"If we can improve the uniformity of the way we compress our targets, we will likely get very close to the conditions that would extrapolate to ignition on NIF. This is what we will be focusing on in the near future" said Valeri Goncharov, director of the LLE theory division.

"Arijit's work is very thorough and convincing. While much work remains to be done, this result shows significant progress in the direct-drive approach," said Betti.

Two additional enhancements were made at LLE: The quality of the target shell was improved to make it more easily compressed, and the diagnostics for measuring what's taking place within the shell were improved. Researchers are now able to capture x-ray images of the target's implosion with frame times of 40 trillionths of a second, giving them information on how to more precisely adjust the lasers.

"What we've done is show the advantages of a direct-drive laser in the nuclear fusion process," said Campbell. "And that should lead to additional research opportunities, as well as continued progress in the field."

Bose says the next step is to develop theoretical estimates of what is taking place in the target shell as it is being hit by the laser, to garner information that could lead to further enhancements.

Two recent LLE papers report that OMEGA experiments match the current NIF record when extrapolated to NIF energies. Igniting a target is the main goal of the laser fusion effort in the United States.

Using graphene to lower the cost and footprint of LEDs

HSINCHU, Taiwan — A white LED (WLED) has been developed using a hybrid metal-organic framework (MOF) material, which provides electrically driven white light emission with a continuous spectrum that matches well with natural sunlight. It could offer an economical, environmentally friendly alternative to WLEDs whose development depends on the photon down-conversion of phosphors containing rare-earth elements.

To reduce the footprint and cost of WLEDs, researchers from National Taiwan University and Academia Sinica designed a direct WLED derived from a strontium-based MOF, graphene and inorganic semiconductor hetero-junctions. Testing of the device showed that the WLED's emission spectrum was continuous, similar to natural sunlight. This is in contrast to currently commercially

available WLEDs, which are composed of three discrete colors (red, green and blue), and which can make the colors of the objects they illuminate appear distorted.

The researchers attribute the successful demonstration of MOF-based, electrically driven white light emission to several factors, including an appropriate band alignment between the MOF and semiconductor layer and to the unusual properties of graphene, including its excellent conductivity properties, its transparency and the small effective mass necessary for the efficient injection of free carriers into a light-emitting active layer.

Widespread use of low-power, long-lasting LEDs in the U.S. could save nearly 348 terawatt-hours by 2027, an amount comparable to the annual output of 44 power plants, according to the U.S. Department of Energy. WLEDs are currently made with rare-earth elements and mining these minerals can be costly and produce toxic waste. Additionally, existing commercial methods for producing WLEDs involve multiple components and steps that can reduce efficiency and quality.

Together with environmentally friendly materials and a low-cost fabrication process, this timely discovery may be useful in the development of solid-state lighting and in reducing global energy consumption.

Novel device adds to interferometry's optical capabilities

ROCHESTER, N.Y. — An advance in interferometry, named the Hilbert-space analyzer, may lead to novel ways of analyzing beams of light that are not dependent on temporal delays.

Interferometers make minute measurements by manipulating beams of light using an optical delay — an effect that's typically achieved by adding length to one of the beam's paths, which slows the signal down. The creators of the Hilbert-space analyzer have found a way to introduce a delay that is unrelated to time.

The device, which was developed by research teams from the University of Central Florida and the University of Rochester, operates as a kind of generalized beamsplitter by introducing a "generalized delay" that avoids adding extra lengths in the beam paths. Instead, it manipulates the beam and transforms it using spatial light modulators.

The research applies quantum mechanics formalism to the field of classical optics and "provides an optical device that has been missing from the arsenal of optics," said associate professor Ayman F. Abouraddy.

The Hilbert-space analyzer can use a traditional delay to obtain the wavelengths from which the signal is constructed via optical interferometry. It can use a generalized delay to extract the contributions of other waveforms, or modal sets, to an optical beam.

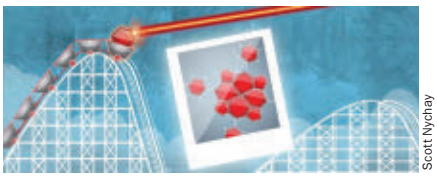
"We don't need to find new approaches

for new modal sets: the Hilbert-space analyzer is a one-stop shop for all your modal analysis needs," Abouraddy said.

"For now, the most interesting application for Hilbert-space analyzers is in optical communications, which uses light to carry information across some distance," he added.

Abouraddy presented "Hilbert-Space Analyzers: Basis-Neutral Modal Analysis via Generalized Optical Interferometry" at Frontiers in Optics (FiO) / Laser Science (LS) in October.

Scientists discern light-driven molecular changes using LCLS laser



Scott Nychay

To understand how molecules undergo light-driven chemical transformations, scientists need to be able to follow the atoms and electrons within the energized molecule as it gains and loses energy. In a recent study, a team of researchers at Argonne, Northwestern University and the Technical University of Denmark used the ultrafast high-intensity pulsed x-rays produced by the Linac Coherent Light Source to take molecular snapshots of these molecules.

LEMONT, Ill. — To better understand how molecules undergo light-driven chemical transformations, a research team from the Argonne National Laboratory, Northwestern University, the University of Washington and the Technical University of Denmark used the Linac Coherent Light Source (LCLS) at the Department of Energy's SLAC National Accelerator Laboratory to image molecules in their excited state. Results revealed an extremely short-lived state of excitation lasting only a few hundred femtoseconds (fs) before the molecule relaxed into a lower energy state. Learning more about this state is a step toward the further development of energy sources.

When the laser pulse hits the molecule, an electron from the outer ring moves into the center, creating a charge imbalance, which in turn creates an instability within the molecule. Another electron from the center migrates back to the outer ring, and the excited electron falls back into the lower open orbital to take its place.

"This first state appears and disappears so quickly, but it's imperative for the development of things like solar fuels," said Lin Chen, senior chemist at Argonne National Laboratory and professor of chemistry at Northwestern University. "Ideally, we want to find ways to make this state last longer to enable the subsequent chemical processes that may lead to catalysis, but just being able to see that it is there in the first place is important."

By using the LCLS, the researchers were able to capture atomic and electronic arrangements within the molecule that had lifetimes as short as 50 fs — about as long as it takes light to travel the width of a human hair.

"Although we had previously captured the molecular structure of a longer-lived state, the structure of this transient state eluded our detection because its lifetime was too short," Chen said.

The challenge, Chen added, is to prolong the lifetime of the excited state through the design of the molecule.

"From this study, we gained knowledge of which molecular structural element, such as bond length and planarity of the ring, can influence the excited state property," she continued. "With these results we might be able to design a system to allow us to harvest much of the energy in the excited state."

For the study, the research team used metalloporphyrin, a molecule similar to the building blocks needed for natural and artificial photosynthesis. Metalloporphyrins are of interest to scientists seeking to convert solar energy into fuel.

The research was published in the *Journal of the American Chemical Society* (doi: 10.1021/jacs.6b02176).

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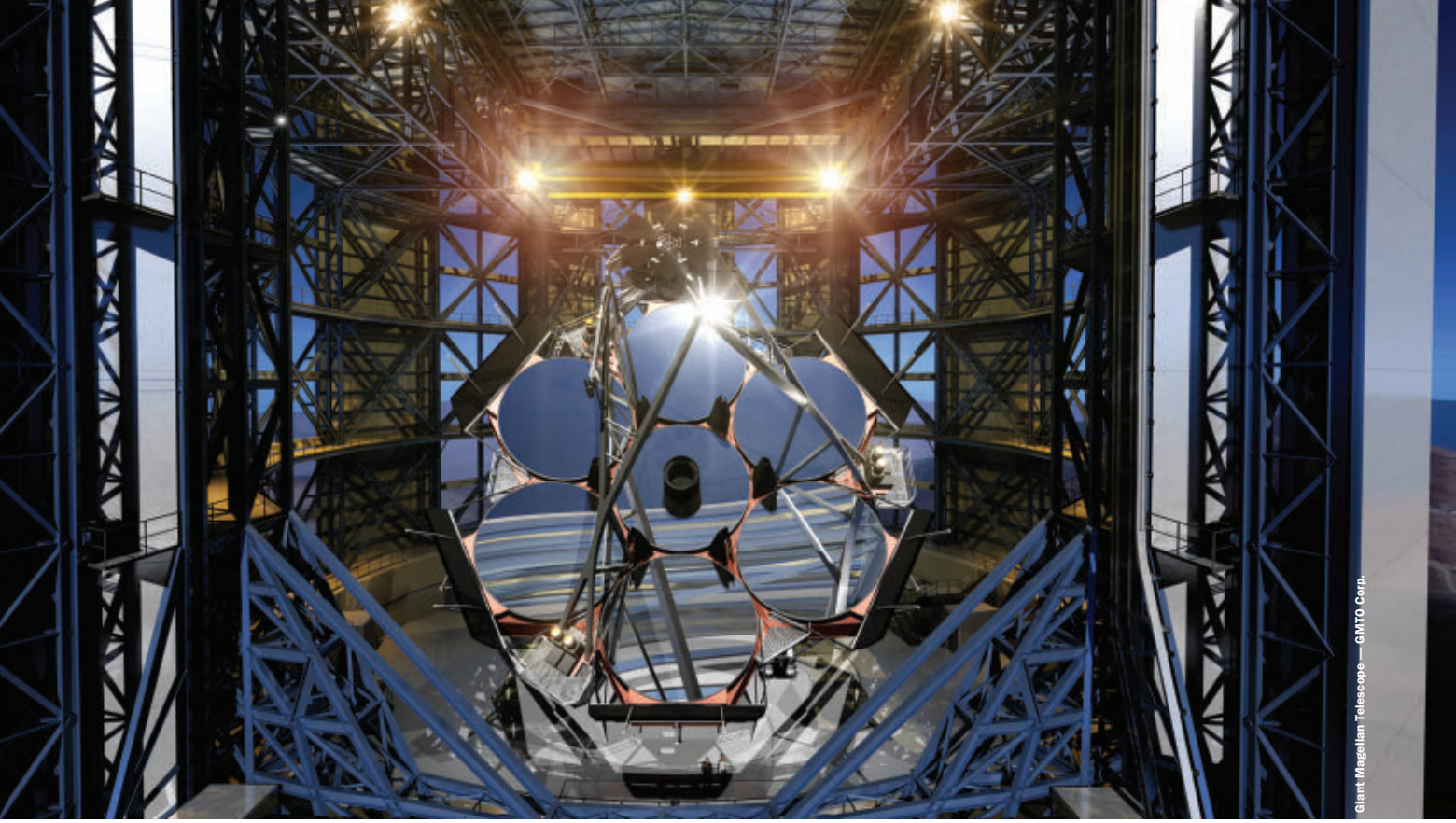


The Giant Magellan Telescope is a segmented mirror telescope that employs seven of today's largest stiff monolith mirrors as segments. Six off-axis 8.4-meter or 27-foot segments surround a central on-axis segment, forming a single optical surface 24.5 meters, or 80 feet, in diameter.

A **High-Resolution View** of the Universe

Adaptive optics on the Giant Magellan Telescope sense optical aberrations caused by atmospheric turbulence and correct them in real time using a deformable mirror.

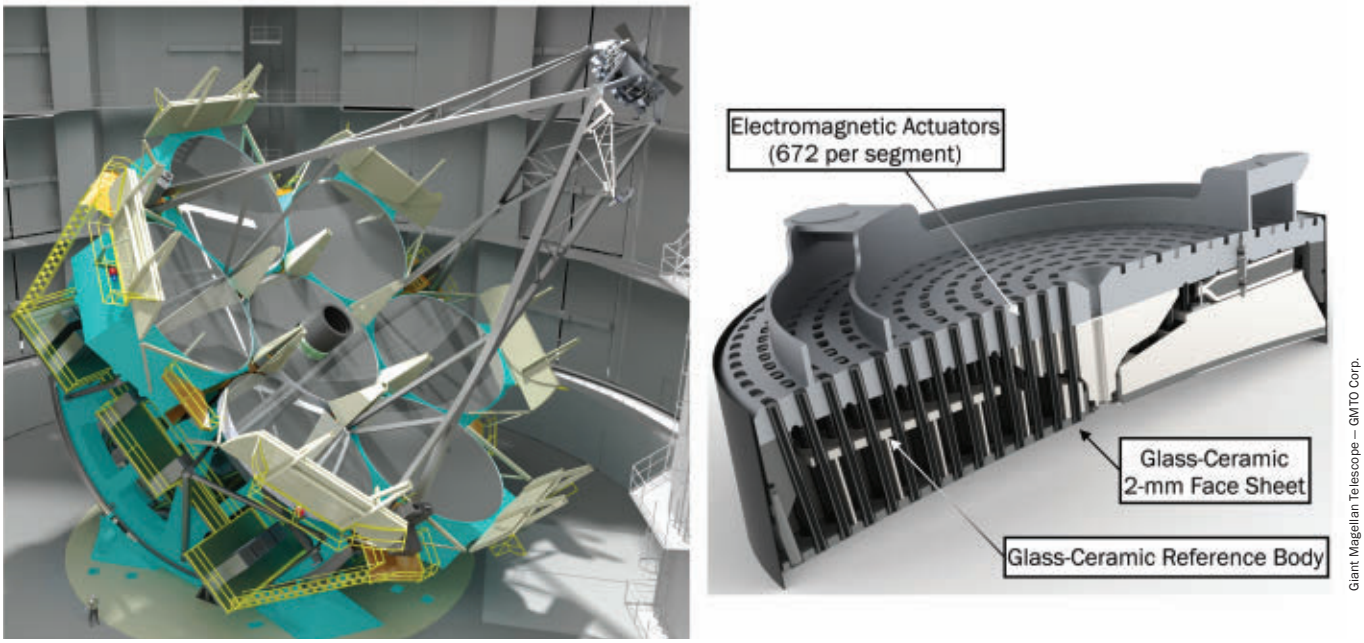
BY ANTONIN BOUCHEZ, GIANT MAGELLAN TELESCOPE ORGANIZATION (GMTO CORP.)

Under ideal circumstances, the resolution of an optical system is limited by the diffraction of light waves. This diffraction limit, the maximum resolution a telescope can achieve, improves linearly with the telescope's aperture. However, the view of the universe provided by ground-based telescopes is typically limited not by diffraction, but by atmospheric blurring due to temperature inhomogeneities and turbulence in the Earth's atmosphere. Even the best astronomical sites in the world, located on remote mountaintops with particularly stable air, degrade diffraction-limited images to 0.6 to 0.7 arcseconds. While this is approximately 100 times finer than the naked eye can achieve, it is no better than the diffraction limit of a modest backyard telescope.

Space telescopes do not suffer from the limitations imposed by atmospheric turbulence. The 2.4-m-diameter Hubble Space Telescope can produce images with detail as fine as 0.04 arcseconds in visible light. The 6.5-m-diameter James Webb Space Telescope, due to be launched in 2018, will have nearly three times higher resolution in the infrared, but its mirrors are not specified to achieve the diffraction limit in the visible.

Adaptive optics

Adaptive optics (AO) allows ground-based telescopes to approach the resolution of comparably sized space telescopes. Adaptive optics systems sense the optical aberrations caused by atmospheric turbulence, and correct them in real time using a deformable mirror. The deformable mirror must be adjusted hundreds of times per second to keep up with the evolving turbulence. Most large ground-based observatories are now equipped with



Rendering of the Giant Magellan Telescope **(left)** and a cross section of an adaptive secondary mirror segment **(right)**.

AO systems to feed their narrow field-of-view infrared instruments, improving their resolution by over a factor of 10. These instruments have made spectacular discoveries, including the first images of planets around other stars, storms on Saturn's moon Titan, and the discovery of a super-massive black hole at the center of our galaxy.

The Giant Magellan Telescope (GMT) is a 24.5-m-diameter telescope being built at Las Campanas Observatory in Chile by a global consortium of universities and research institutions. It is one of three "extremely large telescope" (ELT) projects currently underway, all of which plan to start initial science operations in 2022 to 2024.

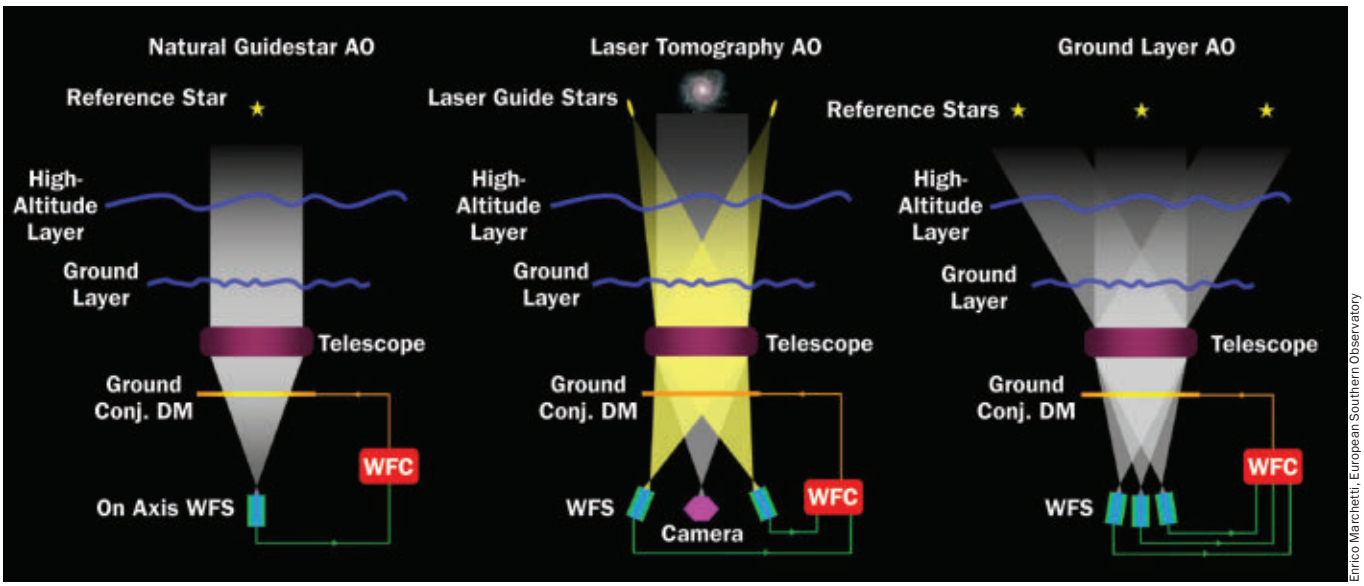
The GMT has a segmented primary mirror composed of seven 8.4-m-diameter glass segments with a common focus. These giant mirror segments are currently being manufactured by the Richard F. Caris Mirror Lab at the University of Arizona, one of the GMT founding institutions. Unlike most current-generation telescopes, GMT incorporates an adaptive secondary mirror, thus providing atmospheric turbulence correction to every instrument on the telescope. This design was pioneered at the Large Binocular Telescope on Mount Graham in southeastern Arizona. The GMT adaptive secondary mirror is segmented, with seven 1-m-diameter circular segments matching those of the primary mirror. Each of these deformable mirror segments has 672 electromagnetic actuators that levitate and bend a 2-mm-thin glass face sheet with permanent magnets bonded to its back. The resulting adaptive mirror can be updated 2,000 times per second, providing precise atmospheric correction with no need for additional optics ahead of the scientific instruments.

A single deformable mirror can only perfectly correct the optical aberrations caused by atmospheric turbulence along a single line of sight through the atmosphere. Alternately, the deformable mirror can be commanded to correct the average turbulence over an extended field of view. This trade-off allows the adaptive optics correction to be tuned to the observations being performed. Bright guide stars near the scientific target of interest are required to measure the atmospheric aberrations with sufficient speed. If these are not available, then artificial guide stars generated by the backscatter of laser light in the upper atmosphere can be used. These considerations have led to the development of a wide variety of AO control techniques, including natural guide star AO (NGAO), ground-layer AO (GLAO) and laser tomography AO (LTAO).

Direct detection of exoplanets

Natural guidestar AO is the simplest form of AO employed on the GMT, used when a bright guide star is available near the scientific target. It provides the highest resolution and highest contrast images, over a narrow field of view. NGAO is particularly well-suited to the study of extrasolar planets orbiting nearby stars, since these stars provide an ideal reference. Over 3,000 extrasolar planets have now been identified, nearly all using indirect detection techniques such as monitoring the Doppler shift of the parent star or the photometric signature of a planetary transit across the parent star. The planets themselves are lost in the glare of the parent star, which is typically 10^4 to 10^8 times brighter and just 0.1 to 1.0 arcseconds away. Adaptive optics provides the only method to directly image these planets and analyze their reflected and emitted light.

The natural guide star AO mode on the GMT will be able to reach planets up to 10^7 times fainter than the parent star in the near-infrared, at just 0.1 arcseconds from the star. This is sufficient to image

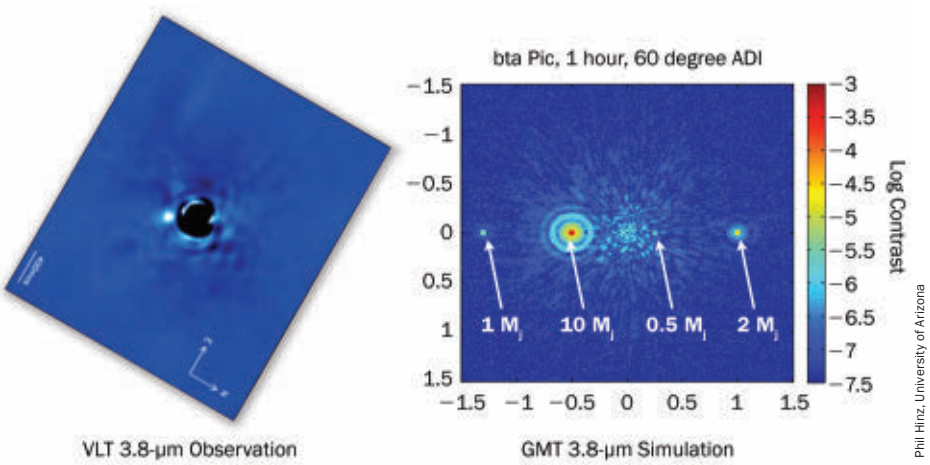


Enrico Marchetti, European Southern Observatory

Schematic representation of three possible adaptive optics control techniques. In each case the output of wavefront sensors (WFS) is analyzed by a wavefront control computer (WFC) to update a deformable mirror (DM). The wavefront sensors can be fed by either real reference stars or back-scattered laser light.

Saturn-mass planets around many stars in the solar neighborhood, and perhaps a small number of "super-Earths," rocky planets several times the Earth's diameter, around the nearest stars. Spectral analysis of the light from these planets can yield vastly more information than the few orbital parameters that the indirect detection methods provide. It could even provide the first signatures of life of these planets, if biomarkers such as the simultaneous presence of ozone and methane are detected. This goal is beyond the reach of present-day telescopes, but well within the capabilities of the coming ELTs.

Ground-layer AO improves a telescope's image quality less dramatically, but over a far wider field of view. This is done by correcting only the portion of the turbulence located near the ground (typically less than 500 m above the telescope), through which lines of sight overlap. The resolution improvement provided is approximately a factor of 2, reducing typical image size to 0.2 to 0.3 arcseconds over fields of view as large as 20 arcminutes (two-thirds the apparent size of the full moon). This is usually sufficient resolution for studies of very distant galaxies, which have low surface brightness and little structure at finer scales. GLAO will therefore allow the ELTs to study the most distant galaxies in large numbers, with unprecedented sensitivity.



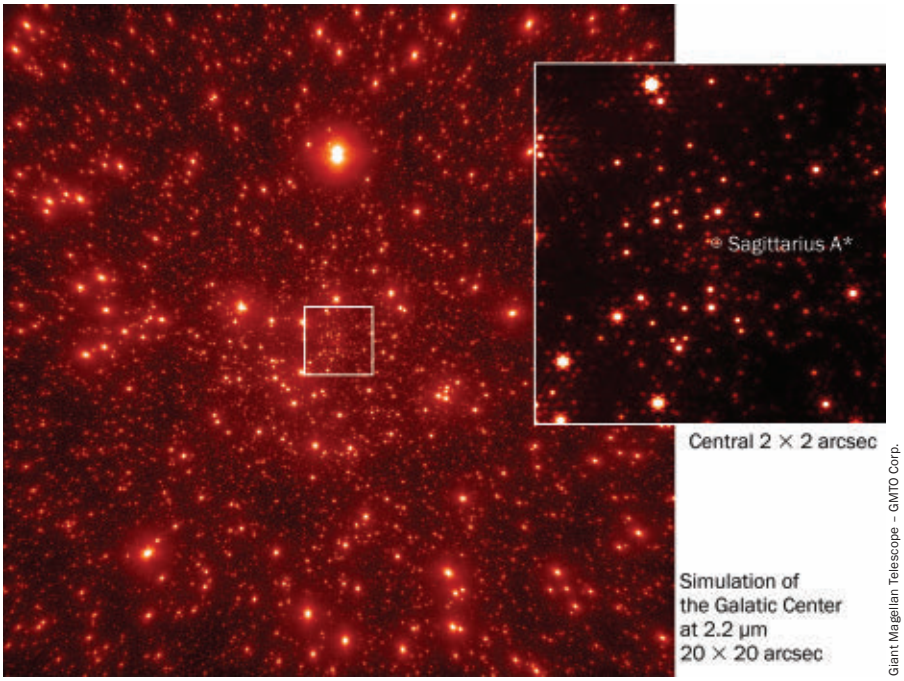
Phil Hinz, University of Arizona

Simulated Giant Magellan Telescope (GMT) image of a hypothetical planetary system orbiting Beta Pictoris, located 63 light years from Earth **(right)** compared to real observations by the European Southern Observatory's Very Large Telescope, which discovered a 10 Jupiter-mass planet[1] **(left)**. GMT will be capable of detecting planets as small as Saturn in this system.

Laser guide stars

One of the most significant astronomical findings enabled by the last generation of 8- to 10-m telescopes was the discovery of a super-massive black hole at the center of the Milky Way[2]. This black hole contains 4 million times the mass of our sun, and dominates the dynamics of the stars in the inner part of the Milky Way galaxy. Only with adaptive optics can the thousands of stars orbiting the central black hole be resolved and their orbital motions measured. These orbits reveal the mass of the central black hole, Sagittarius A*, and also the history of star formation and destruction in its vicinity. Mid-infrared flares emanating from an accretion disk around the black hole have been imaged with adaptive optics, providing evidence of its continual growth[3].

While the millions of stars in the galactic bulge generally provide excellent AO guide stars, Sagittarius A* is hidden behind thick clouds of gas and dust, completely obscuring the region in the visible wavelengths at which wavefront sensors typically operate. Laser guide stars must therefore be used to provide



Giant Magellan Telescope – GMTO Corp.

Simulated Giant Magellan Telescope (GMT) laser tomography adaptive optics image of the region surrounding Sagittarius A*, the super-massive black hole at the center of the Milky Way. Known star positions were provided by Tuan Do and the UCLA Galactic Center Group.

the atmospheric turbulence measurements that enable adaptive optics. Single-laser guide star systems are now deployed at most major observatories, but the ELTs require more sophisticated systems with multiple lasers to sample the wide column of atmosphere through which the telescope is pointing. The GMT system will use six lasers whose measurements will be combined tomographically to derive the optimal adaptive secondary mirror commands in the direction of the scientific target. The resulting resolution of 0.02 arcseconds is sufficient to track the motion of the innermost stars over periods of weeks, and will allow the effects of general relativity to be revealed as stars pass within light hours of the Sagittarius A* event horizon.

Astronomy is a technology-driven science, with unexpected discoveries made with each new generation of larger and more powerful telescopes. The next generation of ground-based ELTs will be revolutionary due to their high spatial resolution — unrivaled by even the largest envisioned space telescopes. The GMT will benefit from a resolution improvement of a factor of 2.5 over currently existing telescopes, enabling the characterization of super-Earths orbiting nearby stars, the study of the most distant galaxies in the universe, and the detection of new physical phenomena in the vicinity of super-massive black holes. However, its most exciting discoveries cannot yet be predicted.

Meet the author

Antonin Bouchez is GMTO's Wavefront Sensing and Control Group Lead, and is responsible for designing and implementing the adaptive optics systems for the Giant Magellan Telescope; email: abouchez@gmto.org.

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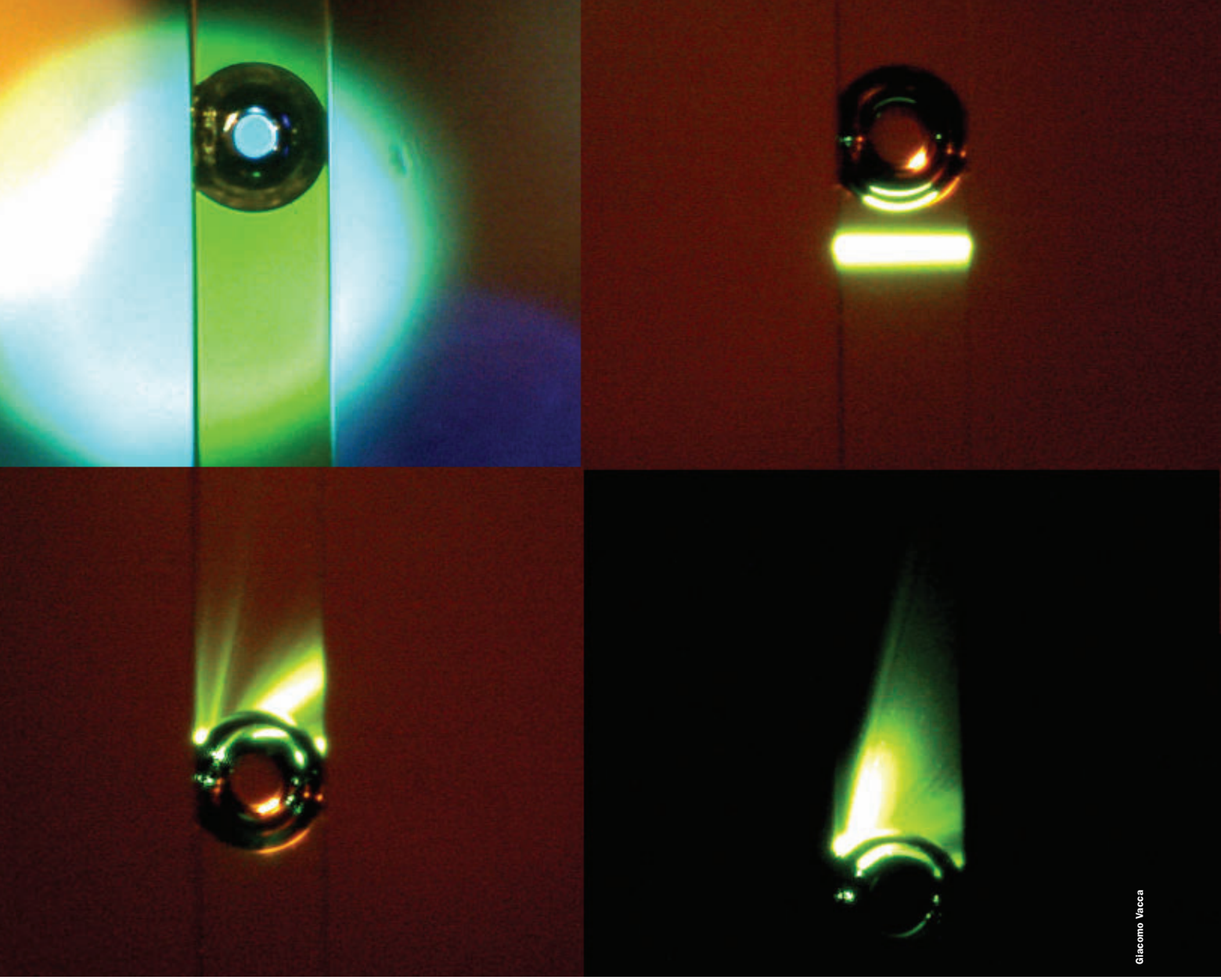


A large vapor bubble in a 250-µm flow cytometer microchannel caused by absorption of high-power green light by fluorescein dye. Bubbles large and small can create mesmerizing interactions with a laser beam, however they are very disruptive to precision cell measurements, and flow cytometer designers go to great lengths to prevent them.

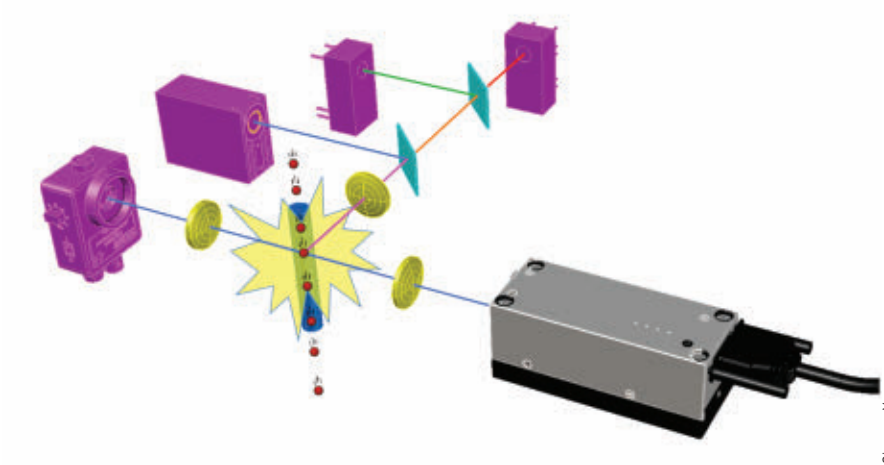
In Vitro Diagnostics, Immunology Spurring Advances in **Flow Cytometry**

Clever innovation and disciplined engineering are helping to create better, smaller and less expensive flow cytometers.

BY GIACOMO VACCA
KINETIC RIVER CORP.

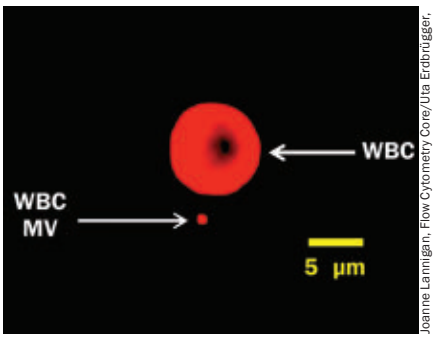
Cells are the building blocks of organisms. From yeast and bacteria to elephants and whales, cells are the fundamental units of both biological structure and function. They have long been the subject of intense study: to better understand how they work, to help develop safer and more effective drug compounds, and to serve as diagnostic proxies of disease.

Flow cytometry is often compared to microscopy, since these two techniques are largely complementary. Microscopy



Giacomo Vacca

Figure 1. Principle of flow cytometry. Cells **(red)** flow one by one past the beam from a laser **(gray)**, and the resulting light signals **(various colors)** are spectrally separated by filters **(cyan)** and detected by photodiodes and photomultipliers **(pink)**. Image created using BeamWise modeling software.



Joanne Lannigan, Flow Cytometry Core/Uta Erdbrügger, University of Virginia School of Medicine

Figure 2. A white blood cell (WBC) and a microvesicle (MV), labeled for surface protein CD45 and captured on a Millipore ImageStreamX imaging flow cytometer under 640-nm excitation. This MV is near the resolution limit at 60× magnification.

generates supremely fine-scaled images of a sample; but it's slow, taking up to seconds to minutes to image in detail just a handful of cells. Flow cytometry, by contrast, provides only a handful of measured parameters on each cell, but at rates of tens of thousands of cells per second. The main trade-off is detail vs. throughput.

Most flow cytometers work by funneling cells from a liquid sample into a narrow stream so they're in single file, and passing them one by one at high speed through one or more interrogating laser beams (see Figure 1). The resulting interactions generate scattered and fluorescent light, and an analysis of these allows counting, identification and characterization of the cells in the sample.

Beckman Coulter

Figure 3. The three detection modules of a 3-laser, 13-color Beckman Coulter CytoFLEX flow cytometer. Each fiber-coupled module contains several compact dichroic filters on removable holders (like the one held up in the image) for spectral separation of signals.

AIDS diagnostics and hematology

Today, flow cytometers are ubiquitous in hospitals, clinical laboratories, cell biology departments, marine biology laboratories, biomedical research institutions and development labs of pharmaceutical companies.

One of the most remarkable success stories of flow cytometry is connected with the global fight against HIV/AIDS. As the epidemic grew in the 1980s, the need for a reliable diagnostic tool to help assess whether someone was getting sick from AIDS became critically important. HIV specifically targets CD4-positive T-lymphocytes (a kind of white blood cell), depleting them and making the patient vulnerable to infection. Flow cytometry can distinguish those cells from all other blood cells — quickly and reliably. The flow cytometry-based test thus became the worldwide gold standard for AIDS diagnosis, and one of the key tools widely adopted in the global efforts to treat sufferers of the disease[1].

An even more widespread application of flow cytometry is routine blood counting. Every time someone gets his or her blood drawn, whether for an annual physical, or to follow up on a treatment, that tube of blood gets sent to a lab, just downstairs or maybe a few hundred miles away, where flow-based hematology analyzers generate a complete blood count (CBC), which includes red blood cells, white blood cells and platelets, in less than a minute per sample. This most common of diagnostic tests is ordered hundreds of millions of times per year, worldwide.

Main applications and unmet needs

But for all the advances since its inception a half century ago, flow cytometry is constantly being pushed further.

The relatively elevated cost and complexity of traditional flow cytometers

Pavilion Integration Corp.

Figure 4. Compact latest-generation solid-state lasers (see penny for scale), from Pavilion Integration Corp.'s Mini-Whisper laser product line.

means that, generally, laboratories share them: Instruments are acquired by a central facility, and then allocated to users across a department, an entire hospital, or even from other institutions. This limits access, and requires expert operators for their operation and maintenance. Simpler, cheaper machines would obviate these problems and foster broader adoption.

Some applications, like infectious-disease testing in remote areas, require instruments to be even smaller, ideally portable and robust. Traditional flow cytometers (such as BD Biosciences' 525-lb LSR II) have long been just the opposite — bulky, lab-bound and complicated to operate. A push has been underway to package flow cytometry in more compact and intrinsically more reliable units. For example, there is a great need for a field-deployable malaria diagnostics solution.

In some fields of research, requirements are bumping up against rather fundamental physical limitations. For example, in recent years it has been increasingly recognized that tiny particles (microvesicles and exosomes) shed from cells can tell us a lot about physiology, disease and recovery[2]. These particles (see Figure 2) can be even smaller than bacteria, however, and they are very challenging to detect on current flow cytometers. Instruments capable of reliably detecting and characterizing these extracellular vesicles would help translate this new area of research into clinical practice.

Another field of biomedicine constantly in need of greater capabilities is immunology. The study of the immune system and its myriad super-specialized "foot soldiers" (mainly white blood cells) requires an ability to distinguish cells based on their surface proteins[3]. Multiplexing (probing as many cell parameters as possible) is key: the more parameters probed simultaneously, the more detailed the picture of the cell population in a sample. But the complexity of running an instrument goes up exponentially with current multiplexing approaches, and traditional flow cytometers max out at around 20 parameters.

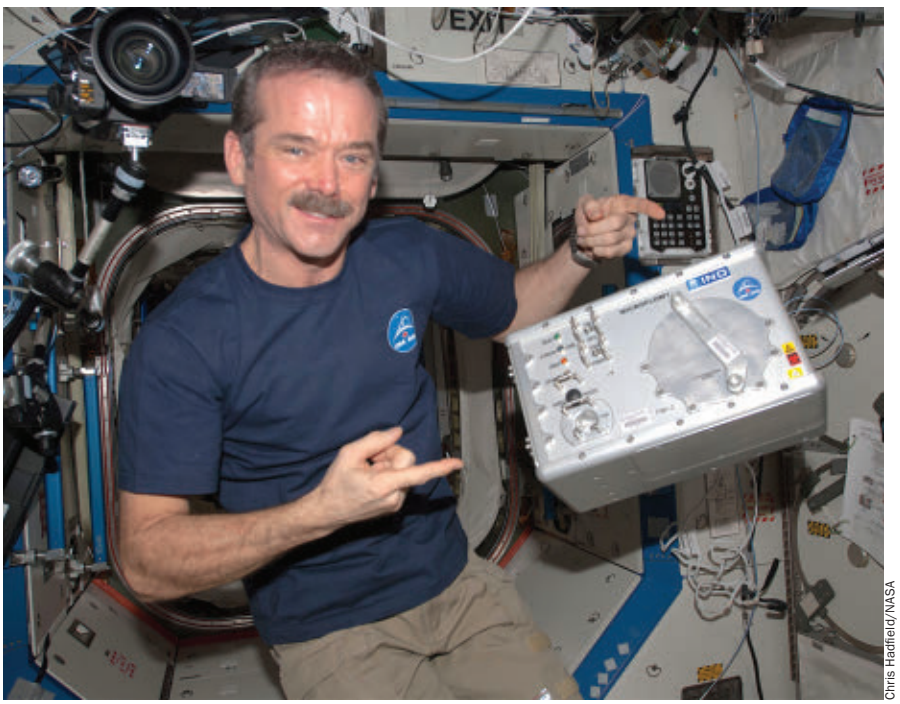
Robustness, ease of use, reliability

The calls for better, smaller, (and/or) cheaper flow cytometers are being answered by both clever innovation and disciplined engineering — and much of it is photonics-related. Early machines were little more than prototypes with a skin, and their legacy is easily seen in the design of instruments still in common use. More recently, design and engineering best practices from other industries have crept their way into flow cytometry,

resulting in systems intrinsically less prone to environmental variations or operator error.

One of the first volleys in this ongoing competitive battle was the introduction of the C6 by Accuri, a Michigan startup later bought by BD Biosciences. The C6, launched in 2008, requires no laser alignment or maintenance by the user. More compact, robust and significantly cheaper than the then-available alternatives, it quickly gained traction in a market with significant pent-up demand for "simpler." Research groups (including the author's, then at Abbott Laboratories) started buying them for their own use, instead of having to rely on time-shared machines in the core labs.

A more recent step in this same direction was the introduction of the CytoFLEX, developed by Chinese startup Xitogen (bought in 2014 by Beckman Coulter). While the Accuri C6 is limited to two lasers and six parameters, the CytoFLEX (Figure 3) can support up to three lasers and 15 parameters, in a small footprint, and with performance that rivals ma-



Chris Hadfield/NASA

Figure 5. Canadian Space Agency astronaut Chris Hadfield, floating in the International Space Station, together with INO's Microflow cytometer. The instrument was tested on the space station to pave the way for health monitoring of astronauts during space missions.

chines many times its size. The CytoFLEX is regarded as being not just "smaller" (which often forces performance trade-offs), but "smaller and as good or better," particularly in terms of fluorescence sensitivity[4].

One of the photonics advances that is making possible this kind of improvement is the continued miniaturization of laser sources. For a long time, flow cytometers had to rely on massive, electricity-guzzling, water- or forced-air-cooled gas lasers, such as argon-ion and helium-cadmium. With the arrival, starting in the early 2000s, of solid-state alternatives, the footprint — both physical and carbon — of flow instruments could be significantly reduced. The latest laser products to hit the market (Figure 4) are as small as a pack of mints — enabling transformative instrument designs in terms of alignment stability and overall size.

Portability for field diagnostics

The Accuri and CytoFLEX are good fits for labs short on bench space and in need of full-featured solutions. But they're far from portable. There are many applications where only a few parameters are needed, but at low cost and a "back-of-a-Jeep" sturdiness, such as bringing AIDS and malaria diagnostics out of urban centers and into unelectrified villages in rural areas.

Partec GmbH, a pioneering German flow cytometry company acquired in 2013 by Japanese diagnostics powerhouse Sysmex, has long made it part of its mission to serve just that kind of a market and global-health need. Partec's CyFlow line of compact, robust flow cytometers enabled deployment of AIDS diagnostics deep into the African countryside of areas hard hit by the epidemic.

Recently, several companies have developed innovative solutions that are even more compact and robust. For example, handyem Inc., a Quebec City-based spinoff of Canada's National Institute of Optics (INO), introduced the HPC-100, a waveguide-based flow cytometer based on a prototype that actually flew on the International Space Station (See Figure 5). The handyem box is one of the most portable flow cytometers yet, and its interrogation design makes it intrinsically alignment-free[5].

Multiplexing for immunology

The immunologist's constant quest for greater multiplexing drove the development of machines with more and more excitation sources and fluorescence detection channels, such as the BD LSRFortessa X-20, which supports up to five lasers and 20 channels. Adding lasers and fluorescence detection bands, however, reaches an effective plateau with instruments like the LSRFortessa. The diminishing returns come in the form of spectral crosstalk: neighboring channels receive unwanted fluorescence spillover, distorting results and adding noise. This is the effect of the relatively broad emission spectra of most organic fluorophores. Unmanageable crosstalk, cumbersome workflows and poorly reproducible results pose a limit to the number of dyes that can be used concurrently.

The introduction of mass cytometry by Toronto-based DVS Sciences, acquired by Fluidigm, was supposed to change all that. Based on mass spectrometry of rare-earth isotopes instead of fluorescence, the company's CyTOF is capable of 35+ simultaneous parameters — ostensibly without any of the compensation headaches of fluorescence-based flow cytometers. The CyTOF has found a receptive audience in immunology[6]. However, mass cytometry is not without challenges — such as limited sensitivity, unanticipated channel-to-channel crosstalk, expensive reagents and equally cumbersome workflows. Not least, the cells in a sample are completely obliterated during analysis, precluding any sorting application.

At Kinetic River Corp., the research team is actively working on new approaches to multiplexing that are compatible with sorting. Preliminary results, using different excitation sources, including high-performance lasers from Toptica Photonics, are encouraging; the goal is to double or more the number of simultaneous parameters currently available for use.

Sensitivity for nanoparticles

The recognition that smaller-than-cells particles can be important harbingers of certain disease states, and diagnostic

entities in their own right, has spurred the field to push the envelope in terms of sensitivity of detection. One approach is to label the microvesicles and exosomes (broadly, extracellular vesicles — EVs) with fluorophores and detect them using standard instrumentation (Figure 2). The challenge there is that EVs, due to their size, do not support the levels of fluorescence staining normally seen in whole cells. Therefore higher-sensitivity instruments are needed.

Another challenge is that, for many applications, fluorescent labeling is not a desirable option — for example, when wishing to sort a fraction of the EV population and conduct further tests on them. In that case, labeling can alter the state and function of the particles, compromising the results. Label-free techniques are then required.

The simplest and most widely used label-free technique is the oldest one in the book: elastic light scattering. In the size range of cells this is known as Mie scattering, but when looking at EVs, you get into the Rayleigh scattering regime. Scattering efficiencies plummet as size decreases, making it inordinately difficult to detect at high throughput particles smaller than 100 nm in size.

Various fixes are under development. Improvements in the optical design (reduction of stray light, increased collection of scattered light, reduction in electronic and system noise sources), increase in the available optical power from solid-state lasers, and signal-processing techniques are all being deployed in the push for detecting the smallest possible particles quickly and reliably. Some instruments addressing this problem include the A50-Micro from Apogee, the Beckman Coulter Gallios and the Small Particle Option on the BD Influx. This may well be the case where all-around solid engineering design and execution, rather than a magic bullet, wins the day.

The future of cell analysis

There is much to look forward to in biophotonics, and flow cytometry is no exception. The relentless evolution of optical components is enabling amazing feats in realms of light excitation, collection and detection, and their application to cell analysis. Photonic developments, pioneered in other areas of science and technology, but which are now being adopted in flow cytometry, include: supercontinuum and pulsed light sources; photonic integrated circuits; spectrally resolved detection using prisms and detector arrays; inexpensive, compact solid-state detectors such as silicon photomultipliers; and more. Biophotonics innovators are hard at work on analytical and diagnostics bottlenecks — there's no shortage of important problems to solve. The prize is better health and saved lives.

Meet the author

Giacomo Vacca is an entrepreneur, optical physicist and inventor (19 issued patents). He has two Harvard degrees and an applied physics Ph.D. from Stanford University. Vacca is president of Kinetic River Corp., a Silicon Valley firm offering custom flow cytometers. He is also co-founder of design automation software firm BeamWise Inc. Email: gvacca@kineticriver.com.

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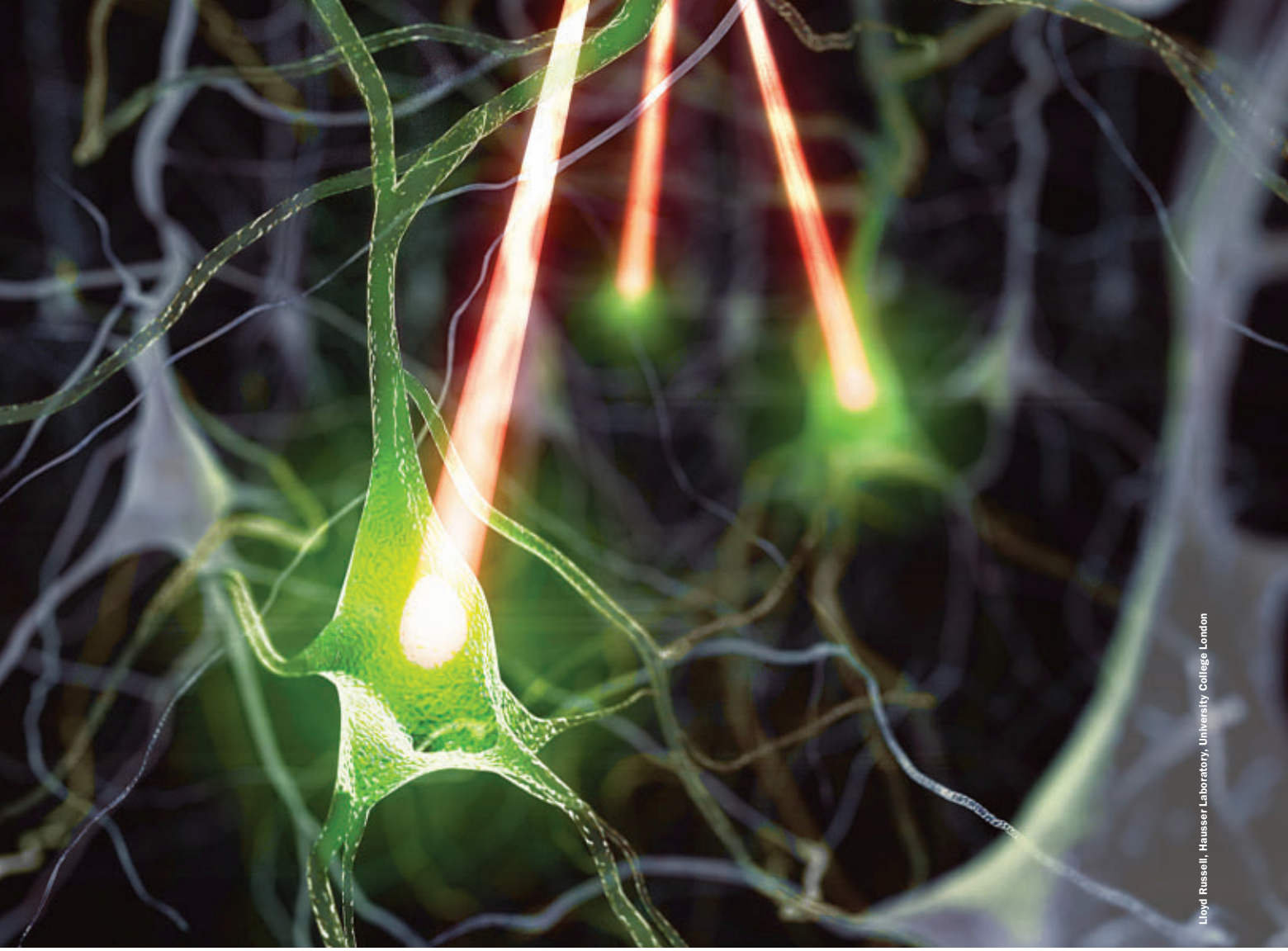


In all-optical physiology studies, lasers are used both to stimulate neurons and to map activity in connected neurons via fluorescent probes such as genetically modified calcium indicators.

Femtosecond Lasers Power New Approaches in Optogenetics

BY DARRYL MCCOY AND MARCO ARRIGONI, COHERENT INC.

Longer-wavelength, ultrastable femtosecond lasers are enabling advances in this dynamic neuroscience technique.

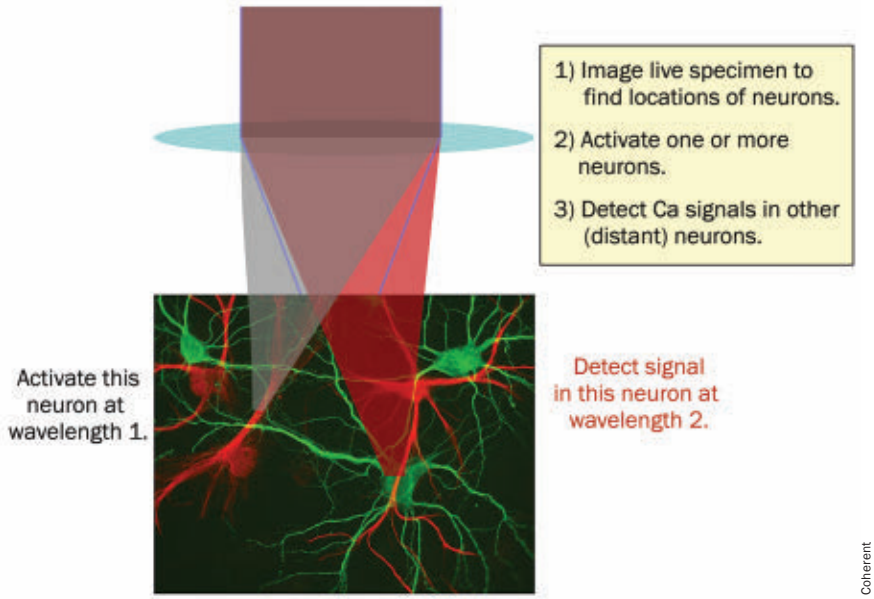
One of the most active and exciting areas in neuroscience is the use of optogenetics to unravel how neural pathways in the brain process and transmit information. Optogenetics involves the use of light-sensitive opsins — a special class of membrane-embedded proteins. Opsins are switchable channels or pumps for specific cations or anions whose on or off state is determined by irradiation with light of an appropriate wavelength. It has been known for decades that neurons transmit signals in the form of an action potential or voltage spike along their membranes. Therefore, if opsins are present in a neuron's membrane, light can be used to influence the flow of charged ions across the membrane, mimic or inhibit the initiation of an action potential, and thereby turn neuron activity on and off.

Small lab mammals such as mice can be genetically modified so that specific opsins are produced in their neurons, or even selectively in only certain types of neurons, thus enabling optogenetic studies of live animals. Specifically, the noninvasive, noncontact nature of light enables optogenetics to be conducted in the cortex and neocortex of these live animals via a small glass window that replaces the upper part of the cranium. The shift to longer laser wavelengths means that some studies can even be conducted directly through the cranium, albeit usually requiring prior thinning of the skull.

In "all-optical" studies, sometimes called all-optical physiology, light is used to both manipulate neurons using opsins and measure activity in the local network. That is possible because neural activity usually triggers increased calcium ion Ca^{2+} concentrations, which can be readily imaged using fluorescent calcium indicators. The burgeoning range of genetically expressed Ca^{2+} probes provides a very powerful tool for this purpose. Since Ca^{2+} concentration and neural activity do not correlate 100% of the time, and changes in Ca^{2+} are slower than the actual voltage changes, there is also growing interest in genetically expressed probes whose fluorescence is modulated directly by membrane voltage.

Femtosecond lasers preferred for multiphoton excitation

Several types of light sources, including filtered lamps and LEDs, can be used to stimulate or excite neurons. However, lasers provide unique benefits of spatial selectivity and high brightness; femtosecond lasers in particular offer specific advantages thanks to their capability to excite multiphoton processes. When tightly focused in a live or fixed tissue sample, the femtosecond laser can drive two- (or even three-) photon excitation of opsins and metabolic probes with minimal photodamage, and with inherent three-dimensional resolution. (Multiphoton excitation has a highly nonlinear dependence on light intensity and only occurs at the beam waist of the focused laser.) This spatial resolution enables activation and interrogation with single neuron resolution.



Coherent

Figure 1. In all-optical physiology experiments with multiphoton lasers, neural activity can be manipulated and monitored at single neuron resolution. The use of two separate wavelengths for photoactivation and detection enables minimization of crosstalk between these 'write & read' channels.

Optogenetics is still in its infancy, meaning that many important scientific discoveries utilizing this technique lay ahead. However, there are also several challenges yet to be overcome to fully exploit this powerful scientific tool.

Minimizing crosstalk

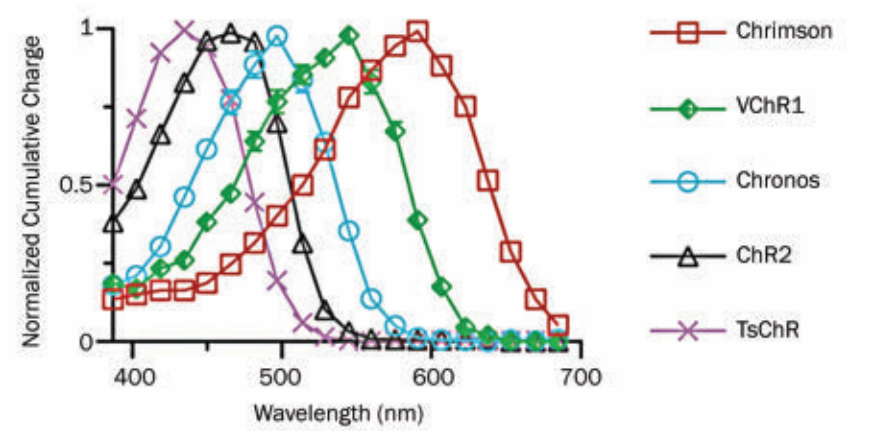
A key challenge in all-optical studies is to minimize crosstalk: ensuring that the laser light used for photoactivation does not significantly excite fluorescent signals from the interrogation probes, or vice versa.

One approach to this problem is to use photoactivators and probes whose absorption peaks are well-separated (Figure 1). Here, two ultrafast laser wavelengths are focused into the sample. Wavelength 1 is used to activate neurons by two-photon excitation and wavelength 2 is used to image activity in other neurons, again via two-photon excitation.

In addition to requiring two independent laser wavelengths, this setup also requires the availability of photoactivators and calcium probes with well-separated spectra. Unfortunately, the two-photon spectra of most activators and probes are quite broad — as much as 50 to 100 nm or even more — and generally wider than the corresponding one-photon spectra. However, developments in this area have been quite rapid. For example, several red-shifted photoactivators have recently been added to the all-optical toolkit, including C1V1, ReaChR and Chrimson. The one-photon absorption peaks can be as long as 600 nm as shown schematically in Figure 2. In theory, these can be used with a range of blue excited Ca^{2+} probes. Nevertheless, the absorption spectra of most activators have a weak, but not negligible, short wavelength tail and complete separation with this scheme has proved challenging. Conversely, researchers can use one of the new red-shifted calcium indicators, such as the RCaMP family, which have one-photon absorption peaks around 550 nm, together with a shorter wavelength photoactivator, such as ChR2, with a one-photon absorption peak closer to 460 nm. Alas, even this is not proving a straightforward route to eliminating crosstalk.

Peak intensity for photoactivation

Initial, proof-of-principle, all-optical experiments involved just a handful of neurons. However, the mammalian brain comprises massive interconnections between myriad neurons. To begin



Edward Boyden, Massachusetts Institute of Technology

Figure 2. The single photon absorption spectrum of Chrimson is significantly red shifted compared to other opsins.

to unravel the mysteries of the brain, researchers want to study larger populations of neurons, simultaneously. Current state-of-the-art experiments involve a few tens of neurons, but some neuroscientists are already discussing the need to study at least 1,000 neurons, which would typically encompass a column of tissue 250-µm across with a depth up to 1 mm.

The main challenge here is the peak intensity needed for photactivation. That is partly because numerous channels have to be recruited to reach a threshold voltage effect. This challenge is compounded with the lower activation cross section intrinsic in two-photon excitation. One frequently used solution to address this challenge was developed by David Tank at Princeton University. His method consists of scanning the focused laser beam in a spiral pattern, progressively covering the entire neuron body or soma until the action potential is produced. This may take something like 30 ms for each neuron. Additionally, or as an alternative approach, the laser power can be divided to cover selective areas of several neurons using computer-controlled holographic illumination with a spatial light modulator (SLM), as developed by Valentina Emiliani at Université Paris Descartes.

Whether the excitation is truly simultaneous or fast but sequential, photoactivation of larger neuron populations inevitably requires higher laser powers — at least several watts of output at the laser, and maybe even tens of watts, although delivered over milliseconds only. This demand for higher power is somewhat offset by the need to avoid photodamage and tissue heating, both of which can be ameliorated by using a low duty cycle and spreading the power among multiple spatially separated targets.

Ytterbium fiber: higher power at longer wavelengths

All-optical studies have created a need for femtosecond lasers emitting multiple watts in the 1040- to 1150-nm range. These wavelengths are at or beyond the limit of the Titanium:Sapphire (Ti:S) lasers that have been the workhorses of multiphoton microscopy for the past 15 years. Further, while a Ti:S-pumped optical parametric oscillator can reach this wavelength range, the power may be inadequate for studying large neuron populations.

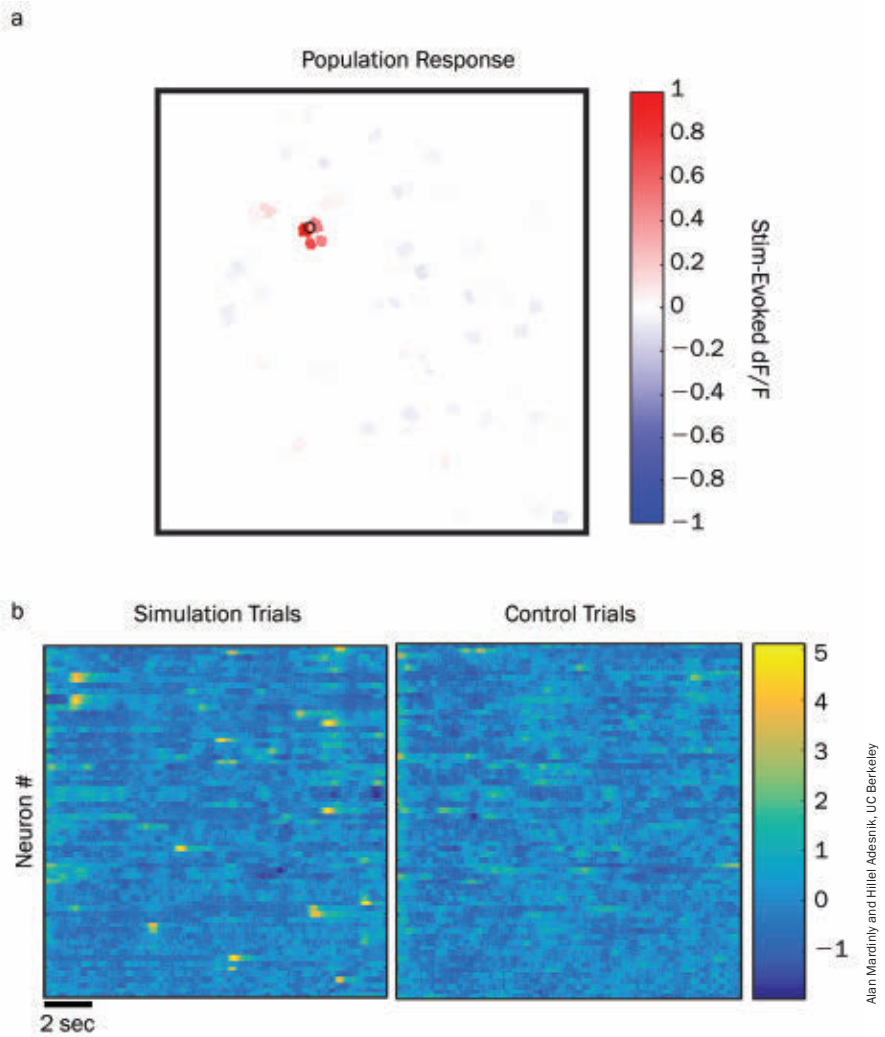
Ytterbium-doped crystals are alternative gain materials, but power scaling causes problems due to cooling and thermal lensing of the bulk gain material. In response, laser manufacturers have developed a new type of femtosecond laser based on ytterbium-doped fiber that can be scaled to several watts, or even tens of watts, at 1030 to 1070 nm. While the first Yb-doped fiber lasers were unable to produce multiwatt powers with pulse durations shorter than about 300 fs, engineers at Coherent found solutions to balance nonlinearity and gain in these high-power lasers. These proprietary approaches have spawned several families of ytterbium fiber-based lasers that are well-suited to optogenetics as well as other near-IR applications. Some of these incorporate an integrated optical parametric oscillator that provides widely tunable output across the near-IR.

Industrial reliability and stability

Solving the pulsewidth/power trade-off in ytterbium fiber provides the combinations of peak average powers required for all formats of optogenetic photoactivation. For example, the most compact of these new lasers delivers over 2 watts of power at a fixed 1070 nm with a pulsewidth $<$55 fs. By combining a more powerful ytterbium fiber with an optical parametric oscillator (OPO) in a single package, the Chameleon Discovery provides widely tunable output, as well as 1.5 watts at a fixed 1040 nm, enabling single laser simplicity for these dual wavelength, all-optical experiments. Thanks to the power scaling potential of ytterbium fibers, other products now offer several watts of tunable output across the near-IR like Monaco with its Opera-F family of optoelectronic pulse amplifiers (OPAs).

Concepts from the world of industrial lasers, such as uptime and data throughput, are positively affecting the world of scientific lasers, minimizing the time from complex experiments to publication of results. The latest scientific lasers are now designed for high reliability 24/7 opera-

When tightly focused in a live or fixed tissue sample, the femtosecond laser can drive two- (or even three-) photon excitation of opsins and metabolic probes with minimal photodamage, and with inherent three-dimensional resolution.



Alan Mardinly and Hillel Adesnik, UC Berkeley

Figure 3. Results from a test study of holographic photostimulation pyramidal neurons in the live brain of a mouse during an active treadmill study. The upper panel **(a)** shows how the programmable phase mask can be used to produce a single target spot, which in this case causes a calcium fluorescence change (dF/F) in four directly targeted neurons. The lower panel **(b)** is a statistical plot showing normalized (z-score) fluorescence deviations using a time-varied phase mask. Here each data column is a time window of approximately 30-msec duration. Each row is a different specific neuron. This trial shows that this phase map method and multiwatt power at 1040 nm enables neurons to be targeted with high spatial selectivity and high temporal resolution.

tion, using rigorous industrial protocols such as Highly Accelerated Laser Testing/Highly Accelerated Stress Screening (HALT/HASS). The accompanying stability is a particular advantage in so-called "chronic" imaging. Here all optical experiments on a target animal are repeated over a period of days or even months to monitor the effects of things like stress, task learning and effects of various drugs. It is therefore vital that the laser(s) delivers a repeatable performance over time.

Recent discoveries

Several research groups are already beginning to publish data from experiments based on these new ytterbium fiber lasers. For example, postdoctoral researcher Alan Mardinly and others in the Adesnik Lab at UC Berkeley have successfully used the Coherent Fidelity and Monaco lasers to activate a wide assortment of opsins, including ChR2, C1V1, Chronos and GtACR1. The high pulse energy of the Monaco and high average power of

the Fidelity-HP have proved ideal for activating or suppressing large sets of neurons. Even more importantly, they can be effectively used with holographic wavefront shaping so that all the targeted neurons can be activated in nearly the exact same instant. This allows for precise temporal control over large populations of neurons in full three dimensions in the intact brains of behaving animals (Figure 3). This will open new possibilities of addressing how information is encoded in the nervous system in the precise timing of individual action potentials in large populations.

Professor Michael Hausser's research group at University College London is on the forefront of development and utilizations of all-optical experiments using two-photon excitation. They were one of the first to acquire a 2-watt ytterbium fiber laser and then a >18-watt laser.

Senior research associate Adam Packer explained a typical experiment: "We express a red-shifted photoactivator together with a shorter wavelength Ca^{2+} indicator in neocortical neurons in vivo. Crosstalk is minimized by using these long wavelength lasers — 1040 nm or greater — to excite the activator while imaging using the 920-nm output from a Ti:S laser.

"In our latest experiments, we have stimulated up to 50 neurons simultaneously at the same time as imaging the responses of these neurons and their neighbors. We image the neurons, select the targets and then create a pattern of focused spots using the SLM and the fiber laser," Packer said.

Twin galvanometers in the beam path enabled Packer's team to "jiggle" the beams in a spiral pattern.

"Using this strategy, we have found that we need 20 to 80 milliwatts of laser power at each neuron, for a duration of 10 ms for reliable neuron firing. This power level appears to cause no significant photodamage or undesirable thermal perturbations. Moving to 20 watts at the laser enables firing more neurons with a good experimental overhead to enable all aspects of the activation and imaging to be fully optimized," he said.

To summarize, some of the latest experimental approaches in optogenetics require simple, turnkey femtosecond lasers with higher power at longer wavelengths than was previously available. To meet this requirement, laser manufacturers have developed lasers based on scalable ytterbium-doped fiber media producing 100 femtosecond-class pulses with the ideal balance of peak and average power.

Meet the authors

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Quantum Cascade Laser
Breakthrough for Advanced Remote Detection

Widely tunable, monolithically integrated mid-infrared semiconductor laser operates at room temperature.

BY MANIJEH RAZEGHI, WENJIA ZHOU, DONGHAI WU, RYAN MCCLINTOCK AND STEVEN SLIVKEN, NORTHWESTERN UNIVERSITY

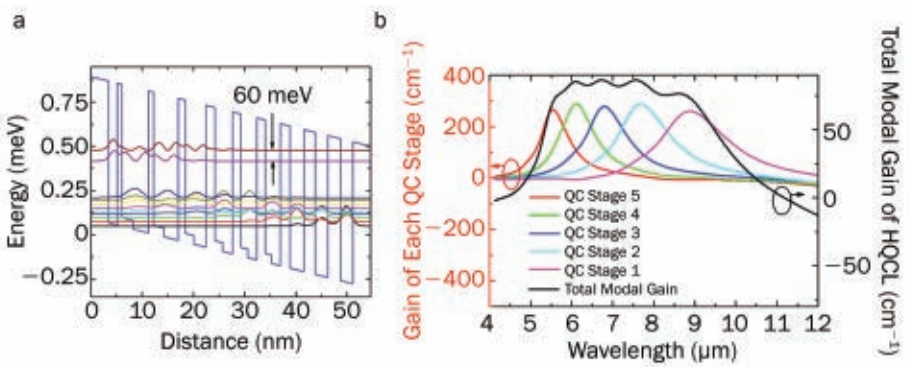

Figure 1. Conduction band diagram and relevant wavefunctions for one emitting stage of a quantum cascade laser based on the $Al_{0.63}In_{0.37}As/Ga_{0.35}As/Ga_{0.47}In_{0.53}As$ material system **(a)**. Simulated gain curve of a five-core heterogeneous quantum cascade laser (QCL) **(b)**.

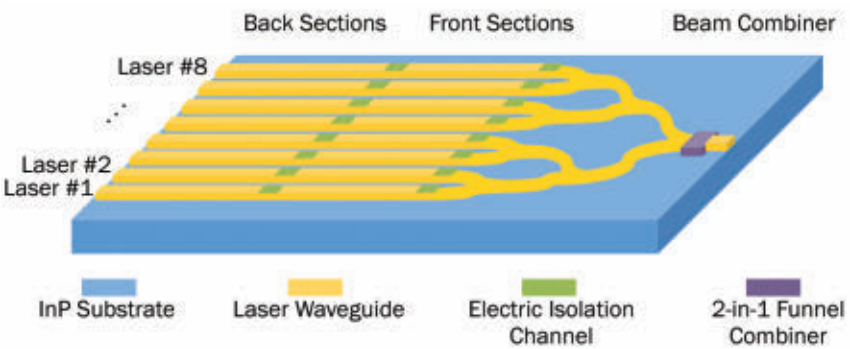

Figure 2. Schematic of the wavelength tunable QCL source with a monolithically integrated sampled grating distributed feedback (SGDFB) laser array and beam combiner.

The atoms in a molecule can bend, stretch and rotate with respect to one another, and these excitations are largely optically active. Most molecules, from simple to moderately complex, have a characteristic absorption spectrum in the 3- to 14-μm wavelength range that can be uniquely identified and quantified in real time. Infrared spectroscopy has been used to study these absorption features and develop different molecular "fingerprints." The benefits of this optical technique, as opposed to chemical sensors or chromatography, are that the detection mechanism requires minimal sample pretreatment and is very fast. While high-performance infrared detectors have existed for a long time, the main challenge in achieving the full potential of tunable laser spectroscopy lies in the performance limitation of the tunable mid-infrared (IR) laser sources.

Before the invention of quantum cascade lasers (QCLs), few mid-IR sources were available. Among them were optical parametric oscillators that convert an input laser wave into two output waves of lower frequency by means of nonlinear optical interaction. Although these oscillators can achieve high output power, they are generally bulky, require large external power supplies and cooling systems, and are easily subject to misalignment or damage.

There are several kinds of interband semiconductor lasers that emit at infrared wavelengths. Among them are lead salt lasers, HgCdTe lasers and Sb-based interband lasers. Since they all are categorized as semiconductor lasers, they are inherently compact. However, interband lasers suffer from performance degradation as the operating temperature and wavelength increases. This is largely due to a rapid increase of the nonradiative recombination rate as a function of temperature.

In contrast, QCLs are well-established mid-IR laser sources, based on intersubband transitions in a semiconductor heterostructure, rather than a combination of electron-hole pairs across the semiconductor bandgap. A basic intersubband transition region incorporates mini band gaps that form an injector region that effectively collects the electrons and injects them into the active region of the next stage. This cascading scheme also gives the name to the quantum cascade laser. QCLs, based on the GaInAs/AlInAs material system, feature very high performance over a broad range of wavelengths between 3 and 14 μm.

For intersubband transitions, the bandgap design becomes independent of in-

Images Courtesy of Northwestern University

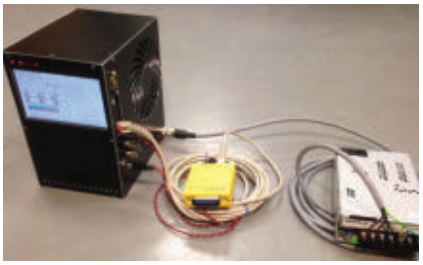

Figure 3. Tunable laser system with the additional power supply.

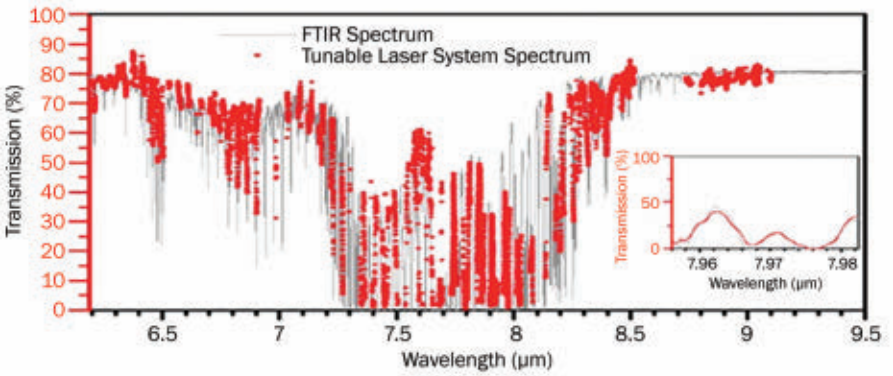

Figure 4. Comparison of the spectrum measured with the tunable laser system **(red dots)** to the expected spectrum measured with the Fourier transform infrared (FTIR) spectrometer. The inset shows a zoomed-in region showing the excellent agreement.

terband material bandgap, which is a characteristic property of the compound semiconductor. The emission wavelength can be tailored by changing only the relative thickness of multiple quantum wells and barriers without changing the material composition. In a broadband heterogeneous QCL (HQCL), multiple stacks of discrete wavelength quantum cascade (QC) stages are incorporated within the same quantum cascade laser waveguide core. The summation of the effective gain of the QC stages features a broad gain over a large wavelength range. This allows selection of the laser emitting wavelength over a wide range using an appropriate tunable feedback mechanism.

Strain-balanced $Al_{0.63}In_{0.37}As/Ga_{0.35}In_{0.65}As/Ga_{0.47}In_{0.53}As$ QCLs were shown to have good performance across the wavelength range 5.2 to 11 μm, and they can be incorporated with a single process step into a HQCL active region. When designing a broadband laser core, it is critical to use wavefunction engineering to avoid any cross-absorption loss. Photons emitted by the optical transition of a long wavelength QC stage are often cross-absorbed by optical transitions between the upper laser level and the next excited state of other QC stages, due to large oscillator strength between them and a large electron population in the upper laser level at high electric fields. The absorption decreases with detuning of the photon energy from the resonant absorption energy. As a result, the energy separation between upper laser level and the next excited state must be reduced well below 124 meV (approximately 10 μm). This may lessen the overall efficiency of a shorter wavelength emitter by decreasing the injection efficiency into the upper laser level and increasing the thermal escape of electrons from the upper laser level, but is necessary in a HQCL to minimize excess loss at longer wavelengths. In our design, a compromise value of 55 to 60 meV was chosen for a balance in the efficiency and the range of operation in the broadband HQCL, (Figure 1a).

Notably, all the cores must operate at the same current density simultaneously, so that maximum gain has to be reached simultaneously for all cores. The modal intensity profile within the waveguide and the modal confinement factors of the QC stages at different photon energies have to be balanced. The net gain curve of the HQCL is calculated by the sum of individual QC stage gain, weighted by the respective modal confinement factors. The total modal gain based on simulation, at a current density of approximately 4 kA/cm^2, is shown in Figure 1b. Wavefunction engineering ensures that the strong losses corresponding to resonant absorption from upper laser levels to higher states (near 60 meV) does not overlap with the HQCL emission energies of interest. The gain is designed to be very flat throughout the wavelength range.

The broadband structure was grown by gas source molecular beam epitaxy on an InP substrate. The threshold current of the HQCLs are much higher than single core devices due to reduced modal confinement factors of each QC stage with respect to a single core device. The devices are doped higher than single core QCLs to ensure that all wavelengths can reach the threshold current before their maximum current at resonant field. The wafer was characterized using a distributed feedback (DFB) laser array. Single mode emission between 5.8 and 9.9 μm was obtained with a maximum power above 300 mW, and most DFB lasers have power output above 100 mW. A relatively flat threshold current between 5.8 and 9.0 μm indicates a flat gain.

Monolithic widely tunable QCL source

A widely tunable laser requires not only a broadband gain medium but also a robust tuning mechanism that allows selecting any wavelength at will within that wide wavelength range. External cavity QCLs with a wide tuning range are commercially available and have been used for many practical applications. However, the peripheral optical components make it sensitive to mechanical shocks and vibrations. Furthermore, the tuning speed is limited by the movement of large grating objects. Monolithic and electrical tuning is possible with DFB QCLs, which have been demonstrated to cover a few tens of cm^{-1}. However, because each element in the array can only tune over such a small range of a few cm^{-1}, the size of the array could be prohibitively large in order to cover a range of hundreds of cm^{-1}. Fortunately, the DFB lasers can be replaced by sampled grating DFB (SGDFB) lasers, which have been demonstrated to extend the tunability of a QCL by one order of magnitude.

Multichannel wavelength-selectable sampled grating distributed feedback (SGDFB) laser arrays can be monolithically integrated with an optical beam combiner to realize even wider tuning on a single chip. The benefit of the beam combiner is that all wavelengths come out of a single output aperture, along with a compact size and fast electric tuning.

The integrated device consists of an eight-laser SGDFB array and a beam combiner section (Figure 2). The primary emitting wavenumber of lasers is spaced

by tens of cm^{-1} by controlling the grating period. The device was fabricated using standard micro fabrication technologies. During operation, one laser is selected and tuned with injected continuous wave (CW) current to the two SGDFB laser sections. The injected CW currents locally change the section temperature, which leads to the change of effective refractive index. A wavelength range of 6.2 to 9.1 µm from a single emitting aperture was obtained by integrating the 8-laser SGDFB laser array with an on-chip beam combiner[1]. This is achieved in a device smaller than a penny.

In order to make the tunable laser source usable in the field, a self-contained tunable laser system was designed and built (Figure 3), weighing about 3 kilograms and measuring 127 mm × 203 mm × 184 mm. It works off of one 48-VDC power supply and contains all of the electronics and control algorithms necessary to drive the individual lasers within the array and coordinate the driving of the laser array and produce the desired wavelength. The system has both a local touchscreen user interface and several remote interfaces (GPIB, USB, RS232 and Ethernet). The lasers in the array are beam-combined into a single aperture and the emission comes out as single collimated output from the front of the system.

The system was calibrated using custom written automatic calibration software to perform nearly 43,000 scans of the laser array and record the spectrum with a Fourier transform infrared (FTIR) spectrometer for different lasers and DC current combinations. For each of the lasers in the array, a colormap is made showing the peak wavelength vs. SGDFB Section A and Section B currents. This is then used to generate optimized paths through the data and create a table of precalibrated scan paths. The software is then able to interpolate along these paths with a resolution of better than 0.1 nm.

In order to use the system for chemical spectroscopy, a wavelength region of interest is selected and each discrete scan-state is downloaded to a dedicated RAM chip on the control board. An on-board or off-board time-base is then used to step through the states stored in the RAM. The upper limit on the laser stabilization time limits the scan rate to about 1000 Hz. In order to demonstrate the scanning capability of the system, a 100-mm single-pass gas cell was filled with natural gas composed primarily of methane at 1 atmosphere. The transmitted light was collected with a cryogenic mercury cadmium telluride (MCT) detector and digitized by a high-speed lock-in amplifier. Figure 4 shows a comparison of the reference spectrum (gray, obtained with a FTIR spectrometer) to that measured with the tunable laser system (red points). Generally, the tunable laser system can accurately measure the spectrum of natural gas. In particular, the inset of Figure 4 shows excellent agreement with some of the fine spectral features.

This technology is at once extremely sophisticated engineering, yet it's also practical and reproducible. Any wavelength in the laser's range can be accessed on demand at room temperature, which is ideal for sensing applications. The compact system, which drives the individual lasers within the array with the conditions necessary to produce any accessible wavelength, is able to do fast wavelength scanning without being limited by the driving hardware electronics. This broadly tunable QCL source with no moving parts will open new opportunities for mid-IR spectroscopy and chemical sensing.

Meet the authors

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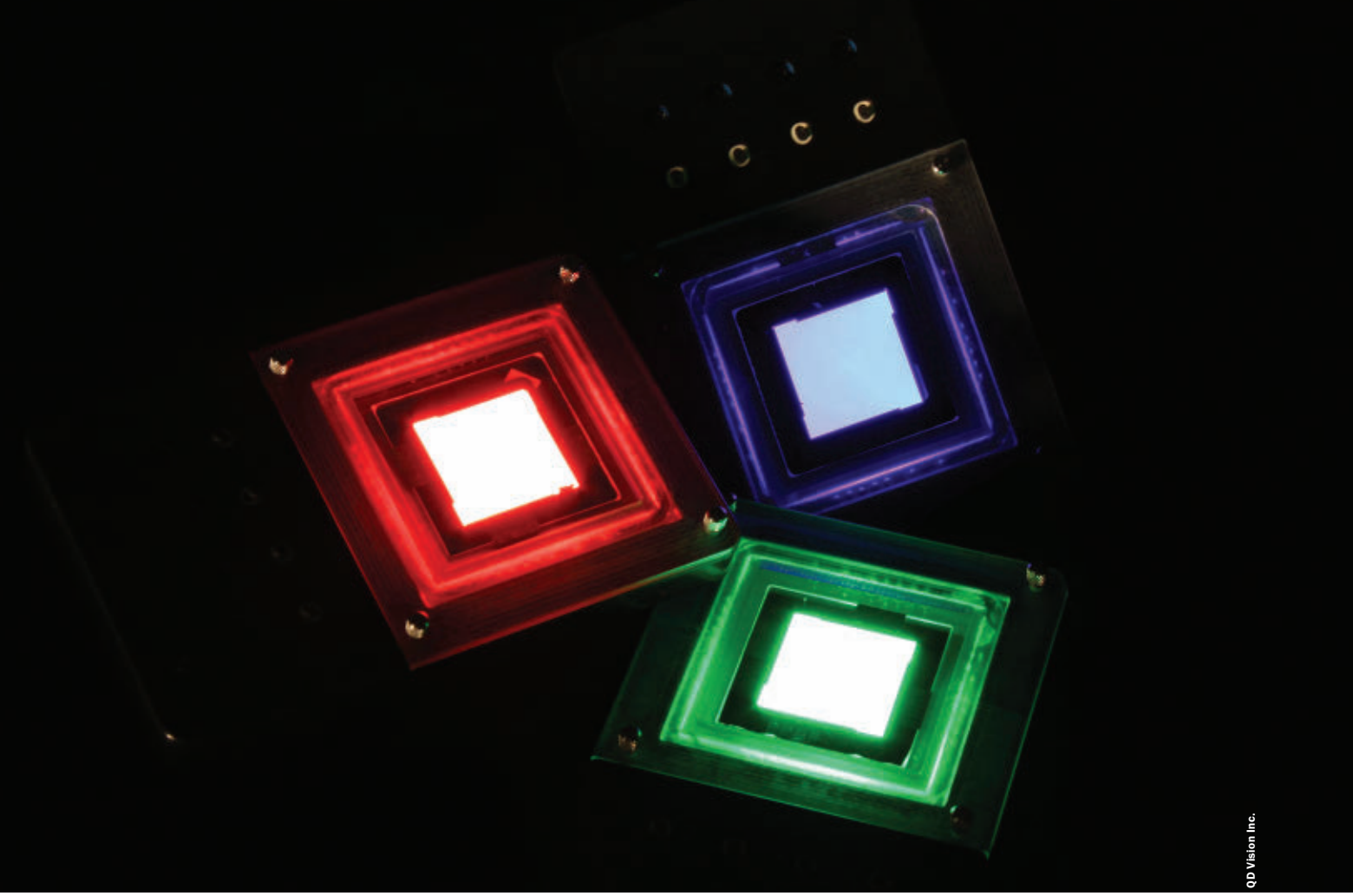
1. W. Zhou and N. Bandyopadhyay, et al. (2016). Monolithically, widely tunable quantum cascade lasers based on a heterogeneous active region design. *Sci Rep*, 6, article no. 25213.



Highly efficient, highly saturated red, green and blue printed QLEDs. The emitting area of each QLED is 20 × 20 mm.

Optical Materials of Tomorrow

Today's optical pioneers are precise, creative and determined to bring to market the next generation of effective and efficient materials.

BY MARIE FREEBODY
CONTRIBUTING EDITOR

From silicon photonics and quantum dots to metamaterials and carbon nanotubes, innovative materials promise a faster, brighter and more integrated future. While some materials have already enjoyed a measure of commercial success, for others, the future promises anything from niche applications right up to market disruption and displacement of existing technologies.

With the rise of high-performance digital systems and the expansion of internet traffic, the exigency for advances in optical materials is growing. At Intel, serious work is underway to introduce silicon photonics to remove networking bottlenecks, eventually replacing copper wires and interfaces with optical fibers.

"The predicted growing need for optical interconnections in applications like optical waveguides, optical data storage, holographic parameters and recording materials, and laser crystals is leading to extensive research being undertaken in the field," said Rakesh Singh, assistant manager of semiconductors at Allied Market Research, a market report specialist based in Portland, Ore. "The pioneering research in the parallel optical interconnections for cloud computing such as data transfer between backplanes, boards and chips, as well as within the chip, is the latest advancement in optical material."

Earlier this year, unprecedented storage of 360 TB/disc was demonstrated by scientists at the University of Southampton in England. Using nanostructured glass, the team from the university's Optoelectronics Research Center developed five-dimensional (5D) digital data with a virtually unlimited lifetime at room temperature and thermal stability up to 1000 °C.

Nanosys Inc.

Two vials of photoluminescent quantum dots **(right)** next to a prototype blue electroluminescent QLED device **(left)**.

Data is recorded using a femtosecond laser, which writes in three layers of nanostructured dots separated by 5 mm. A very stable and safe form of portable memory, the technology could be useful for organizations with large archives, such as national archives, museums and libraries, to preserve their information and records.

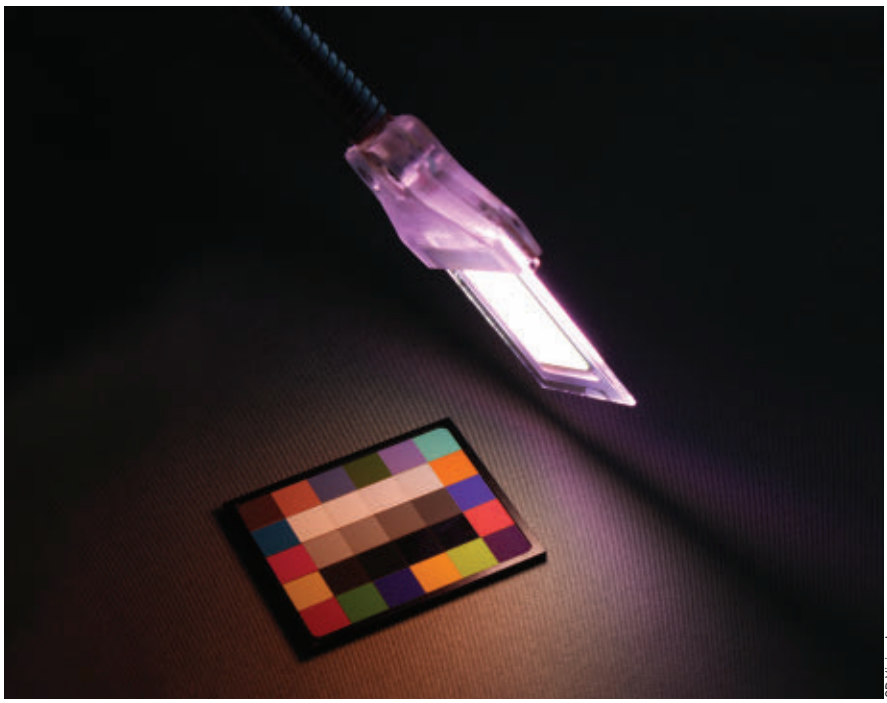
Metamaterials

A material that has captured the imagination and the headlines since it was first fabricated in 2006 is metamaterials. David Smith at Duke University in Durham, N.C., and fellow researchers found that when precisely arranging photonic crystals into patterns of two or more distinct materials, light would suddenly behave very strangely.

Rather than following the usual rules of nature, electromagnetic radiation could be diffracted in such a way as to be confined within the material — and the promise of invisibility cloaks was born.

Fast-forward 10 years to today and optical cloaking has yet to "materialize," leaving some scientists dismissing optical metamaterials as no more than a headline-grabbing fantasy. But there are others who are hard at work, dogged in their attempts to bring optical metamaterials to reality.

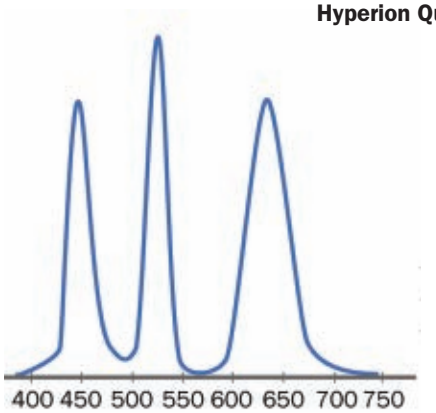
According to a report compiled by analyst Andrew McWilliams and published by technology market research report publishers BCC Research, based in Wellesley, Mass., the total global market for metamaterials was estimated at $307.7 million in 2015, but is expected to grow to more than $1 billion by 2020, and nearly $2.5 billion by 2025.



QD Vision Inc.

White QLED comprising a mixture of solution-processed QDs with high color rendering index.

Hyperion Quantum Dots



Color	Wavelength (nm)	FWHM (nm)
Blue	445.7	24.5
Green	528.8	23.5
Red	641.8	43.6

Nanosys Inc.

>90% BT.2020 Color Gamut

<100 ppm Cd Concentration

100% RoHS Compliant With No Exemption Needed

The spectrum created by Nanosys Hyperion Quantum Dots enables displays to create greater than 90 percent of the BT.2020 UltraHD TV broadcast standard for color without requiring an exemption to the European RoHS Directive.

Today's plasmonic metamaterials incarcerate and enhance light for use as sensor elements in micrometer-sized arrays for the next generation of biosensors.

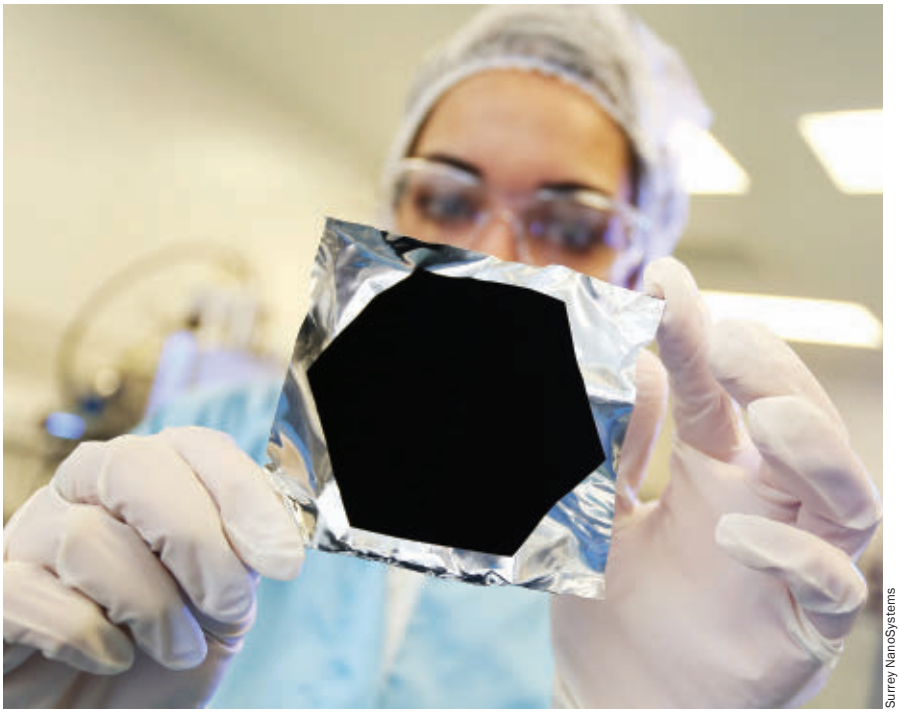
"The most remarkable development of plasmonics is its application in surface-enhanced spectroscopy in which it acts as the surface for molecule absorption in order to enhance Raman scattering," Singh said. "Researchers are making efforts for fabricating photonic chips for fast and reliable biological detection. It will take up almost three to four years for these applications to become reality."

A scientist with a keen focus on bringing about more commercial applications is professor Ortwin Hess, Leverhulme Chair in Metamaterials and Deputy Head of the Condensed Matter Theory group at Imperial College London.

"After all the exciting general discoveries related to imaging, cloaking and

Surrey NanoSystems

Vantablack, the so-called "super-black" material, is so dark that human eyes struggle to discern its dimension and shape.



Surrey NanoSystems

Surrey NanoSystems

Vantablack was created by U.K.-based Surrey NanoSystems by growing a CNT forest directly on a sheet of aluminum.

stopping of light, research and attention in the optical metamaterials field has on the one hand continued to push boundaries and explore new functionalities, but at the same time also become more application-oriented," Hess said.

Examples of advances in optical metamaterials include the search for ways to avoid or compensate for losses, to look for new familiies of materials — particularly compound semiconductors, to facilitate integration with lasers and LEDs, and to provide an exciting platform for new types of lasers and emitters.

"The fact that we now even discuss applications and functionalities that work in scales much smaller than the wavelength of light is truly revolutionary and was not around in optics 15 years ago — and still not present in most textbooks," Hess added.

Hess has recently begun working with a company in Cambridge, England, to design and realize CMOS-compatible "metasurface" structures for thermal emitters used in gas sensors. Such "metasurfaces" enable radiation to be controlled by spatially selective patterning.

This innovation can also be used for circular polarization control and beam-splitters for circularly polarized light. This technology is expected to gain significant importance in the coming years and set a new paradigm in the world of optical materials and its future applications.

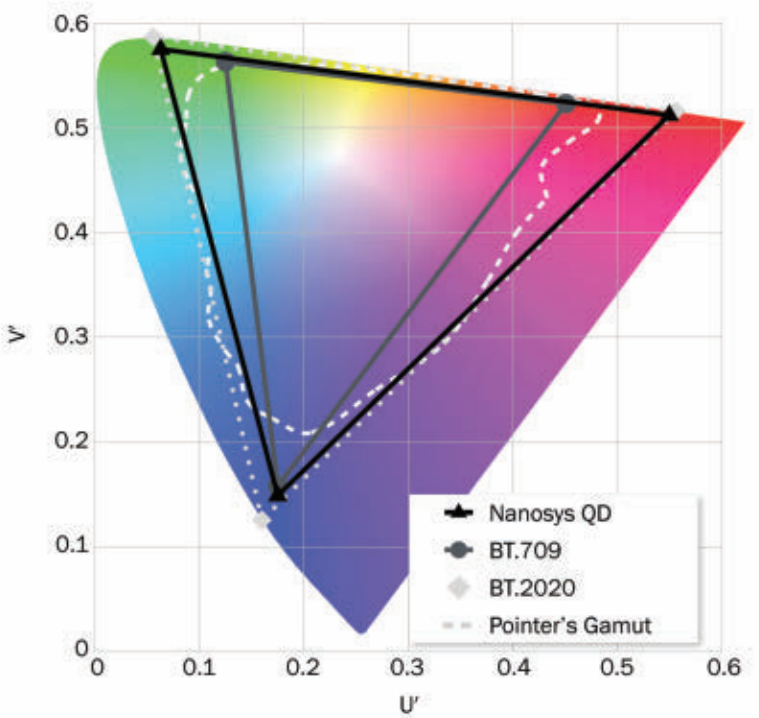
Incorporating metamaterial concepts into compound semiconductor platforms could open up some promising avenues to explore. However, Singh cautions that an application such as nano-sensing is unlikely to leave the lab — or even the theoretical modeling stage — anytime soon.

Carbon nanotubes

Thanks to their unique structure, carbon nanotubes (CNTs) offer an almost unlimited number of configurations, each

‘The fact that we now even discuss applications and functionalities that work in scales much smaller than the wavelength of light is truly revolutionary and was not around in optics 15 years ago — and still not present in most textbooks.’

Professor Ortwin Hess, Leverhulme Chair in Metamaterials and Deputy Head of the Condensed Matter Theory group at Imperial College London.



Nanosys Inc.

This graphic helps to capture the differences in BT color standards. The multicolored horseshoe-shaped area represents all the colors that the average human eye can detect. The area within the dashed gray line, labeled ‘Pointer’s Gamut,’ contains all the colors found in nature. The solid dark gray line labeled BT.709 represents the colors that a standard HD TV can reproduce. Finally, BT.2020 and Nanosys Quantum Dot (QD) is also plotted here. The U′, V′ axes are arbitrary values on the color space chart introduced by the CIE (International Commission on Illumination).

of which offer intriguing optical properties.

When a thin sheet of carbon is rolled into a nanotube, it forms a tube with a particular diameter and twist, defined as its chirality. Each chirality absorbs a narrow range of optical wavelengths, and because several hundred different chiralities are possible, scientists can access more parts of the electromagnetic spectrum than ever before.

“Owing to their excellent conductive properties, CNT-enhanced materials are developed for flexible electronics and transparent coatings,” said Alexandre Clerbaux, marketing and business development manager at Nanocyl SA, Belgium. “Such materials are used for touchscreens to replace scarce resources like indium tin oxide and for novel organic photovoltaics systems.”

When it comes to making solar cells, optical materials must be combined in such a way as to maximize the number of charge carriers generated and to then efficiently transfer them to their respective electrodes. CNTs offer the opportunity to create lightweight, flexible solar cells that can be processed at low temperatures — making them cheaper to make than their silicon counterparts.

There have been tremendous advances in recent years, but market viability has yet to be achieved. With today’s CNT photovoltaics increasing their power conversion efficiencies, combined with the additional benefits of low-temperature processing and their lightweight flexible nature, scientists are convinced that they will one day become commercially attractive.

Super-black coating

As well as applications in solar energy generation, CNTs are being added to other materials to absorb light so effectively that the human eye strains to process it. Vantablack, the so-called “super-black” material, was created by U.K.-based Surrey NanoSystems Ltd. by growing a CNT forest directly on a sheet of aluminum.

“This material is so dark that human eyes struggle to discern its dimension and shape — a phenomenon that gives an impression as though one was looking into a black hole,” said Nanocyl’s Clerbaux.

Vantablack holds the world record as the darkest man-made substance and although originally developed for satellite-borne blackbody calibration systems, its unique optical properties make it ideal for a host of light-suppression and light-management problems. Applications include optical power dumps in laser and visual projection systems; aesthetic purposes in luxury goods and artworks; solar energy absorbers and concentrators; and cold shields in infrared imaging systems.

Quantum dots

Quantum dots (QDs) have gone from hype to reality. Great strides have been made in quantum efficiencies, reliability and color control, so much so that QD-based TVs or QD monitors are now available to buy.

“There has been a lot of advancement in commercializing QD technology over the past five years, solving the last mile problem including reliability, scalability and cost,” said Peter Kazlas, director of Advanced Product Development at QD Vision Inc., in Lexington, Mass. “Ad-

vanced material development takes a lot of time and commitment, but it's worth it. Samsung invested early, and the most, in QD material development and that's why they are leading the LCD industry today with their premium QD-based SUHD TVs even outpacing OLED TV sales."

Most of today's efforts are focused on packaging and integrating quantum dots into displays in new ways that enable lower cost and better performance. This includes integrating QDs into display color filters, which can more than double the power efficiency of a display, and developing flexible, emissive QD displays than can be printed at low cost.

"QLEDs that operate in electroluminescent mode present a leap-frog opportunity over OLED technology," Kazlas said. "Better color, lower voltage and printability is a winning combination for next-generation displays and lighting."

Nanosys Inc., QD specialists based in Milpitas, Calif., are currently working on QLEDs, which it believes is the future of QDs for displays.

"We are developing QLEDs, using the quantum dots as an emissive material — think OLED display but with quantum dots instead of organic emitters," said Jeff Yurek, corporate communications manager at Nanosys Inc. "Today, QD displays are built just like LED displays. The quantum dots are added to the backlight of the display in the form of a translucent plastic film that's loaded with dots. In this mode, the QDs are improving existing LED displays by enabling them to be more power efficient and deliver better color."

Although the quantum efficiency of red and green QLEDs basically matches those of commercial OLEDs with much better color, the efficiency of blue devices remains an issue — as does large-scale printing and reliability. These challenges must first be overcome before the market can be reached.

While the timeline for Nanosys' QLED displays remains confidential, its Hyperion Quantum Dots was launched in May this year. The technology enables displays to deliver over 90 percent of the BT.2020 (latest color standard that replaces BT.709) Ultra HD broadcast standard for color gamut.

This brings a significantly wider, more accurate range of colors to TV screens that Yurek says matches the range of colors found in the natural world, making watching TV more like looking out of a window. Crucially, this development comes with cadmium levels below the 100-ppm limit established by the European RoHS Directive.

Display makers currently have a particular interest in cadmium levels since rumors emerged that European policy makers may put to an end the current RoHS exemption for displays containing more than 100 ppm of cadmium by 2018.

"This left display makers wondering how they would support the BT.2020 color gamut standard in the next few years without an exemption," Yurek said. "This is accomplished by combining an entirely cadmium-free red quantum dot with a green quantum dot engineered to have an exceptionally narrow emission spectrum and ultra-low cadmium."

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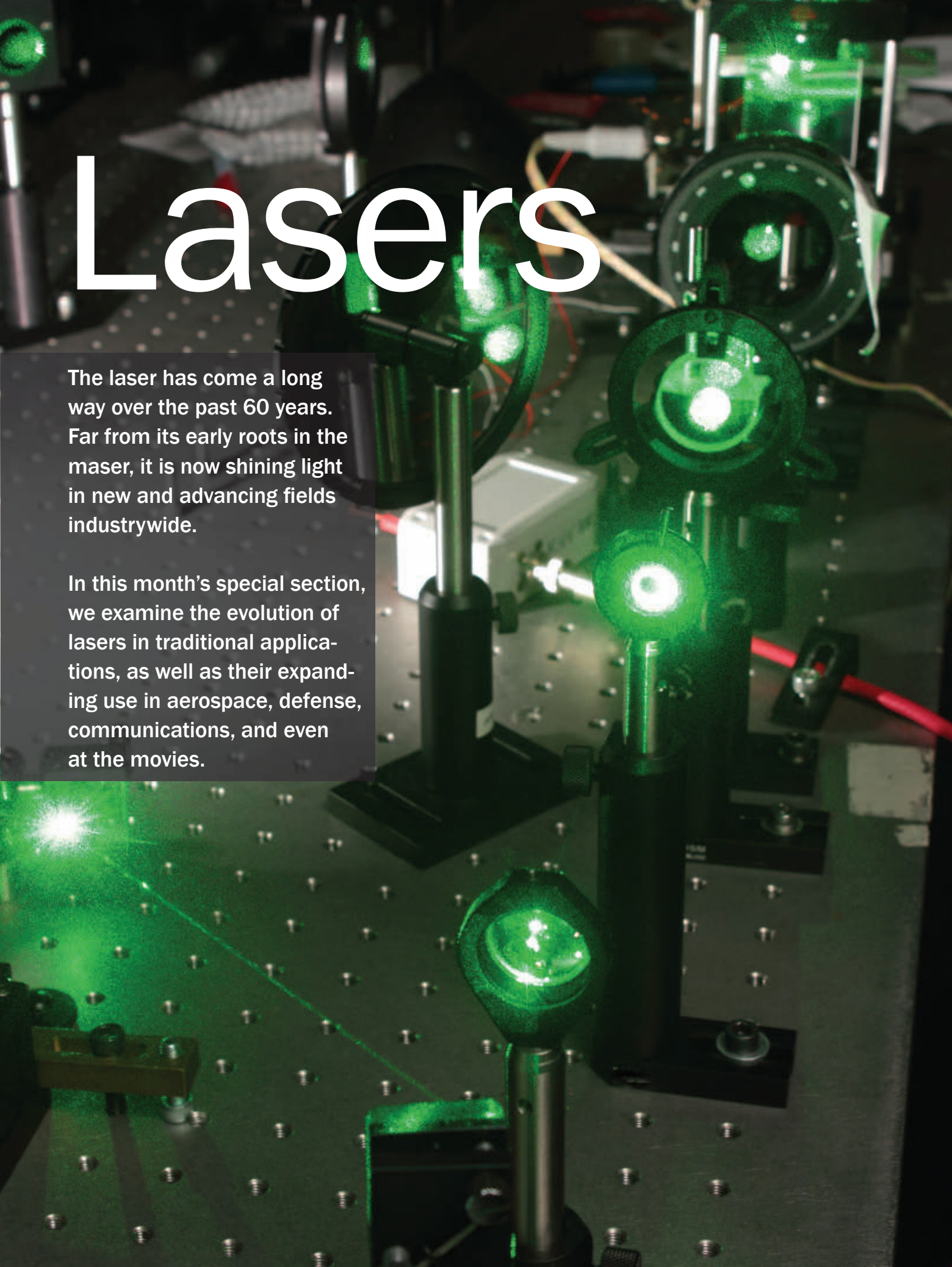
Lasers



The laser has come a long way over the past 60 years. Far from its early roots in the maser, it is now shining light in new and advancing fields industrywide.

In this month's special section, we examine the evolution of lasers in traditional applications, as well as their expanding use in aerospace, defense, communications, and even at the movies.

The Aerospace Corp.

3 Questions

INTERVIEW

Walter Buell, principal director of the Electronics and Photonics Laboratory at The Aerospace Corp. in California, first became interested in lasers and optics more than 30 years ago. When his high school physics teacher allowed him to teach a lab class on interference and diffraction, he "was hooked."

Buell studied physics and optics as an undergrad, and began to engage in the research environment. Since then, his work has been mainly in the application of lasers in atomic physics, such as laser cooling and atomic clocks, and in laser remote sensing — principally in synthetic aperture ladar.

Photonics Spectra spoke with Buell about advances in the lasers field, and what he anticipates for the future.

Q: What are some innovative, exciting advancements you are seeing with lasers, and how are they helping to evolve the field?

A: Two of the major evolutions in laser technology today are: 1) capability for fairly dramatic reductions in size, weight and power (SWaP) requirements, and 2) increased flexibility in wavelength and temporal waveform. New materials and advances in sources like quantum cascade lasers are enabling field and commercial applications that used to be the purview of academic labs. Hybrid architecture lasers (for example, semiconductor laser seeds amplified by fiber and bulk amplifiers) enable long-range communications and remote sensing with advanced waveforms and the potential for electrical efficiency exceeding 30 percent.

At the cutting edge of such low SWaP, high-performance sources are chip-scale integrated photonics where lasers, modulators, frequency converters, and so on, can be integrated onto a single photonic chip via monolithic or heterogeneous integration. Quasi phase-matched materials are realizing their potential for high-efficiency nonlinear wavelength conversion at power levels sufficient to support a wide range of applications in laser sensing. A decade ago I had a tongue-in-cheek line in a journal paper to the effect that "generally, tunable sources are not sufficiently stable and stable sources are not broadly tunable." Clearly, laser technology has advanced to the point where this is no longer true, and laser sources are available as commercial products with performance only dreamed of a few years ago.

Q: What new applications are laser technologies finding?

A: Laser remote sensing — for example, laser radar — had been an important application area almost since the invention of the laser, but recent advances in laser and detector technology have enabled a proliferation of applications. Examples include lidar altimetry from space, airborne lidar mapping, and even "lidar on a chip." The advances in high-efficiency, compact and robust fiber lasers [are] beginning to make inroads into laser communications from and in space, with multiwatt high-bandwidth lasers being small enough to fit into CubeSat pico- and nanosatellites.

Advances in complex and high-performance but low-SWaP lasers is taking laser spectroscopy out of the lab, into the field and beyond the bounds of Earth. Already, laser-induced breakdown spectroscopy has been used in an instrument on the surface of Mars, and new missions that require compact and efficient multiwavelength systems are being developed for lunar and interplanetary petrochronology instruments.

In addition to SWaP improvements, integrated photonic technology enables dramatic potential for functional consolidation of photonics-based devices, including atomic time/frequency references and optical signal processing devices. One example is wide-band photonic receivers for RF [radio frequency] compressive sensing, where integrated photonic circuits are being investigated to replace free-space optics, and yield order-of-magnitude reductions in sensor system size and weight with full retention of sensing capability. Another potential outlet for photonic integrated circuitry is high-performance chip-scale atomic clocks, where the generation and stabilization of clock signals require a high degree of control over pump lasers and spectroscopy-based health and status monitors.

Q: What do you foresee for the future of laser technology and potential applications?

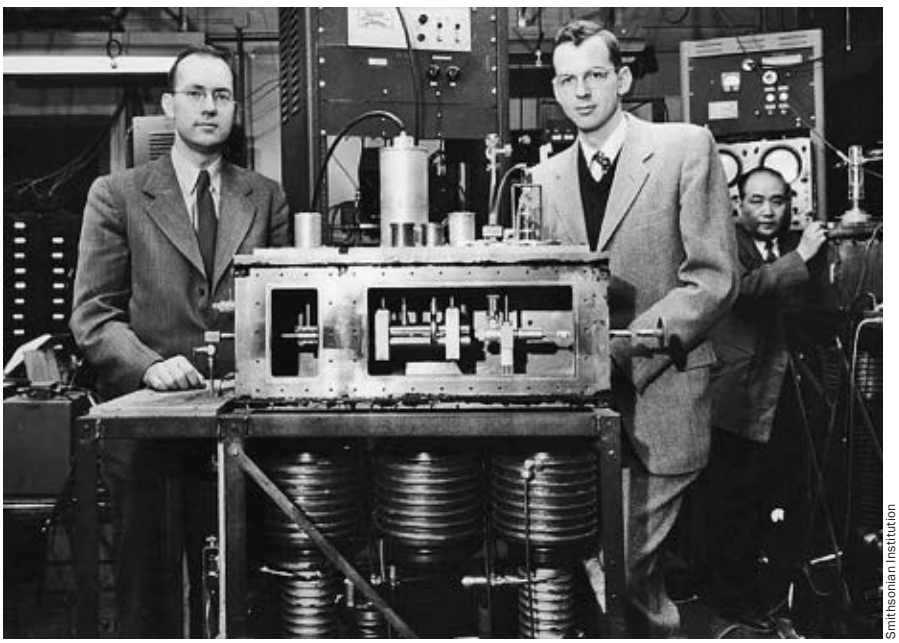
A: One exciting area I see is the integration of lasers and other photonic elements into the Internet of Things for sensing, networked communication and high-bandwidth/high-speed signal processing. This involves lasers not as stand-alone elements, but fully integrated elements of complex systems. The capabilities of advanced laser technologies also depend critically on advances in other technology areas. For example, recent advances in lidar mapping depends at least as much on development of high-bandwidth photon-counting detector arrays as on laser development, and on advances in computing capability, algorithm development and data fusion with other sensors.

Other application areas for laser technology, such as medicine and materials processing, are not new but are likely to benefit from accelerating improvements in laser performance capability and reliability. In laser manufacturing, process optimizations are likely to invoke novel laser performance capabilities in the temporal waveforms and instantaneous powers that can be applied toward long-standing objectives such as material deposition and removal, surface treatments and fatigue mitigations, particularly in specialty materials unique to specific markets.

From **Masers to Lasers** in Space — and at the Cinema!

Well beyond its first successful demonstration in 1960, the laser has found its way into applications that are the stuff of Hollywood movies — and into the movie theater, too.

BY JUSTINE MURPHY
SENIOR EDITOR



Smithsonian Institution

Charles Hard Townes **(left)** is pictured in 1954 with the maser he developed with then-graduate student James P. Gordon **(right)** and then-postdoctoral researcher H.J. Zeiger (not shown). The device radiated at a wavelength of a little more than 1 cm and generated approximately 10 nW of power.

Sixty years ago, physicists Charles Hard Townes, James P. Gordon and H.J. Zeiger demonstrated the maser (microwave amplification by stimulated emission of radiation). It wasn't long before Townes and fellow physicist Arthur Schawlow proved that masers could be made to operate in the visible and infrared regions. Around the same time, research by Gordon Gould, then a graduate student at Columbia University, found that a concentrated beam of light could push technology beyond the maser, and coined his concept the laser — for light amplification by stimulated emission of radiation. In 1960 — based on theoretical work by Townes, Schawlow and Gould — engineer and physicist Theodore H. Maiman built and demonstrated the first working example.

The technology advanced quickly after that first ruby laser, and applications soon followed. For decades, lasers have been finding new applications, from consumer electronics to global telecommunications, industry, science and medicine. Now, they are reaching new heights in aerospace and enhancing the movie experience.

Look, up in the sky!

The first laser-powered aircraft took to the skies in 2003. Developed by a team from NASA's Marshall Space Flight Center, the Dryden Flight Research Center and the University of Alabama in Huntsville, the plane was powered by an invisible ground-based laser that was tracking the aircraft in flight, and directing its energy beam at specially designed photovoltaic cells carried on-board to power the plane's propeller.

In the years since this development, lasers have become a versatile tool for aerospace applications. Among them, according to Laserage Technology Corp. — a laser component manufacturer in the medical and aerospace industries — is hermetic laser sealing of electronic and optoelectronic packages on spacecraft to protect such systems. Employing laser processing (e.g., welding, drilling and coating) in the aerospace industry provides flexibility in design and manufacturing, resulting in lighter components and, potentially, reduced costs.

Laser frequency combs are another technology shown to advance aerospace applications. Created by a laser that emits continuous pulses of light spanning almost the entire visible spectrum, these combs are used for precisely measuring the frequency of light from a variety of sources. This technology also helps telescopes achieve unprecedented accuracy in spectral measurements.

A team from three German institutions — the Max Planck Institute of Quantum Optics, the Kiepenheuer Institute for Solar Physics, and the University Observatory Munich — led the research. By attaching a laser frequency comb to the Kiepenheuer solar telescope in Tenerife in the Canary Islands, light from both the comb and the sun was coupled to a single optical fiber connected to a spectrograph.

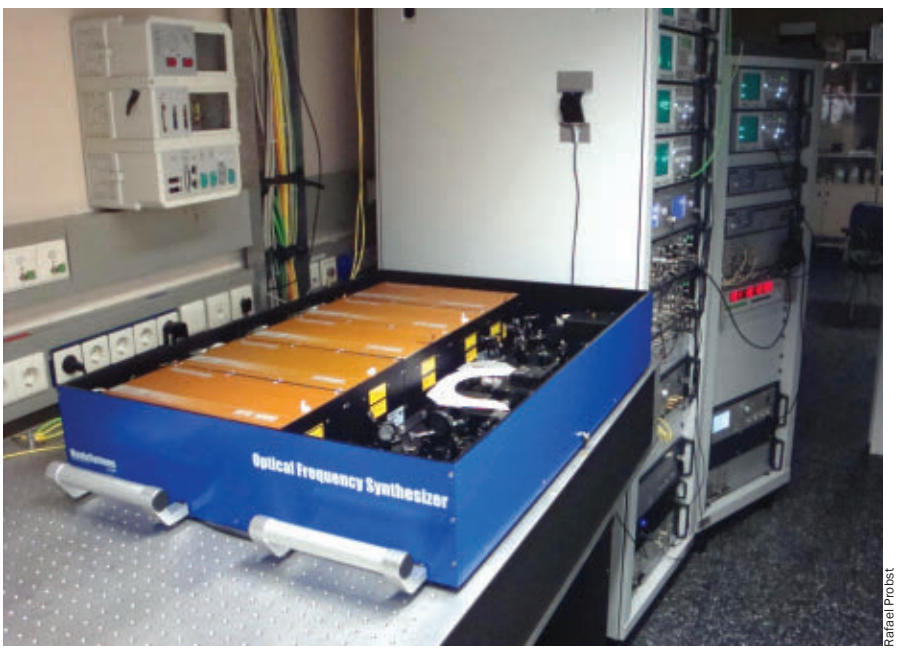
"An important aspect of our work is

that we use a single-mode fiber, which takes advantage of the wave nature of light to enable a very clean and stable beam at its output," said Rafael Probst, a post-doctoral candidate at the Max Planck Institute of Quantum Optics. "This type of fiber is quite common in telecom and laser applications, but its applications in astronomy are still largely unexplored."

The laser frequency comb technique has been shown to improve calibration by about a factor of 100 over a temporally separated fiber transmission. In combination with this calibration, the laser frequency comb method enables extremely robust and accurate spectroscopic measurements. This technology could allow astronomers to more accurately measure a planet's Doppler shifts, essentially increasing the chance of spotting Earth-sized, habitable planets, and additionally enabling better study of the sun, distant stars and exoplanets.

NASA is looking beyond Earth's orbit also with its Lunar Laser Communication Demonstration (LLCD). In it, the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft orbiting the moon has been able to downlink data to two receiver terminals using a laser beam. While the organization communicates with its spacecraft primarily via radio waves, the Deep Space Network (DSN) relies on large antenna arrays around the globe. Engineers are working to switch to optical frequencies instead, according to Francesco Marsili, a microdevices engineer at NASA's Jet Propulsion Laboratory. This would increase the data rate of the communication links, and rely on technology such as lasers mounted to the spacecraft that are pointed at optical telescopes on Earth to downlink data.

"With the huge quantities of data from missions that are going farther and farther away from the Earth, we need higher bandwidth communications systems," said Chip Barnes, chief engineer for the Ball Aerospace Civil Space business unit. Advancing such communications systems will require further development of optics and photonics technologies, and more efficient lasers.



Rafael Probst

A laser frequency comb.

NASA

An artist's concept of NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE), showing the Lunar Laser Communications Demonstration (LLCD).

Battling biological agents

Bioweapons are a growing concern among military leaders. In Canada, they are taking a proactive approach to such threats.

The Defence Research and Development Canada (DRDC) Valcartier, a government agency, is currently seeking to investigate how lasers could help detect airborne biological and chemical agents, and ultimately offer early warning of these types of weapons. According to a request for proposals filed in September, DRDC is dedicating $850,000 to this project, which will involve studying "the phenomenology of the optical and infrared signals from chemical and biological material" to be able to "process and analyze these signals from acquired data set during either field trial, including aerial, or laboratory data acquisition campaign."

The U.S. military is studying the use of lasers, as well, but for advancement of fighter jets and similar aircraft (for the detection of weapons, bombs and other potential threats). The Air Force Special Operations Command has been moving toward installation of a high-energy laser and tactical off-board sensors to an AC-

U.S. Air Force

A U.S. Air Force AC-130W gunship.

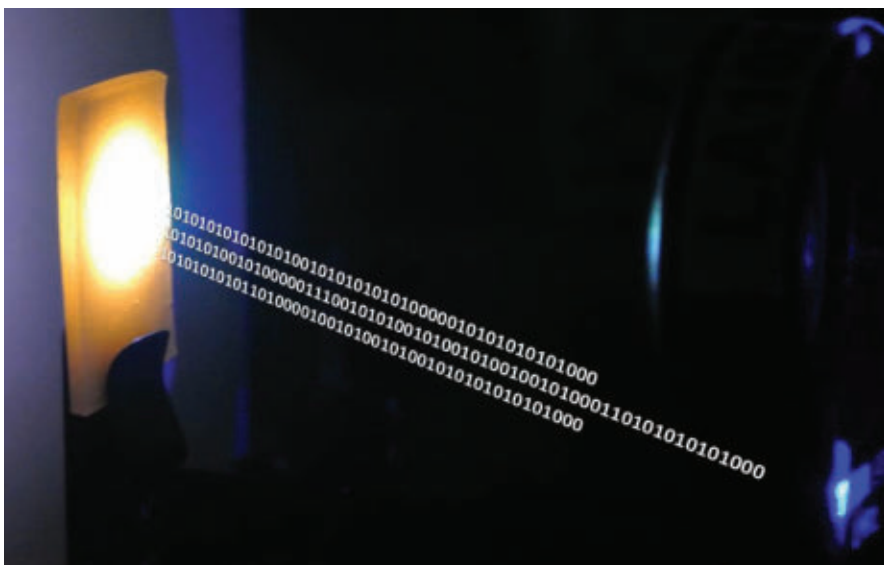
130W gunship on military fighter jets. The request for funding (from the Department of Defense) for this research has been made, according to information from FlightGlobal — an agency that provides data, insight and other services for the aviation industry — and the work could begin by 2020.

Multimedia lasers: from Wi-Fi to the movies

Laser weapons were once only the stuff of movies and television. Now, lasers are becoming part of the picture in applications from data communications and lighting to projection. In this increasingly digital age, users are constantly looking for better, faster wireless connectivity. Wi-Fi and Bluetooth, both well-established technologies, already offer high speed, but now scientists are seeing room to grow.

A team from the King Abdullah University of Science & Technology (KAUST) in Saudi Arabia has demonstrated that white light from lasers could provide data speeds up to 2 GB/s. To do this, they have developed a way to shorten the wavelength of the electromagnetic waves used for transmitting information — a nanocrystalline material that rapidly makes white light out of blue light. Parts of the electromagnetic spectrum that are unregulated and more energy-efficient are used for visible light communication (VLC), thus producing white light.

"VLC using white light generated in this way is limited to about one hundred million bits per second," said Boon Ooi, a professor of electrical engineering at KAUST.



King Abdullah University of Science & Technology

A nanocrystal-based material converts blue laser emission to white light for combined illumination and data communication.

To clear this hurdle, the researchers employed a solution-based method that incorporated a conventional nitride phosphor to develop nanocrystals made from cesium lead bromide. When illuminated by a blue laser light, the nanocrystals emitted green light and the nitride emitted red light; combined, the two produced a warm white light. The white light generated "was of a quality comparable to present LED technology," according to the researchers. So in addition to faster Wi-Fi, they have found that such light could have another use.

"We believe that white light generated using semiconductor lasers will one day replace the LED white light bulbs for energy-efficient lighting," Ooi said.

And while lasers still aren't recommended for popping popcorn, you can now find them at the movies.

Developed jointly by Dolby Laboratories, Christie Digital and Necsel, the Dolby Vision Cinema Laser Projector — winner of the 2016 Prism Award for Displays and Lighting — is set to enhance the "premium cinema experience with high contrast, high brightness, a wide color

Christie Digital

The Dolby Vision laser projection system is set to enhance the cinema experience, and make it more engaging for moviegoers.

gamut and excellent 3D performance," and make it more engaging for viewers.

"Cinema projection does not get any better than this," said Don Shaw, senior director of product management at Christie.

The system employs optics and image processing for high dynamic range, and enhanced color technology provides a high-contrast, high-brightness color range that matches what is visible to the human eye. The technology uses two high-frame-rate-capable 4K laser projection heads (by Christie), featuring a customized light path. Combined with a 6P modular laser light source, the laser system creates high-contrast images and ultra brightness. According to Necsel, the system provides "strikingly vivid and realistic images, and makes viewers feel like they are in the movie's world."

"We'll be delivering audiences a richer, more detailed viewing experience with up to 14 foot-lamberts on-screen in 3D and up to 31 foot-lamberts for 2D Dolby Vision content," Shaw said, noting that this exceeds ultra-bright industry standards.

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Lasers & Laser Diode Modules Directory

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www.teradiode.com

TOPTICA Photonics Inc.
Victor, N.Y.
www.toptica.com

TRUMPF Inc.
Farmington, Conn.
www.us.trumpf.com

World Star Technologies
Toronto
www.worldstartech.com

Lasers, Diode, Tunable External Cavity

AXSUN Technologies
Billerica, Mass.
www.axsun.com

New Focus
Santa Clara, Calif.
www.newport.com/newfocus

Photodigm Inc.
Richardson, Texas
www.photodigm.com

Sacher Lasertechnik GmbH
Marburg, Germany
www.sacher-laser.com

Santec Corp.
Komaki, Japan
www.santec.com

Lasers, Diode-Pumped Solid-State

B&W Tek
Newark, Del.
www.bwtek.com

Cobolt AB
Solna, Sweden
www.cobolt.se

Coherent Inc.
Santa Clara, Calif.
www.coherent.com

Continuum
San Jose, Calif.
www.continuumlasers.com

Datalogic Industrial Automation, Laser Marking
Bologna, Italy
www.datalogic.com/eng/products/industrial-automation/laser-marking-pc-17.html

Frankfurt Laser Co.
Friedrichsdorf, Germany
www.frlaserco.com

HUBNER GmbH & Co. KG
Kassel, Germany
www.hubner-photonics.com

Integrated Optics UAB
Vilnius, Lithuania
www.integratedoptics.com

IPG Photonics Corp.
Oxford, Mass.
www.ipgphotonics.com

JENOPTIK Laser GmbH, Healthcare & Industry
Jena, Germany
www.jenoptik.com/lasers

Kimmon Koha Co. Ltd.
Centennial, Colo.
www.kimmon.com

Laser Quantum Ltd.
Stockport, England
www.laserquantum.com

Laser S.O.S. Ltd.
St. Ives, England
www.lasersos.com

Laser-export Co. Ltd.
Moscow
www.laser-export.com

Laserglow Technologies
Toronto
www.laserglow.com

LASOS Lasertechnik GmbH
Jena, Germany
www.lasos.com

Lee Laser Inc.
Orlando, Fla.
www.leelaser.com

Lumentum Operations LLC
Milpitas, Calif.
www.lumentum.com

Melles Griot, Light Sources Group
Carlsbad, Calif.
www.mellesgriot.com

Militram Corp.
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www.militram.com

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www.national-laser.com

Norlase
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www.norlase.com

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www.omicron-laser.de

Pantec Medical Laser
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www.pantec-medicallaser.com

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Ronkonkoma, N.Y.
www.photonix.com

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www.powertechnology.com

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RMI Laser LLC
Lafayette, Colo.
www.rmilaser.com

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Edinburgh, Scotland
www.uniklasers.com

Lasers, Femtosecond

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Lasers, Fiber

American Laser Enterprises LLC
Wixom, Mich.
www.a-l-e.net

B&W Tek
Newark, Del.
www.bwtek.com

Clarus Engineering Corp.
Princeton, N.J.
www.clarusengineering.com

Datalogic Industrial Automation, Laser Marking
Bologna, Italy
www.datalogic.com/eng/products/industrial-automation/laser-marking-pc-17.html

Gooch & Housego
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www.goochandhousego.com

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www.ipgphotonics.com

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www.jenoptik.com/lasers

Kimmon Koha Co. Ltd.
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KMLabs (Kapteyn-Murnane Laboratories Inc.)
Boulder, Colo.
www.kmlabs.com

Lumentum Operations LLC
Milpitas, Calif.
www.lumentum.com

MPB Communications Inc.
Montreal
www.mpbcommunications.com

NKT Photonics A/S
Birkerod, Denmark
www.nktphotonics.com

Nufern
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www.rmilaser.com

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www.frlaserco.com

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www.laserquantum.com

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www.quantel-laser.com

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www.quantel-laser.com

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www.rmilaser.com

Lasers, Ti:Sapphire

Coherent Inc.
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www.continuumlasers.com

GT Advanced Technologies
Salem, Mass.
www.gtat.com

KMLabs
(Kapteyn-Murnane Laboratories Inc.)
Boulder, Colo.
www.kmlabs.com

Laser-export Co. Ltd.
Moscow
www.laser-export.com

Photonics Industries International Inc.
Ronkonkoma, N.Y.
www.photonix.com

Swamp Optics LLC
Atlanta
www.swampoptics.com

Lasers, Ultrafast Pulsed

Biophotonic Solutions Inc.
East Lansing, Mich.
www.biophotonicsolutions.com

Coherent Inc.
Santa Clara, Calif.
www.coherent.com

Continuum
San Jose, Calif.
www.continuumlasers.com

HAMAMATSU

Hamamatsu Corporation
Bridgewater, N.J.
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IPG Photonics Corp.
Oxford, Mass.
www.ipgphotonics.com

JENOPTIK Laser GmbH,
Healthcare & Industry
Jena, Germany
www.jenoptik.com/lasers

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Boulder, Colo.
www.kmlabs.com

Micro-Controle Spectra-Physics SAS
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www.newport.com

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Regensdorf, Switzerland
www.onefive.com

PicoQuant GmbH
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www.picoquant.com

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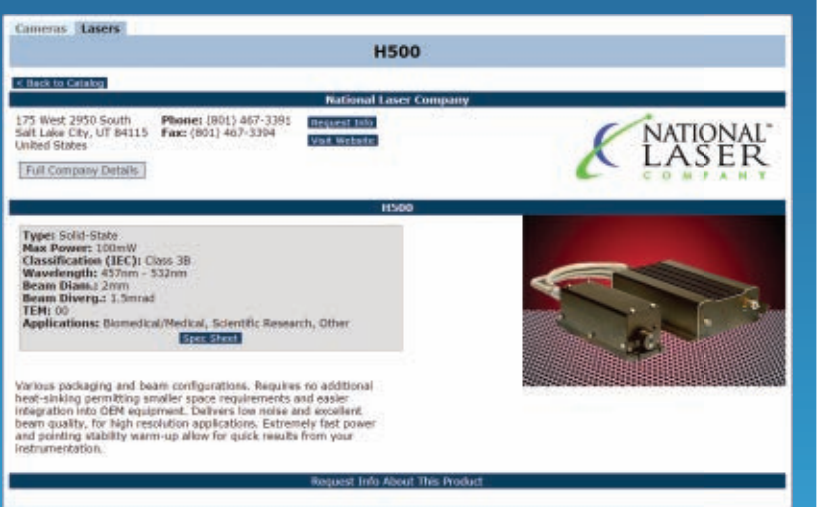

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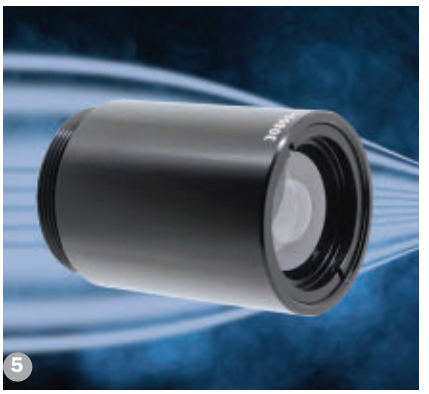

5

6

1 Nd:YAG Laser

Quantum Composers Inc. has announced the MicroJewel ultracompact, neodymium-doped yttrium aluminium garnet (Nd:YAG) laser. The diode-pumped, solid-state laser features a high-performance multiwavelength Jewel and mid-IR option. The MicroJewel is the perfect solution for customers who have limited space and/or limited power. Military-grade mounting for resonator optics make it rugged and robust. Three inches long and just under 40 g, the laser is designed to be integrated into systems requiring a small footprint, including compact, handheld units. It serves a variety of industrial and laboratory applications including laser radar, breakdown spectroscopy, particle image velocimetry and cube satellite systems.
eprieskorn@quantumcomposers.com

2 Spectroscopy System

Princeton Instruments has released the FERGIE spectroscopy system, an aberration-free spectrograph with a built-in, low-noise, cooled detector. A spectral resolution of 0.13 nm/pixel with a 1200 g/mm grating fares well when compared to the resolution afforded by larger spectrographs with longer focal lengths. Additionally, FERGIE's diffraction-limited imaging with a >60 lp/mm spatial resolution throughout the focal plane yields high signal-to-noise ratios and permits multichannel spectroscopy. A built-in detector permits high-sensitivity spectral capture from 190 to 1100 nm.
dfbaum@princetoninstruments.com

3 Hyperspectral Cameras

3D-One offers the Avior series of hyperspectral cameras. The devices are specifically designed for OEM customers seeking a compact and robust solution for hyperspectral imaging. The camera is commercially available for customers in industrial machine vision and medical imaging fields who intend on using their own spectral processing and optical technologies. The cameras feature a global shutter CMOS sensor with Imec filter technology for hyperspectral imaging. The design of the camera is optimized for size, weight and power with a form factor of 46 mm and a mass of <175 g. Industry standard CameraLink interface guarantees reliable data transfer and robust synchronization. The interface features PoCL to enable single cable operation of the camera.
info@3d-one.com

4 Focal Length Calculator

Goyo Optical Inc. has announced Goyo North America's Focal Length Calculator. The web tool allows users to quickly and easily calculate the most effective lens focal length for their system, ensuring the aspect ratio of the sensor size equally pairs with the aspect ratio of the object being imaged. Based on the sensor size, working distance and field of view are entered into the tool. The Focal Length Calculator computes the effective focal length while also providing the best lens options.
info@goyonorthamerica.com

5 UV Lens

Resolve Optics Ltd. has released an optimized, antireflection-coated, 10.5-mm UV lens for an automatic return fire system to be used in conjunction with a solar blind filter stack operating over a bandwidth of 240 to 280 nm. Mounted lenses are required to provide a 360° view, enabling the system to detect the UV from muzzle flashes, identify its location and return fire to that location automatically. Rugged construction provides high-resolution UV images from 10 m to infinity with minimal distortion.
sales@resolveoptics.com

6 CCD Camera

QImaging offers the Retiga LUMO CCD camera for bioluminescence and routine fluorescence imaging. The device enables the detection and quantification of ultralow-light luminescence signals by coupling deep cooling with FPGA-based intelligent features that correct defective pixels and remove accumulated dark current. Seventy-five percent peak quantum efficiency combined with low-noise electronics reveals the weak signals missed by industrial cameras. Ultralow-noise readout mode enables exposure times of up to 60 minutes. Deep sensor cooling and dynamic dark frame correction deliver data over long exposures, and 50-MHz two-port readout delivers frame rate for finding, focusing and imaging samples.
info@qimaging.com

Compact UV Lamp

Spectronics Corp. has announced the Spectroline MiniMAX UV-5G compact lamp for laboratory applications. A battery-operated, 5-W, short-wave UV lamp, the UV-5G combines miniature size with maximum power, making the device portable and effective. It weighs 11 oz. Applications include the UV sanitizing of disease-causing microrganisms and UV degradation studies.
paul.perillie@spectroline.com

Optical Sensor Module

AMS AG offers the TMD3700 optical sensor module for color, ambient light and proximity sensing. The small 4 × 1.75-mm footprint has a height of 1 mm for next-generation mobile phones with tight layouts and mechanical design constraints. A wide 45° field of view, an ambient light sensing accuracy of ±10 percent and an operating range of 200 mlux to 60 klux behind dark glass enable smartphones to measure the surrounding light environments and automatically adjust display color and brightness for optimal viewing. The TMD3700 color sensor channels have UV- and IR-blocking filters and a dedicated converter allowing simultaneous data capture necessary for accurate measurements. The combination of photopic color and ambient light sensing enables smartphones to perform real-time adjustment of display properties such as white point, color gamut and color saturation.
darrell.benke@ams.com

Measurement Card

Anritsu Co. has announced a 40/100-G measurement card option that expands the analysis capability of its Network Master Flex MT1100A optical transport tester. The module supports the generation and measurement of 100-GbE signals using RS-FEC, OTN, SDH/SONET, Ethernet and other technologies. The Network Master Flex MT1100A can be used by engineers and field technicians to ensure transport equipment, core networks and data centers operating up to 100G are in compliance with the RS-FEC standard. The Advanced Module MU110013A has various clock outputs at the CFP2 port to verify optical module quality. The module provides the ability to encode/decode IEEE 802.3bj RS-FEC for 100 GbE transport, as well as correctable/uncorrectable errors for threshold FEC tolerance testing.
kim.collins@anritsu.com

Transceiver

Fiberstore has announced the SFP-10G-SR Compatible 10GBASE-SR SFP+ 850-nm, 300-m DOM Transceiver from Cisco Systems Corp. Every transceiver is individually tested on a full range of equipment. It is a cable choice for data center, enterprise or service providers, and is compatible with Cisco, Arista, Juniper, Dell, Brocade and other brands.
sales@fs.com

Scan System

Scanlab AG has released the basiCube 10 scan system, optimized for use with 532-nm green laser light. The system is ideal for laser marking applications, laser-based glass engraving and the processing of precious metals, silicon wafers and other materials that respond poorly to typical IR wavelengths. It also enables the generation of fine contours by focusing to very small spot sizes while simultaneously maintaining excellent beam quality and low heat development. The device allows engraving 3D shapes inside a glass body or welding copper wires directly onto the silicon substrates of integrated circuits. Applications include medical products, decorative items and semiconductor components.
info@scanlab.de

Microscope Stage

Prior Scientific Inc. offers the H112 microscope stage, featuring a travel range of more than 300 × 300 mm. The H112 is fully compatible with a wide range of microscopes and can accommodate wafers with diameters up to 12 in. or samples up to 25 kg in weight. It also works with many robot arm wafer loaders. The transmitted light area allows transmitted and reflected light applications to be performed. The large area scanning capability of the H112 stage is precise with a minimum step size of 0.04 µm and a repeatability of ± 0.7 µm. The microscope stage is ideal for the accurate and precise scanning of semiconductor wafers, photo masks, flat panel displays and printed circuit boards.
info@prior.com

Elemental Spectrometers

Spectro Scientific Inc. has introduced the SpectrOil 100 series of elemental spectrometers, providing quick, laboratory-precise measurement of elemental concentrations in a variety of fluid types. The SpectrOil 100 series eliminates the delay and expense of off-site laboratory analyses, as minimal training is needed to operate the system. The analysis process involves no sample preparation or use of solvents or gases, reducing cost per sample, and the spectrometers' 30-s analysis time provides immediate, simultaneous multielement results. The SpectrOil 110 provides a basic engine wear package, while the SpectrOil 120 includes standard and extended range packages with wear metals, coolants, fuels and custom application options.
www.spectrosci.com

Line Scan Cameras

JAI AS has announced two new high-speed, monochrome line scan cameras for its Sweep series. The SW-4000M-PMCL model is equipped with a 4-K CMOS monochrome line sensor, delivering a scan rate of up to 200 kHz. The SW-8000M-PMCL features an 8-K CMOS line sensor delivering a scan rate of 100 kHz. Both cameras are available with an F-mount and M42 mount. Eight- and 10-bit data output is handled via a Camera Link Deca interface.
camerasales.emea@jai.com

Integrated Sphere Source

Gooch & Housego has announced the OL 455-

STATEMENT OF OWNERSHIP MANAGEMENT AND CIRCULATION OF PHOTONICS SPECTRA
September 30, 2016
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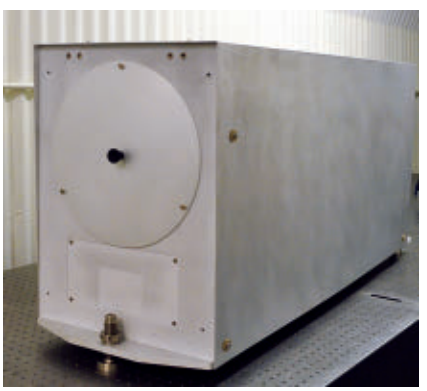
President

new products

6KSA Elongated Integrating Sphere Source. The device features an elongated sphere design to reduce the nonuniformity by a factor of 10×. An aperture drive design increases accuracy while shortening the seek time for finding a specific luminance target. A heated monitor detector holds the detector at a steady temperature to reduce settling time and nonlinearity as luminance rises or falls.
orlandosales@goochandhousego.com

Laser Modules

II-VI Inc. has announced laser diode modules, VIS and near-infrared lasers, narrow line-width lasers and Q-switched lasers. A 9xxnm fiber-coupled diode laser offers output powers from 140 to 300 W. The module is a single-emitter cascaded design that allows higher output powers with increased wall plug efficiency and simplified thermal management. A 1060-nm single-mode laser diode seed module delivers kink-free powers of up to 1.5 W in ns pulse operation, enabling fiber laser systems with highly efficient pulse amplification and improved frequency conversions. A new line of high-power multibar stack laser diode modules is also available.
info@II-VI.com



Vacuum-Compatible Beam Expanders

Optical Surfaces Ltd. has announced vacuum-compatible beam expanders for high-power laser applications. The expanders are aspheric mirror-based devices offering either beam expansion or reduction capabilities. Incorporating high precision off-axis mirrors, they provide an unobstructed output and highly efficient transmission and can be used with collimated polychromatic light without the need of any fine focus adjustment. Available in a wide range of fixed or variable magnification configurations, the beam expanders are designed to be easy to use for accurate, unobstructed expansion and contraction of any collimated input light source. Manufactured to >5 λ surface accuracy, the expanders feature an off-axis design that produces no central obscuration. Efficient transmission is obtained, unspoiled by spider diffraction patterns. The devices incorporate smooth-running mechanics that do not require lubrication, optical designs that avoid use of glues and cements that might outgas, and sandblast-finished metalwork that eliminates stray light without the need for anodizing.
sales@optisurf.com

Servo Controller

Physik Instrumente LP offers the E-873.3QTU three-axis digital servo controller for miniaturized precision positioning and handling tasks. The device complements the size of the ultracompact positioners it controls, has integrated power amplifiers and an integrated interpolator, and is macro-programmable for stand-alone functionality of each channel. The controller is equipped with a data recorder for high-speed tracing, ID chip compatibility for quick startup, on-the-fly parameter changes, and exchange of system components without recalibration. Applications include precision alignment and automation, photonics, bionanotechnology, metrology, microscopy, and micromanipulation.
info@pi-usa.us

Lidar Module

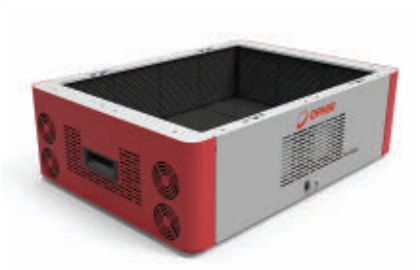
Invisage Technologies Inc. has announced the Spark Micro-LiDAR SML20 module. The previously announced Spark4K 13-MP, 1.1-µm NIR sensor enables the SML20 module to sense structured light patterns with high acuity at a range of 20 m, even in direct sunlight, allowing drones to self-navigate at a much higher speed. With a sensor module of 8.5 × 8.5 × 4.5 mm, the device is ultralight, compact and low power. The SML20 is ideal for drones and other mobile autonomous devices that require a lighter, more power-efficient alternative to conventional lidar without the limitations of ultrasonic and stereo-camera depth sensing systems.
jennifer.lillie@invisage.com

Optical Modules

Finisar Corp. offers a new family of 100-Gbps optical modules, extending communication reaches in modern enterprise and hyperscale data center environments. Based on the QSFP28 form factor, the comprehensive portfolio includes an eSR4 extended short reach transceiver designed for 200-m reaches, an eCWDM4 extended coarse wavelength division multiplexing transceiver for 10-km reaches and an eLR4 extended long reach transceiver for 20-km reaches, each operating using four 25-Gbps channels.
sales@finisar.com

LED Luminaire Measurement System

Ophir Photonics Group has released the FluxGage LED luminaire measurement system. The FluxGage system uses solar panels as the light detector, measuring flux, color and flicker to evaluate the performance of LED-based products.



The all-in-one photometric test system uses 2 pi geometry. A spectrometer is incorporated for color measurement of the spectrum, correlated color temperature, color rendering index, deep UV and chromaticity. There is also a fast photodetector for flicker measurements. No fibers are needed. The measurement system is three times smaller and costs less than equivalent integrating sphere products. It is designed for R&D use during development and production for incoming inspection and quality control of new and replacement parts.
sales@us.ophiropt.com

2D Material Growth Process

Oxford Instruments PLC has announced MoS_2 growth process using the Nanofab nanoscale growth system. Single-layer MoS_2 is a direct band-gap semiconductor with wide-ranging applications in optoelectronics such as LEDs, photovoltaics, photodetectors and biosensors, while multilayer MoS_2 is an indirect band gap semiconductor for digital electronics. The process was developed on a Nanofab system equipped with precursor delivery modules capable of delivering a wide range of liquid, solid and metal organic precursors suitable for 2D materials growth. Offering growth on a range of substrates including sapphire and atomic layer deposition alumina, the system is capable of depositing other 2D transition metal dichalcogenides.
www.oxinst.com/mos2

Thermoelectric Modules

Phononic has released the pico-TEC series of high-performance, solid-state, thermoelectric modules for temperature control in optoelectronics and fiber optics.The pico-TECs are manufactured using advanced automated semiconductor fabrication technology, providing superior performance and reliability with ultrathin form factor flexibility. A device height of less than 0.7 mm with a typical ΔT max of 65 K and a Qc max of 25 W/cm2 or more. In addition to the ultrathin and ultrasmall footprint, the pico-TECs offer accurate temperature control, reduced power consumption and application-specific design options.
www.phononic.com

Optical Engines, Transceiver Solutions

Ranovus Inc. has released a highly scalable Optical Engine and 200-Gbps CFP2 optical transceiver solution for the data center interconnect market. A multiwavelength subsystem based on a single quantum dot laser source is capable of generating multiple wavelengths simultaneously. Ring resonator-based SiP modulators provide an efficient wavelength to modulate a wavelength-division multiplexing optical signal without multiplexing or demultiplexing architectures. The company's optical engines and modules offer a disruptive value proposition in attaining the lowest-cost connectivity solutions compared to Coherent-based and other Direct Detect solutions.
mike@louvanpr.com

Micro-Intradyne Coherent Receivers

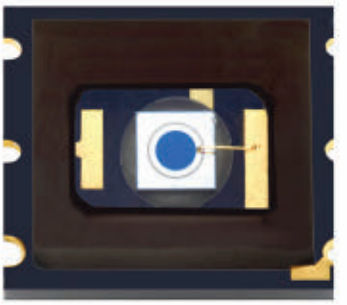
NeoPhotonics Corp. has released a sampling of HB Micro-ICRs, or Class-40 High-Bandwidth Micro-Intradyne Coherent Receivers, capable of supporting 64-Gbaud symbol rates, which is double the bandwidth of standard 32-Gbaud ICRs. The HB Micro-ICR supports higher order modulation up to 64 QAM, which when coupled with NeoPhotonics ultra-narrow linewidth, external-cavity Micro-ITLA laser, can achieve 600 Gbps over Datacenter Interconnect distances of 80 km. The HB Micro-ICR is designed to support the Optical Internetworking Forum Implementation Agreement for Micro-Intradyne Coherent Receivers. The HB Micro-ICR form factor is designed to fit into both CFP2-ACO and CFP-DCO pluggable modules.
sales@neophotonics.com

Underground Cable Terminal

OFS Fitel LLC has announced the SlimBox Underground Terminal used to connect distribution cables in the outside plant network to drop cables in FTTx networks. The SlimBox Underground Terminal enables quick and easy connections through drop cables with fusion splicing, splice-on connectors or mechanical connectors. It has one area for storage and splicing, as well as a separate area for the management and activation of subscribers. The mechanical sealing system supports round drop cables, making the terminal well-suited for both underground and aerial applications. The terminal can be configured with fusion splices, and spliced and connectorized drops. It can also house two factory connectorized 1 × 8 splitters, a single factory connectorized 1 × 16 splitter, and unconnectorized splitters.
shsalyer@ofsoptics.com

Photodiodes

First Sensor AG offers the Series 9.5 Avalanche Photodiodes, featuring increased sensitivity in the near-IR wavelength range up to 950 nm. Due to its fast rise time and very low dark current, the photodiodes are ideal for applications with low light intensities and high modulation frequencies



such as laser rangefinding and laser scanning. The slow increase of the amplification with the applied reverse bias voltage of the Series 9.5 allows for easy and precise adjustments of high gain factors. They provide a quantum efficiency of >80 percent in the 730- to 930-nm range and have the option of equipping different band-pass filters. The very flat leadless ceramic-carrier surface-mount package is suitable for reflow soldering in industrial printed circuit board assembly. Other housing options are available upon request.
technical.press@first-sensor.com

Spectrometer

Avantes BV has released the AvaSpec-HERO spectrometer based on a high-sensitivity compact optical bench. The device features USB3 and Ethernet with a high aperture, a cooled back-thinned CCD detector and low noise. The instrument is equipped with thermoelectric cooling, enabling long integration times in low-light applications. A selection of gratings and replaceable slits offer configuration for a wide range of applications in the 200- to 1160-nm range. Applications include fluorescence, Raman and absorption, among others.
info@avantes.com

Image Sensors

ON Semiconductor offers the P3 versions of the Python 1300 and 5000 image sensors, with half the frame rate and data ports of the original models. The Python 1300 achieves 105 fps with 2 LVDS ports, while the Python 5000 achieves 100 fps with 4 data ports. The P3 models can be adapted to affordable camera models with high image quality at a 4.8-µm pixel size, high sensitivity, dynamic range and low noise, as well as CMOS technology. Customers with barcode and inspection tasks in the food industry, as well as traffic applications, can benefit from these sensors.
info@framos.com

LED Driver

GlacialPower has announced the GP-HS35P-48CA LED driver with a rated power output of up to 33.6 W for LED lights from 33 to 48 V. The driver offers energy-saving features and a smooth output waveform with low distortion. It closely follows European Union and other directives for safety and energy efficiency. The nominal input voltage range is 100 to 277 VAC with a maximum input range of 90 to 305 VAC. With a compact, durable design that avoids common maintenance issues, the IP67-rated LED driver is ideal for interior and exterior applications.
sales@GlacialTech.com

Happenings

NOVEMBER

14th European Short Course on Time-Resolved Fluorescence Spectroscopy (Nov. 7-10) Berlin. Held by PicoQuant GmbH and the Center of Fluorescent Spectroscopy. Contact PicoQuant, +49 30-6392-6929, info@picoquant.com; www.picoquant.com.

● **VISION (Nov. 8-10)** Stuttgart, Germany. International trade fair for machine vision. Contact Messe Stuttgart, +49 711-18560-0, info@messe-stuttgart.de; www.messe-stuttgart.de/en/vision.

● **Neuroscience (Nov. 12-16)** San Diego. Presented by the Society for Neuroscience. Contact +1 202-962-4000, program@sfn.org; www.sfn.org/annual-meeting/neuroscience-2016.

● **OSA Light, Energy and Environment Congress (Nov. 14-17)**. Leipzig, Germany. Contact +1 202-416-1907, custserv@osa.org; www.osa.org/en-us/meetings/osa_meetings.

● **OSA Fourier Transform Spectroscopy Conference (Nov. 14-17)** Leipzig, Germany. Colocated with OSA Light, Energy and Environment Congress. Contact +1 202-416-1907, custserv@osa.org; www.osa.org/en-us/meetings/osa_meetings.

● **FABTECH (Nov. 16-18)** Las Vegas. Contact +1 888-394-4362, information@fabtechexpo.com; www.fabtechexpo.com.

Aggregation Induced Emission Conference (Nov. 18-20) Guangzhou, China. A Faraday Discussion of the Royal Society of Chemistry. Contact RSC, +44 0-1223-43-2254/2380, adam.kirrander@ed.ac.uk; www.rsc.org/events/detail/19001.

DECEMBER

● **Cell Biology 2016, ASCB Annual Meeting (Dec. 3-7)** San Francisco. Contact The American Society for Cell Biology, +1 301-347-9300, ascbinfo@ascb.org; www.ascb.org/2016meeting.

NANOP 2016 (Dec. 7-9) Paris. Nanophotonics and Micro/Nano Optics International Conference. Contact +33 6-16-68-24-85, nanop2016@premc.org; www.premc.org/nanop2016/.

MediSens 2016 (Dec. 13-14) London. Presented by Sense Media Events. Contact +44 0-208-133-5116, enquiries@medisens-conference.com; www. medisens-conference.com/.

SEMICON Japan (Dec. 14-16) Tokyo. SEMI Japan Customer Service, +81 3-3222-5988, jcustomer@semi.org; www.semiconjapan.org.

JANUARY

A3 Business Forum (Jan. 18-20) Lake Buena Vista, Fla. Contact AIA Advancing Vision & Imaging, +1 734-994-6088, info@a3automate.org; www. a3automate.org/events/a3-business-forum/.

● **SPIE Photonics West (Jan. 28-Feb. 2)** San Francisco. Contact +1 360-676-3290, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/photonics-west.

● **SPIE BiOS (Jan. 28-Feb. 2)** San Francisco. Colocated with SPIE Photonics West. Contact +1 360-676-3290, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/photonics-west/bios-expo.

FEBRUARY

● **Advanced Manufacturing Expo (Feb. 7-9)** Anaheim, Calif. +1 (310) 445-4235, UBMCanonConferences@ubm.com; www.anaheim.ubmcanon.com.

MedTechWorld MD&M West (Feb. 9-11) Anaheim, Calif. Contact UBM Canon, +1 310-445-4235, ubmcanonconferences@ubm.com; www.mdmwest.com.

● **Laser Additive Manufacturing Workshop (Feb. 21-22)** Houston. Contact Laser Institute of America, +1 800-345-2737 (from within the U.S.), +1 407-380-1553 (international), lam@lia.org; www.lia.org/conferences/lam.

SPIE Advanced Lithography (Feb. 21-25) San Jose, Calif. Contact SPIE, +1 (360) 676-3290, customerservice@spie.org; http://spie.org/x10942.xml.

Photoptics Fourth International Conference on Photonics, Optics and Laser Technology (Feb. 27-29) Rome. Contact Photoptics Secretariat, +351-265-520-185, photoptics.secretariat@insticc.org; www.photoptics.org.

MARCH

PIC International Conference (March 1-2) Brussels. The Photonics Integrated Circuits Conference is colocated with the Sixth CS International Conference focusing on the compound semiconductor industry. Contact Angel Business Communications, +44 0-2476-718-970, info@picinternational.net; www.picinternational.net.

● **AERODEF Manufacturing (March 6-9)** Fort Worth, Texas. Contact SME +1 800-733-4763 (U.S. and Canada), +1 313-425-3000 (outside U.S. and Canada), service@sme.org; www.aerodefevent.com.

PAPERS

OSA Biophotonics Congress: Optics in the Life Sciences (April 2-5) San Diego
Deadline: Abstracts, Nov. 29
The Congress is a group of meetings to report on progress in the development and application of instrumentation, bringing together industry leaders whose work is making significant advances in biological and medical research utilizing optical technologies. Papers are invited for the following meetings: Bio-Optics: Design and Application; Novel Techniques in Microscopy; Optical Molecular Probes, Imaging and Drug Delivery; Optical Trapping Applications; and, Optics and the Brain. Contact: OSA Technical Papers staff ,+1 (202) 416-6191, cstech@osa.org; www.osa.org/en-us/meetings/osa_meetings

SID Display Week (May 21-26) Los Angeles
Deadline: Abstracts, Dec. 1
Society for Information Display's Display Week 2017 comprises augmented and virtual reality, digital-signage display solutions, display materials and processes, and wearable displays. Submissions are solicited on display technologies for AR and VR systems; 3D sensing and imaging technologies; spatial tracking, localization, mapping and navigation techniques; end-to-end system integration; LED implementations leveraging flip-chip and chip-on-board solutions; automated and programmed color uniformity and calibration; down-conversion materials including quantum dots; OLED materials processing; nanofabrication; wearable applications; among others. Contact the Society for Information Display, +1 203-502-8283, jbuckley@pcm411.com; www.displayweek.org.

SPIE Optics + Photonics (Aug. 6-10) San Diego
Deadline: Abstracts, Jan. 23
This meeting will present the latest research in optical engineering and applications, nanotechnology, sustainable energy, and organic photonics. Abstracts will be accepted for four conferences: NanoScience + Engineering, with topics including metamaterials, graphene and spintronics; Solar Energy + Technology with topics including photovoltaics, thin-film solar technology and solar fuels; Organic Photonics + Electronics including OLEDs, OFETS, OPVs and perovskites; and, Optical Engineering + Applications, which will include the topics optical design and engineering, astronomical optics and instrumentation, and remote sensing. Contact: SPIE, +1 (360) 676-3290, customerservice@spie.org; http://spie.org/

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An invisibility cloak for the non-magical world?

Greek mythology is filled with references to an "invisibility cap" worn on occasion by Hades, Hermes and Athena that gave the wearer the power to become invisible. And today, legions of moviegoers are familiar with the title character of the Harry Potter series donning an "invisibility cloak" for all sorts of mischief.

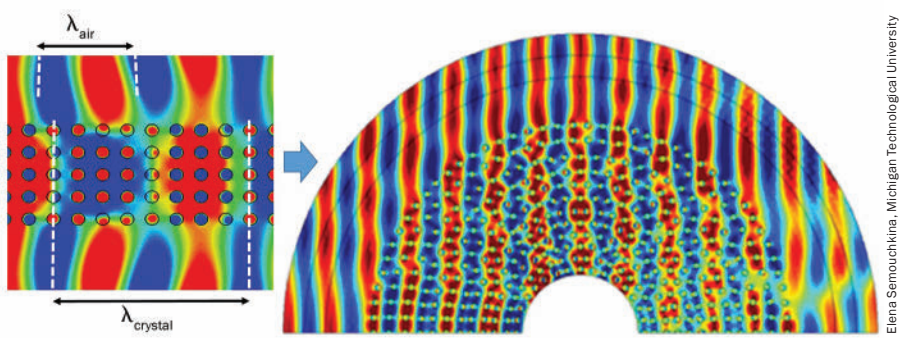
Yet despite being the stuff of fiction, researchers have been intrigued with developing a real-world version of an invisibility cloak that would have all sorts of viable uses, from allowing pilots landing a plane to turn the cockpit floors transparent or surgeons who could use this form of optical camouflage to see through their hands and instruments during surgery.

A research team from Michigan Technological University (MTU) is one step closer to "building" a cloak of invisibility with the help of photonic crystals.

Initially, to create such a cloak, researchers turned to metamaterials — synthetic composite materials that exhibit properties not usually found in natural materials, especially a negative refractive index. However, the resonant nature of metamaterials made the invisibility phenomena difficult since they require homogenization and experience inter-resonator coupling.

Dielectric photonic crystals, with inherent insulating properties, can be made practically lossless up to optical frequencies. They promise wider bandwidth, are free from homogenization and coupling problems, and allow for spatial dispersion of the cloak medium, which is required for accurate wave manipulation. In short, the waves move faster in the dielectric photonic crystal than in air, and the waves pass through the cloaked object, creating the illusion of invisibility.

Elena Semouchkina, MTU associate professor of electrical and computer engineering and adjunct professor at Pennsylvania State University, and her team discovered that by varying the size of the dielectric atoms in crystals and their permittivity — the measure of how an electric field affects and is affected by a dielectric medium — superluminal phase velocities of waves can be achieved. Simply stated, the waves will move faster than the speed of light.



Elena Semouchkina, Michigan Technological University

A light wave moves faster in a photonic crystal than in air, and passes through the cloaked object.

"By adjusting the lattice constants in such crystals properly, it is possible to control their refractive indices in a wide range. Then, building the cloak medium from fragments of crystals with various lattice constants can be used for obtaining spatial index dispersion requested by the transformation optics for cloaks," said Semouchkina.

In her work, she has used metamaterials composed of dielectric materials. Later, she took another approach to cloaking objects using multilayer coatings formed from ordinary dielectrics. Semouchkina even proposed a cloak composed of specially designed dielectric lenses. She has found that "incorporation of dielectric photonic crystals can make devices with superior functionalities a reality at frequencies ranging from microwaves to optics."

Semouchkina's next goal is to work out an approach for reliable anisotropy control — the variable behavior of propagating waves in different directions — in engineered photonic crystal media. Her team also plans to extend the approaches to a larger class of devices using transformation optics.

While the idea behind invisibility cloaks remains a magical entity, science suggests it can be done by simply controlling and manipulating the flow of light.

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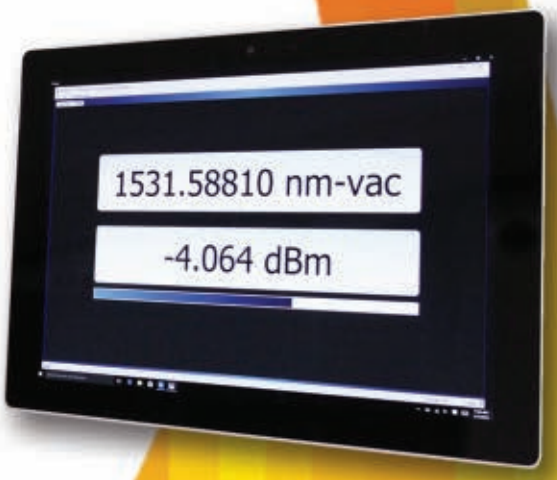

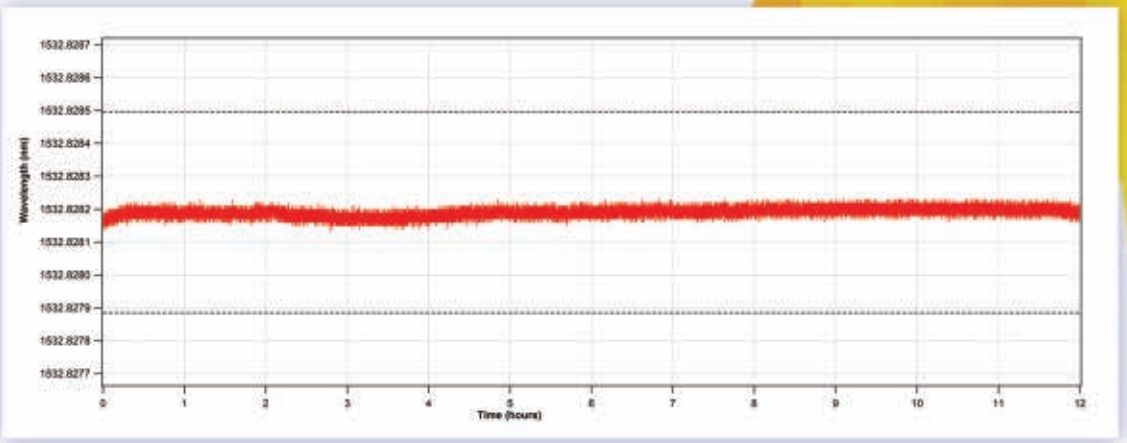

Long-term wavelength measurement data of a DFB laser locked to an absorption line of acetylene. The specified accuracy is given by the dashed lines.

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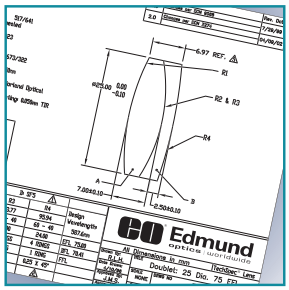

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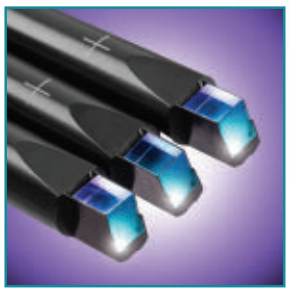

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