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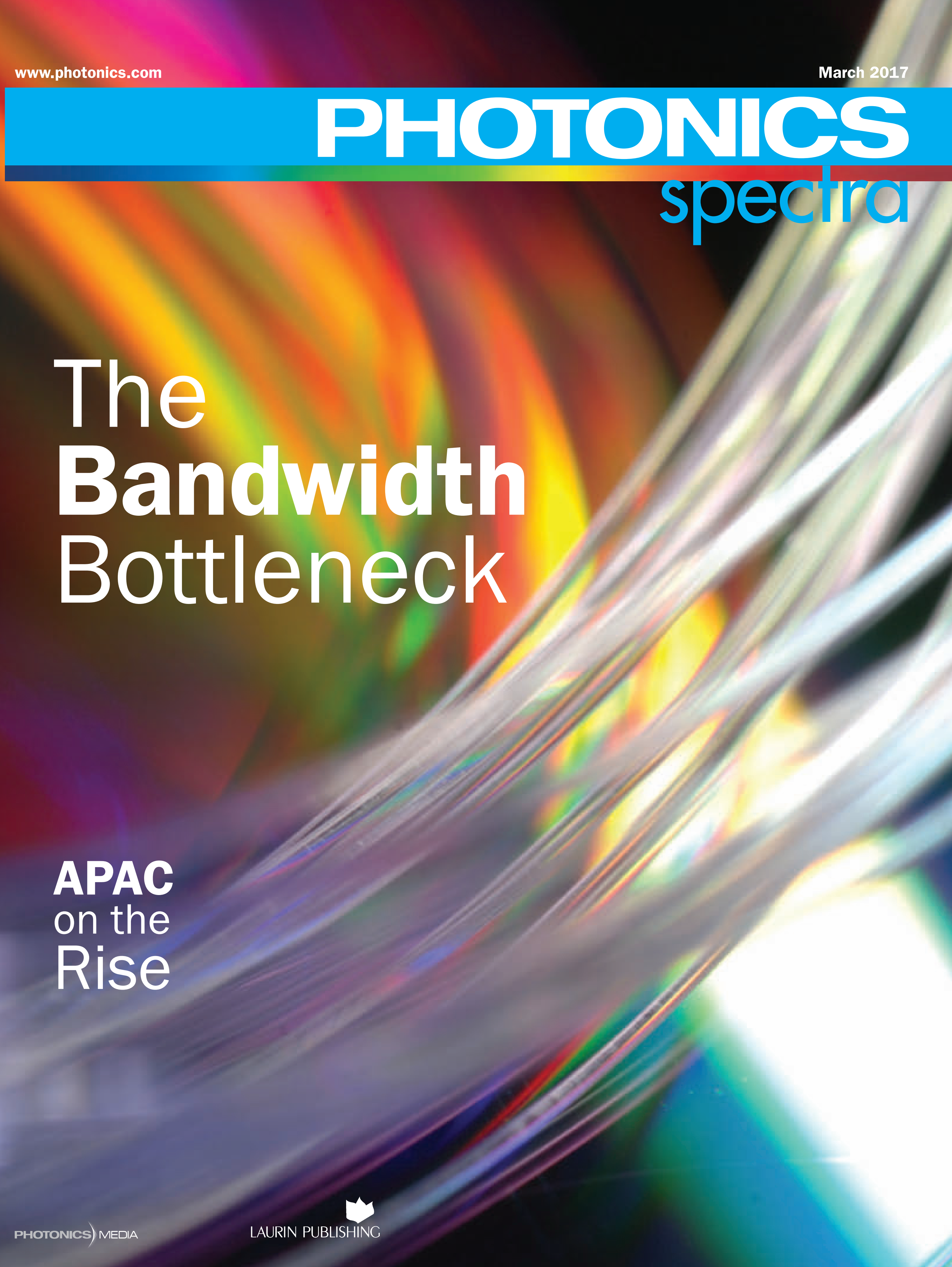

The **Bandwidth** Bottleneck

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Content

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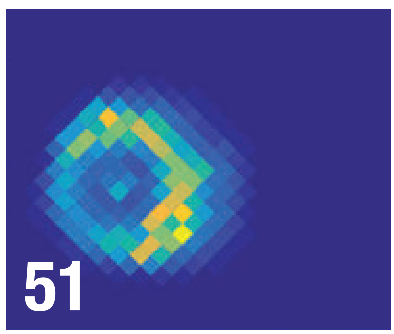
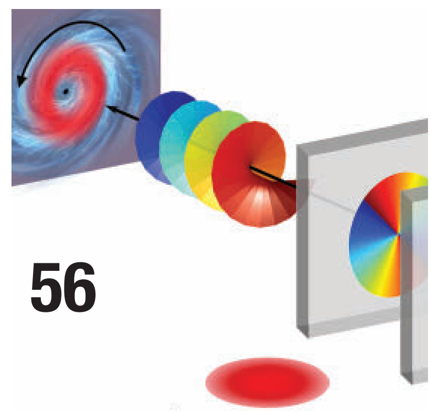
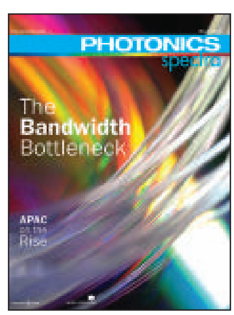
Features







THE COVER
Innovations in optical fiber. Courtesy of Corning. Cover design by Senior Art Director Lisa N. Comstock.

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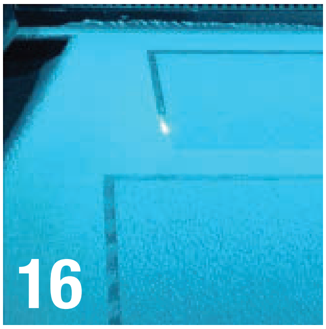
PHOTONICS: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing.



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editorial COMMENT

Smart Cameras, Smart Sensors, Smart Cities

Some have hailed the smart city trend as the most transformative thing to happen to the metropolis since urban renewal a half century ago. What started as a utopian dream of the future is inching toward reality in many cities including Singapore, Barcelona and London, all of which have made strides in the creative use of technology for smart traffic management, power metering and real-time environmental monitoring.

Smart cities rely on intricate networks of sensors, cameras and wireless devices that report data in real time, allowing officials to respond to circumstances faster, be they spikes in energy use, transportation bottlenecks or environmental threats.

For this, the March issue, we highlight exciting advances in sensors and cameras that may one day help bring the smart city concept closer to achievement.

Sharp Laboratories' Tim Smeeton and his colleagues have developed a compact laser that is more effective than gas discharge lamps and less expensive than conventional solid-state lasers. It emits in the UVC spectral range, particularly important for chemical, biological and gas sensing, given the strong and specific interaction between these wavelengths and potentially harmful analytes found in air and water. For details, read "Compact UVC Laser Shows Promise for Environmental Sensing," beginning on page 40.

The prospect of developing a smarter camera, one capable of intelligently extracting pixel light intensity information needed for imaging extreme contrast scenarios, has driven Nabeel Riza to create a whole new camera technology. In "CAOS Smart Camera Captures Targets in Extreme Contrast Scenarios," beginning on page 51, Riza shares how this sensor, working in unison with CMOS sensors, can smartly extract scene contrast pixel light intensity information using time-frequency coding of selected agile pixels.

Also in this issue:

- "For Optical Fiber, More Bandwidth Looms," by Contributing Editor Hank Hogan, beginning on page 36.
- "New 4G Optics Technology Extends Limits to the Extremes," beginning on page 46, by Nelson Tabiryan and David Roberts of Beam Engineering for Advanced Measurements and researchers from the U.S. Army Natick Soldier RD&E Center.
- "Optical Metrology Techniques Harness Structured Light Beams," by Carmelo Rosales-Guzmán, University of the Witwatersand; Aniceto Belmonte, Polytechnic University of Catalonia; and Juan P. Torres, ICFO and Polytechnic University of Catalonia, on page 56.
- "Optical System Optimization: Analyzing the Effects of Stray Light," by Richard Pfisterer of Photon Engineering LLC, beginning on page 60.
- "Asia-Pacific Eyes Photonics Market Growth," beginning on page 66, by Senior Editor Justine Murphy, is included in this month's APAC special section on page 65.

We hope you enjoy the issue!

Michael D. Wheeler

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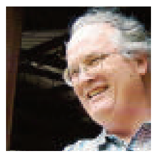
CONTRIBUTORS

Aniceto Belmonte
Aniceto Belmonte is a researcher in electromagnetic optics and photonics, working on free-space optical communications, laser remote sensing and coherent imaging. Page 56.

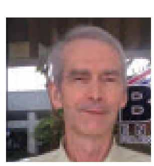


Hank Hogan
Contributing Editor Hank Hogan holds a Bachelor of Science degree in physics from the University of Texas at Austin. Hogan worked in the semiconductor industry and now writes about science and technology. Page 36.

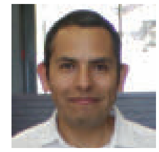
Brian R. Kimball
Brian Kimball is a research physicist at the U.S. Army Natick Soldier RD&E Center, with interests in the interaction of light with nanophotonic structures. Page 46.

Justine Murphy
Justine Murphy is Photonics Media senior editor. She is an award-winning journalist with more than 15 years of experience in the field. Page 66.

Nabeel A. Riza
Nabeel A. Riza has a Ph.D. in electrical engineering from Caltech. He is Chair Professor of Electrical and Electronic Engineering at University College Cork in Ireland. Page 51.



David Roberts
David Roberts is chief systems engineer at Beam Co. since 2013. His expertise includes IRCM, lidar, laser targeting, designation, rangefinding, and SWIR and MWIR active imaging systems. Page 46.



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Carmelo Rosales-Guzmán, Ph.D., is a postdoctoral researcher in the structured light lab at the University of the Witwatersrand. Page 56.

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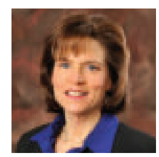

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Diane Steeves is team leader of the Nanomaterials Science Team at the U.S. Army Natick Soldier RD&E Center. Her research interests include nanomaterials for sensor and eye protection applications. Page 46.

Nelson Tabiryan
Nelson Tabiryan, a pioneer in liquid crystal photonics developments and an OSA Fellow, is the CEO and president of Beam Co., founded in 1996. Page 46.

Juan P. Torres
Juan P. Torres is at ICFO-The Institute of Photonic Sciences and the Polytechnic University of Catalonia. His research focuses on the areas of quantum and nonlinear optics, and fundamentals and applications of structured light. Page 56.

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What's Online:

Introduction to CITE: Commercialization of Innovative Technology Through Entrepreneurship

Thurs., April 13, at 1 pm EDT

Are you the developer of innovative technology that you are ready to bring to market? This webinar — presented by David Krohn and based on his popular lecture series — is for anyone seeking potential opportunities for marketing and selling a new technology, whether it is a product, a service or a groundbreaking idea. In this webinar you will learn how to focus R&D with an eye toward commercialization; how to source funding; and how to develop and manage the resources required for successful commercialization. Please note: there is a registration fee for this webinar. For more information and to register, visit **www.photonics.com/webinars**.

Free Webinars — Register Today!

Integrating Camera Technology Into a Successful Machine Vision Solution

Fri., March 10, at 1 p.m. EST

Join vision technology veteran Rex Lee, Ph.D., for tips and insights on how to build a machine vision system that meets your business needs. In this webinar he will discuss the components of a comprehensive machine vision system, including cameras, lighting, lenses, sensors and detectors. He will also explain how to design a system that has the components needed for optimal performance. To register, visit **www.photonics.com/W115**.

Transition Mode Reactive Sputtering Using PEM

Wed., March 15, at 1 p.m. EDT

You will leave this webinar with a thorough understanding of how Denton Vacuum provides a fully integrated Plasma Emission Monitoring (PEM) system with its thin-film deposition system. Presenter George Papasouliotis, Ph.D., is the Chief Technology Officer of Denton Vacuum and holds more than 50 U.S. patents in thin-film deposition and plasma processing. To register, visit **www.photonics.com/W119**.

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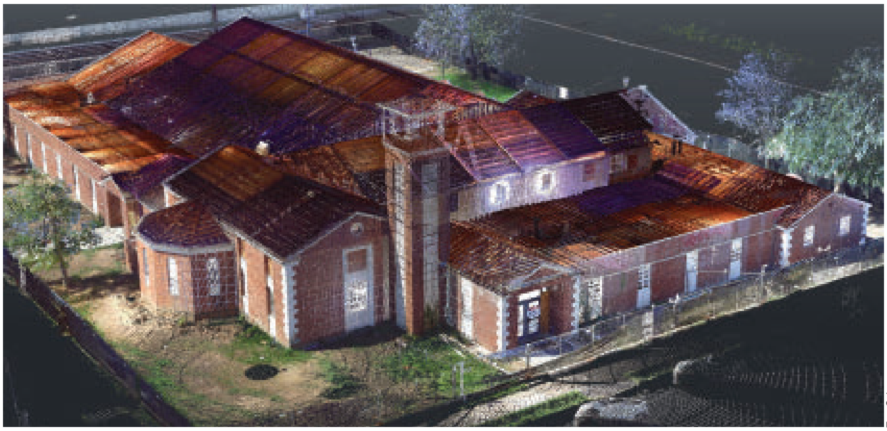
Adaptive reuse project transforms with lasers



Eco3d

3D laser-scanned image of Meetinghouse at 3080.

Eco3d

3D image cut to see inside of building.

Structured Real Estate

The outside of Meetinghouse at 3080. It was once a church and will be converted to commercial office and retail space.

A church in Scottsdale, Ariz., is being renovated and turned into commercial office and retail space with help from a 3D laser scanner.

The church, located in the heart of Old Town, has high ceilings, exposed wood beams, stained glass, and many nooks and crannies that could be missed with the human eye. Eco3d — a portfolio company for Ecoark Holdings Inc. — was hired by Structured Real Estate to take the measurements.

Using a FARO Focus X330 laser scanner with a measurement speed of up to 976,000 points per second and a ranging error of less than 2 mm, the scan significantly cut the man-hours it would have taken had the measurements been done manually. Ken Smerz, president and CEO of Eco3d, told Photonics Media the laser scanner was chosen for this project because of its short-range accuracy and speed.

“The scan only took half a day, even with setting the scanner up in multiple positions to capture the whole site,” said Smerz. “The scanner provides a non-contact, comprehensive, highly accurate measurement.”

Eco3d scanned the inside and outside of the building now known as Meetinghouse at 3080, digitally documenting the structure with an 83-station scan. With a resolution of three million points per scan, the process helped Structured Real Estate see parts of the building that were difficult to measure manually, eliminating additional time and cost for the project.

Conor Keilty, development manager at Structured Real Estate, said it was imperative to have a complete understanding and accurate representation of the building’s existing conditions to go forward with the adaptive reuse project.

“The laser-scanning technology allows us to gain that understanding in record time by replacing days of field measuring and dozens of visits to the site with the convenience of flying through the point cloud model at our office,” said Keilty. “The laser scan allowed us to uncover details and conditions that would have gone unnoticed until construction, enabling coordination and resolution of conflicts before they ever occurred.”

Eco3d's portion of the project may be finished as their laser-scanning resources were utilized in the entry stage of the process, but their impact will be seen for a long time.

"This is absolutely the future. Currently in the industry, we are at the very early stages of adoption," said Smerz.

"Laser-scanning measurement technology is being used in less than six percent of potential applications, therefore the democratization of this technology in the marketplace over the next few years will be sensational to watch."

Autum C. Pylant
autum.pylant@photonics.com

$1.27B — value of the process spectroscopy market by 2022 as reported by Radiant Insights

NYS bolsters photonics start-ups

New York State is establishing a $10 million, multiyear Photonics Venture Challenge in Rochester. The business competition aims to support start-up companies that commercialize these technologies through a business accelerator program; a top award of $1 million will be given to the most promising start-up.

There are currently no accelerator programs in the world with a photonics focus, and the Rochester region is uniquely poised to build a nationally, or globally, recognized program.

"Rochester has quickly become a leader in innovative manufacturing and now is the time to build on that momentum to ensure sustained economic growth for the entire region," said Gov. Andrew Cuomo. "With more than 120 companies anchored by some of the nation's top research institutions, the Finger Lakes Region is now one of the world's leading centers for the photonics industry. What better place than Rochester to establish this challenge and help focus entrepreneurial resources on the photonics industry in order to create a collaborative environment for start-ups to grow and thrive."

The basic elements of the Photonics Venture Challenge are:

- Ten to 15 start-ups will be selected for the program through an annual competitive application process, each receiving an initial investment ranging between $100,000 and $125,000 in exchange for equity. Selections for the first round will be made by fall 2017.
- Participants will go through a four- to six-month structured accelerator program where they will build products, access customers and refine their business models, and gain initial market traction. The program will provide work space in the Rochester region and access to regional assets, resources, labs and so on, and connections to mentors and industry partners.

Each year's competition will conclude with a large-scale "Demo Day," where all teams present in a public forum to an audience that will include venture capitalists, optics/photonics companies, and other industry players.

The program's three most promising start-ups will compete for additional "best in class" funding investments: $1 million for first prize and $500,000 for second and third prizes, announced at the Demo Day.

The award winners must live and operate in the Rochester region for at least one year following their award, ideally within or near the AIM Photonics Testing Assembly and Packaging (TAP) facility at Eastman Business Park or within or near the Sibley Square business accelerator headquarters.

The Photonics Venture Challenge builds on Gov. Cuomo's announcement in December 2016 that the state-of-the-art AIM Photonics Manufacturing Facility will be located in Eastman Business Park at ON Semiconductor. The facility will be used to test, assemble and package chips that use photons in place of electrons for increased performance of semiconductor circuits.

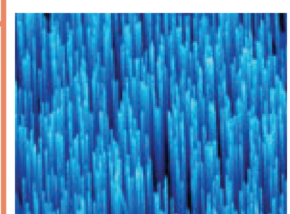
This month in history

What were you working on five, 10, 20 or even 50 years ago? *Photonics Spectra* editors perused past March issues and unearthed the following:

2012

An ultrafast imaging system developed at MIT differs from other high-speed imaging systems in that it can capture light scattering below the surface of solid objects, such as the tomato depicted here. Courtesy of Di Wu and Andreas Velten, MIT Media Lab.

2007



When researchers removed a sapphire substrate from the chemical vapor deposition furnace, they noticed arrays of P-type ZnO nanowires about 2 µm long and 50 to 60 nm in diameter on its surface, seen here in a low-magnification scanning electron micrograph.

1997

It took 33 hours and 11 minutes spread among five spacewalks, but NASA astronauts were able to complete electronic installations for a new solar drive array, fine guidance sensor, engineering/science tape recorder and optical control enhancement kit aboard the Hubble Space Telescope.

1967

A British men's tailoring chain, Montague Burton, discovered a new application for lasers in the cutting of cloth for suiting. The 40-W gas laser, moving on a pattern determined by a computer working from a stereoscopic photograph of the customer, can cut cloth at an inch per second, and heat-seal the edges.

DARPA's TUNA program enters final phase of development

The U.S. Department of Defense's Defense Advanced Research Projects Agency (DARPA) has completed the initial phase of its Tactical Undersea Network Architecture (TUNA) program, intended to develop concepts and technology to restore connectivity for U.S. forces when traditional tactical networks are knocked offline or otherwise unavailable.

TUNA seeks to develop and demonstrate novel, optical-fiber-based technology options and designs to temporarily restore radio frequency (RF) tactical data networks in a contested environment via an undersea optical fiber backbone. The concept involves deploying RF network node buoys — dropped from aircraft or ships — that would be connected via thin underwater fiber-optic cables. The small-diameter fiber-optic cables will last 30 days in the rough ocean environment — long enough to provide essential connectivity until primary methods of communications are restored.

"Phase 1 of the program included successful modeling, simulation and at-sea tests of unique fiber-cable and buoy-component technologies needed to make such an undersea architecture work," said John Kamp, program manager of DARPA's Strategic Technology Office. "Teams were able to design strong, hair-thin, buoyant fiber-optic cables able to withstand the pressure, saltwater and currents of the ocean as well as develop novel power generation concepts."

During the first phase of the program, the University of Washington's Applied Physics Lab developed a unique concept called the Wave Energy Buoy that Self-deploys (WEBS), which generates electricity from wave movement for supplying power to floating buoy nodes on the open sea. The WEBS system is designed to fit into a cylinder that could be deployed from a ship or aircraft.

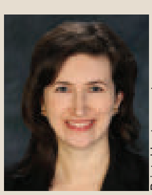
The project enters its second and final phase for the design, implementation, testing and evaluation of the system in laboratory and at-sea demonstrations.

DARPA is responsible for the development of emerging technologies for use by the U.S. military.

• Elbit Systems Ltd. received $35M in contracts to supply laser designator systems in the Asia-Pacific Region.•

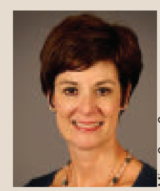
PEOPLE IN THE NEWS

Technical glass developer Berliner Glas Group has appointed **Acis Demandt** as its chief operations officer. Demandt will be responsible for the supply chain management and production in the operations division of Berliner Glas and all of its facilities. He brings experience in both national and international facilities, with fluency in Chinese, Japanese and English. As a member of the executive board, Demandt will join CEO **Andreas Nitze**, Chief Financial Officer **David Schwem**, and Chief Technology Officer **Volker Schmidt** in their commercial responsibility to the company. The Berliner Glas Group develops, produces and integrates optics, mechanics and electronics into customer solutions for the semiconductor, laser, space, medical, metrology and display industries.


Bristol Instruments

Optical interferometer-based instrumentation developer Bristol Instruments Inc. has appointed **Kristina Schanz** as its marketing communications manager. Schanz brings more than 12 years of marketing experience in a variety of industries. Prior to joining Bristol Instruments, she was the marketing associate and program manager of the American Red Cross Blood Services. She also held prior marketing roles with The Gunlocke Co. LLC and the fiber optics division of Schott North America Inc. Schanz holds a bachelor's degree in electronic media, arts and communication from Rensselaer Polytechnic Institute.

Stephen Petranek has joined the board of directors of imaging technology developer NexOptic Technology Corp. A technology futurist and award-winning author, Petranek is co-executive producer of the National Geographic mini-series "MARS," which is based on and inspired by his book "How We'll Live on Mars," published by Simon & Schuster and the TED Conferences. Petranek's book was partly a result of extensive conversations and interviews with **Elon Musk**, CEO of Space-X, and senior management and leading scientists at NASA. Petranek is the former editor-in-chief of the world's largest scientific magazine, *Discover*, and was the senior editor for sciences at *Life* magazine. Earlier in his career, Petranek was the editor of *The Washington Post*'s magazine and editor-in-chief of the *Miami Herald*'s Sunday magazine. Mr. Petranek is also a recipient of the prestigious John Hancock Award for Business and Financial Writing. NexOptic is a developer of optics and lenses for cameras, telescopes, mobile devices, binoculars, computer imaging, medical imaging, gaming and more.


MicroCare Corp.

Precision cleaning product manufacturer MicroCare Corp. has appointed **Guylaine Guerette** as its senior marketing manager. Guerette holds a degree from Endicott College and spent 18 years of her career in marketing at Brady Corp., where she managed multichannel programs and led campaign deployments. At MicroCare, Guerette will be responsible for synchronizing marketing programs across all four business units. MicroCare is a developer of precision cleaning, coating and lubrication products for the electronics, metal finishing, transportation, photonics, medical devices and aerospace industries.

Electrical and mechanical solutions provider Fairlead Integrated LLC has appointed **Luke Ritter** as the CEO of its defense technology company Fraser Optics. Ritter is a U.S. Naval Academy graduate and holds an MBA from Old Dominion University. Prior to joining Fraser, he was executive vice president at Ridge Global, reporting directly to the Honor-

RhySearch to receive ion beam sputtering system with optical monitor system

RhySearch, the Center for Research and Innovation in the Alpine Rhine Valley, will receive its first SPECTOR Ion Beam Sputtering system coupled with the Quest Optical Monitor System from Veeco Instruments Inc.

RhySearch, based in Switzerland, will use Veeco's technology to deposit optical thin films for advanced laser mirrors and anti-reflective coating applications.

"We see tremendous opportunity to advance next-generation optical applications from research to high-volume production, and we need an industry-proven platform to accomplish that," said Richard Quaderer, managing director of RhySearch. "Veeco's SPECTOR system will enable us to achieve optical coatings of the highest quality, and the Quest OMS ensures we are maximizing our investment with precise control of the thin-film deposition process."

The SPECTOR platform generates high-quality optical thin films with improved levels of productivity and throughput. Unlike evaporative coatings, ion beam sputtered thin films are deposited at high energies, giving thickness control and low defect densities for laser coating applications. The Quest system enhances the SPECTOR platform capability by coupling cutting-edge broadband monitoring control with the stability of ion beam deposited films.

able Tom Ridge, the first U.S. Secretary of Homeland Security and former Governor of Pennsylvania. Ritter's professional experience includes senior executive assignments at multiple defense contractors serving the national defense and homeland security markets. Ritter will split his time between Fraser's executive offices in Maryland and the manufacturing plant in Pennsylvania. Fraser Optics is a defense technology company that designs and produces stabilized optical technology products for the defense, homeland security, law enforcement and commercial markets.

Optical measurement technology developer Photon Control Inc. has appointed **Neil McDonnell** as chair of the board of directors. McDonnell, who joined the board in November 2016, succeeds **Michael Goldstein**, who will remain as executive director and acting CEO. With these changes, Photon Control's board remains composed of five independent directors and one executive director. Photon Control designs, manufactures and distributes a wide range of optical sensors and instruments to measure temperature, pressure, position, and flow for users in the semiconductor, oil and gas, power, life sciences and manufacturing industries.

OPIE, OPIC advance photonics in Japan

Japan is set to host Optics and Photonics International Exhibition 2017 (OPIE 2017) — including the Optics and Photonics International Congress 2017 (OPIC 2017) — bringing together academia and industry to discuss light and light-based technologies as global solutions for sustainable development across the world.

The most influential exhibition in Japan, OPIE 2017 will be held in Yokohama, which is 30 minutes from Tokyo, April 19-21. More than 400 exhibitors from Japan and other countries around the world will attend. OPIE 2017 will consist of exhibitions including: Laser Expo, Lens Expo, IR & UV Expo, Positioning Expo, Medical & Imaging Expo, Space & Astronomical Optics Expo, and also a new expo, Machine Vision.

OPIC 2017 will be held in conjunction with OPIE 2017, and has 11 international specialized conferences including:

- **The 6th Advance Lasers and Photon Sources (ALPS '17)**, sponsored by The Laser Society of Japan.
- **The 3rd Biomedical Imaging and Sensing Conference/The 4th Optical Manipulation Conference (BISC/OMC '17)**, sponsored and organized by SPIE.
- **Conference on Laser Energy Science/Laser and Accelerator Neutron Sources and Applications 2017 (CLES/LANSA '17)**, sponsored by IFE Forum, Institute of Laser Engineering, Osaka University and The Graduate School for the Creation of New Photonics Industries.
- **International Conference on High Energy Density Science 2017 (HEDS 2017)**, sponsored by The Laser Society of Japan.
- **International Conference on Nano-photonics and Nano-optoelectronics (ICNN 2017)**, sponsored by the Institute for Nano Quantum Information Electronics, The University of Tokyo.
- **Information Photonics 2017 (IP '17)**, sponsored by The Optical Society of Japan.
- **Laser Display and Lighting Conference 2017 (LDC '17)**, sponsored by The Optical Society of Japan.
- **The 5th International Conference on Light-Emitting Devices and Their Industrial Application'17 (LEDIA '17)**, sponsored by Akasaki research Center (ARC), Nagoya University.
- **Light Driven Nuclear-Particle Physics and Cosmology (LNPC '17)**, sponsored by Hiroshima University.
- **Laser Solutions for Space and the Earth (LSSE 2017)**, sponsored by the executive committee of Laser Solutions for Space and the Earth.
- **International Conference on X-ray Optics and Applications 2017 (XOPT '17)**, sponsored by RIKEN SPring-8 Center, Research Center for Ultra-Precision Science & Technology Osaka Univ.

For more information, visit www.opie.jp/en/index.php and www.opicon.jp.

OPIE 2017

Federal Reserve Security places LaserMax order

Laser gun sight manufacturer LaserMax Inc. has received an order from the U.S. 4th District Federal Reserve Security Force for its Guide Rod lasers used in the security-force-issued Glock G17 and G19 pistols.

"The adoption of the Guide Rod lasers from a security force of this prestige is an incredible testament to the trust and confidence these guys put in our product," said Chris Gagliano, director of military products for LaserMax. "Getting to work with the tactical response team at the Federal Reserve is a great honor and we are thrilled to have them utilizing our Guide Rod laser systems on their duty sidearms."

The primary duty of uniformed division officers is to provide law enforcement and force protection services to Federal Reserve facilities. Other than administrative matters and violations of Federal Reserve Bank regulations, Federal Reserve Security Forces respond to police, fire, medical incidents and site security issues in and adjacent to their assigned facilities.

"We are so happy that the 4th District Federal Security Force has joined the growing list of federal and local law enforcement agencies that recognize the tactical advantage that laser aiming devices provide officers," said Chris Tinkle, chief sales officer of LaserMax. "I have enormous respect for the job these officers do, and providing the tools and training to increase their shooting proficiency is a wonderful achievement for LaserMax."

$1.81B — value of the ultra-hard material cutting machines market by 2024 according to a research report released by Transparency Market Research

LightPath acquires ISP Optics

Optical component and assembly manufacturer LightPath Technologies Inc. has acquired precision optics manufacturer ISP Optics Corp. for $12 million in cash with a balance of five-year subordinated notes issued to the sellers.

LightPath also announced the completion of a previously announced underwritten public offering of 8 million shares of its Class A common stock, including the full exercise by the underwriters of their option to purchase 1 million shares of Class A common stock to cover over-allotments, at a public offering price of $1.21 per share. Net proceeds amount to approximately $8.85 million.

"We are excited to have consummated the acquisition of ISP Optics Corp. as planned and welcome ISP employees to the expanding global LightPath team," said Jim Gaynor, president and CEO of LightPath. "This transformative acquisition was made possible through a fully subscribed underwritten public offering of common stock. The offering successfully attracted to the company numerous high-quality institutional investors, in addition to personal investments from members of our executive management team and board of directors. The combination of LightPath and ISP positions us for continued growth with greater scale and scope to offer a comprehensive platform of visible and infrared solutions."

LightPath designs, manufactures and distributes optical and IR components including molded glass aspheric lenses and assemblies, IR lenses and thermal imaging assemblies, fused fiber collimators, and gradient index GRADIUM lenses for the industrial, medical, telecommunications, testing and measurement industries.

Space Photonics receives patent for free space laser communications

Space-qualified optics developer Space Photonics Inc. has received its seventh patent in the technology sector that includes free space laser communications.

The new patent, titled “Simultaneous Multi-Channel Optical Communications System with Beam Pointing, Switching and Tracking Using Moving Focal Plane Devices,” and the company’s other patents, use specific inventions for very rapid and extremely accurate angular pointing and tracking of free space laser communications beams used for ultrahigh-capacity digital signals commonly used in ground-based internet networks. The technology will provide a much needed boost for emerging global networks using satellites, aircraft and high-altitude balloons.

“This patent is by far the most valuable we’ve received. It provides innovative but simple techniques for pointing and tracking laser communications beams sent and received from moving airborne and space-borne vehicles. It does this without using heavy gimbals or moving prisms and mirrors commonly used by others with techniques that are much less accurate for laser beam angular tracking and pointing. Using lasers also can replace certain standard radio frequency transceivers used on orbiting satellites,” said Chuck Chalfant, president and CEO. “The patent title can put you to sleep but is descriptive.”

Space Photonics is a developer of space-qualified fiber optics, optoelectronics, anti-tamper technologies and free space optics equipment for space applications and Earth-based deployments.

Luster LightTech named Chinese distributor of nLight fibers

Semiconductor, laser and fiber manufacturer nLight Corp. has appointed Luster LightTech Group as its distributor in China.

Luster LightTech will provide sales and support for nLight’s active and passive optical fiber products. nLight LIEKKI active optical fibers are fabricated using a direct nanoparticle deposition process, resulting in high performance and high reliability.

Luster LightTech has more than 20 years of experience in the sales and marketing of fiber optic products, as well as 10 years in China’s fiber laser industry.

• Rigaku Analytical Devices Inc.’s KT-100 Katana laser-induced breakdown spectroscopic handheld analyzer named one of the 100 most innovative products of 2016 by *R&D Magazine*.•

MKS' Ophir Business Unit named Utah Manufacturer of the Year

The Ophir Business Unit, part of the Light and Motion Division of MKS Instruments, has been named the 2016 Utah Manufacturer of the Year for "Outstanding Performance in Operational Excellence, Economic Achievement, Workplace Safety, Community Outreach and Fidelity to the Principles of Free Enterprise."

Gary Wagner, general manager of Ophir, said this is the second time the Ophir Business Unit has received the award.

"This is a tremendous accomplishment by our Logan, Utah, team," said Wagner. "We are humbled by the honor and pleased to be recognized for our dedication to customer service, continuous improvement and lean principles."

The Ophir Business Unit provides a complete line of instrumentation including power and energy meters, and beam profilers, and is celebrating 40 years of precision laser and LED measurement equipment manufacturing.

Ophir

From Ophir (left to right): Gary Wagner, general manager; David Maughan, production supervisor; Martin Turpin, production; Mike Jensen, senior director of operations; and Ryan Weeks, assistant customer service manager.

$1.1B — value of the global lidar market by 2023 according to a report by Global Market Insights

University of Pitt., Ansys receive NASA grant

Additive manufacturing (AM) researchers at the University of Pittsburgh's Swanson School of Engineering and simulation software company Ansys Inc. are among 13 university-led proposals to capture an Early Stage Innovations (ESI) grant from NASA's Space Technology Research Grants Program.

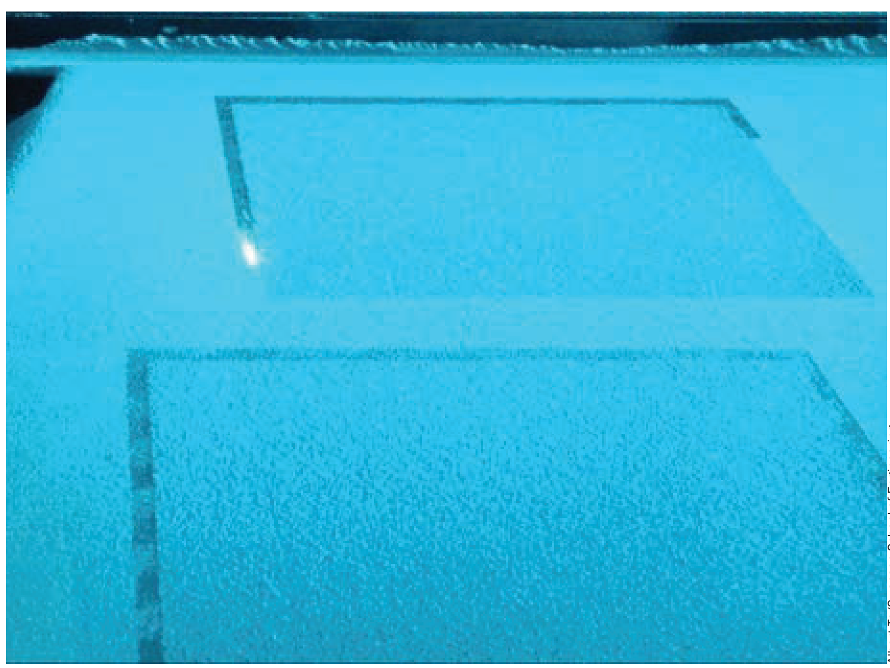
ESI grants promote innovative, early-stage technologies that address high priority needs of America's space program. The Pitt team's award is worth $500,000 over the course of three years.

"Additive manufacturing now allows us to produce complex metal components that are strong enough to replace machined parts in mechanical applications," said Albert To, associate professor of mechanical engineering and materials science and director of the Ansys Additive Manufacturing Research Laboratory. "However, because of the process parameters and materials used in AM, the microstructure within a part or between different parts can vary widely. Thanks to NASA, our research will focus on developing a new simulation tool to predict the microstructure evolution and stability of Inconel 718, a common nickel superalloy used in laser-based AM in industry."

The research team's proposal noted that NASA is keenly interested in improving the performance of structural components for high-temperature applications such as jet engine parts, where both creep and strength are critical and need to be anticipated.

"Currently, the only way to certify an AM part for space missions is to perform extensive microstructure and property characterization experiments on it, which is both time-consuming and expensive," said co-investigator David Conover, chief technologist for mechanical products at Ansys. "The outcome of this research will potentially enable simulation-based certification of both AM parts and substantially lower the expense of certification."

The goal of the Space Technology Research Grants program is to accelerate the development of space technologies in their earliest stages to enable future systems capabilities and missions for NASA, other government agencies and the commercial space sector. The program is funded by NASA's Space Technology Mission Directorate, which is responsible for developing the cross-cutting, pioneering new technologies and capabilities



Albert To/Swanson School of Engineering

A laser interacts with Inconel powder inside the EOS DMLS M290 at the Swanson School's ANSYS Additive Manufacturing Research Lab.

needed by the agency to achieve its current and future missions.

"NASA's Early Stage Innovations grants provide U.S. universities the opportunity to conduct research and technology development to advance NASA's scientific discovery and exploration goals," said Steve Jurczyk, associate administrator for NASA's Space Technology Mission Directorate. "Partnering with academia in advancing these critical areas of research ensures we are engaging the best and brightest minds in enabling the agency's future robotic and human space flight missions."

$10.9B — value of the mobile virtual reality market by 2021 according to market intelligence firm Tractica

PhotonicSweden

ADB Safegate Sweden wins photonics prize

Airport safety technology developer ADB Safegate Sweden AB has been awarded the optics and photonics prize presented annually by PhotonicSweden to the best Swedish company in the industry.

ADB Safegate, formed from the March 2016 merger of ADB Group and Safegate Group, whose operations date back to 1973, provides intelligent lighting and photonics-based systems to airports worldwide for safe and efficient navigation and handling of aircraft on the ground. System capabilities include the docking of the aircraft at the gates based on laser radar technology and robust LED-based positioning lights for runways.

Award criteria includes a combination of technological innovation, successful economic venture and profitability.

"ADB Safegate's innovative development of photonics solutions has contributed greatly to it becoming the world leader in products and solutions for the safe and efficient navigation in airports," said PhotonicSweden in a citation. "The company's products are distributed worldwide and have given ADB Safegate steady growth and good profitability. The company's products help to increase the safety of air traffic and its travelers as well as to reduce energy consumption at airports."

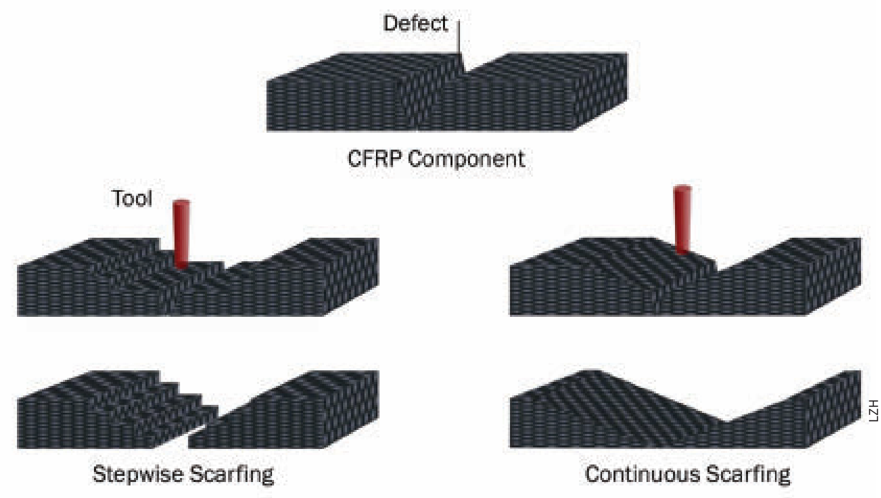
Vectronix, Optics 1 merge, receive Army contract

Electro-optical systems developer Vectronix Inc. has merged with its optical systems subsidiary Optics 1 Inc. to form Safran Optics 1 Inc. and has subsequently received a $304 million U.S. Army contract for a laser designation system.

The multiyear contract will provide the Laser Target Locator Module II, a high-tech, handheld laser target locator with a GPS receiver.

Vectronix is a developer of integrated handheld module and precision systems for observation, detection, location and targeting solutions. Optics 1 provides lens design, optical engineering and optical design services from prototype through production. Safran Optics is an electro-optical systems developer.

Laser Zentrum Hannover, Apodius laser repair fiber-reinforced plastics



Stepwise and continuous scarfing as a preparation for repair.

Laser Zentrum Hannover EV and Apodius GmbH are collaborating on a project to repair fiber-reinforced plastics by combining a measuring device for fiber layer orientation with a laser-based repair process.

The goal of the fiber orientation measuring unit is to repair defects in fiber-reinforced plastic workpieces, avoid the replacement of parts and save money.

"For the manufacturers, this means saving time and costs," said Dietmar Kracht, executive director of Laser Zentrum Hannover. "And the longer the lifetime of a component, the better the ecological balance and the resource efficiency is."

The project is funded by the German Federal Ministry for Economic Affairs and Energy within the framework of the Central Innovation Program for a duration of two years.

• The FMPA Fast Multichannel Photonics Alignment Engine from Physik Instrumente LP has been named to the Top 100 most technologically significant analytical/test products in the 2016 R&D Awards. •

Invenios acquires Varioptic

Micro-fabrication foundry Invenios LLC has acquired Varioptic, a liquid-lens developing business unit of Parrot Drones SAS, for an undisclosed amount.

"We are very happy to have completed the acquisition of Varioptic" said Ray Karam, president of Invenios. "Combining the expertise of Varioptic and Invenios will further grow the liquid lens business and permit us to access new markets; therefore, this acquisition is excellent news for Varioptic, Invenios and for our customers."

Founded in 2002 in Lyon, France, Varioptic was acquired in May 2011 by Parrot. Varioptic's liquid lens technology enables variable focus, variable tilt or variable cylindrical lenses with no moving parts. Main markets include barcode readers, medical devices, industrial cameras and defense.

Invenios has been working on improving Varioptic's Optical Image Stabilization lens with an enhanced, low-cost and scalable design. The acquisition will streamline liquid lens development efforts and enable broader market access with an extended product portfolio.

Invenios specializes in the design, development and manufacturing of microfluidics, MEMS and 3D microstructures.

Renishaw expands, moves into new U.S. facility

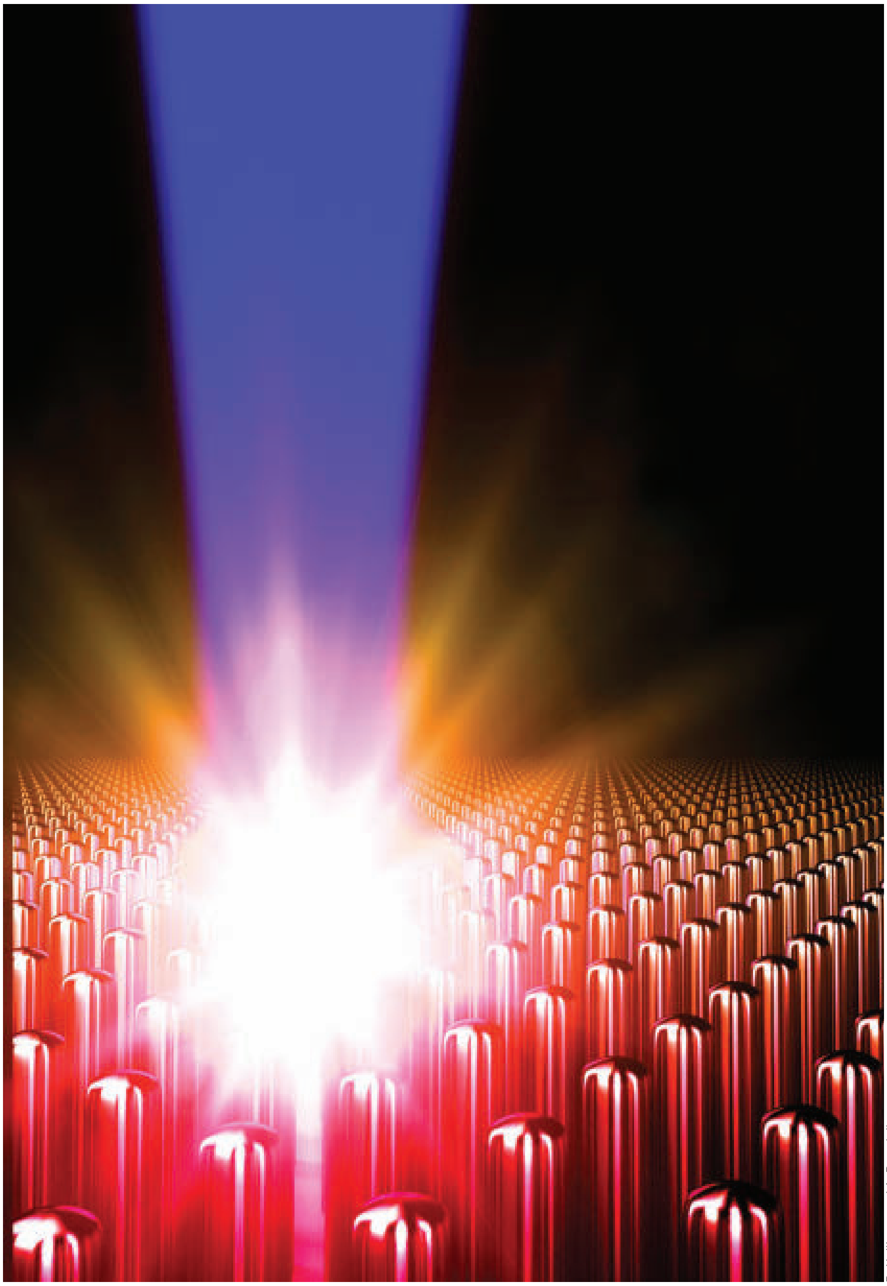
Precision measurement technology developer Renishaw Inc. is readying for growth as it begins to move into its new 133,000-sq-ft office, warehouse and U.S. headquarters.

The two-story facility will include space for product development, testing, warehousing and distribution. It will also house the new U.S. Additive Manufacturing Solutions Center, part of Renishaw's network of global solutions centers opening over the next year.

Renishaw plans to set up regional technical and sales offices throughout the U.S. "With the popularity and adoption of industry 4.0 and smart factory philosophies, our products and services are relevant to a larger and more diverse group of manufacturing operations," said Howard Salt, president of Renishaw.

Renishaw is an engineering company that focuses on measurement, motion control, health care, spectroscopy and manufacturing.

Compact lasers recreate conditions inside stars


R. Hollinger and A. Beardall

Representation of the creation of ultrahigh-energy-density matter by an intense laser pulse irradiation of an array of aligned nanowires.

FORT COLLINS, Colo. — With compact lasers that use ultrashort laser pulses irradiating arrays of aligned nanowires, scientists are recreating the extreme conditions found in stars. Previously, this was only possible with large "stadium-sized" lasers, as the energy density contained in the center of a star is many billions of atmospheres, compared with the single atmosphere of pressure on Earth's surface.

Researchers at Colorado State University (CSU) have accurately measured how deeply these extreme energies penetrate the nanostructures by monitoring the characteristic x-rays emitted from the nanowire array, in which the material composition changes with depth.

Numerical models validated by the experiments predict that increasing irradiation intensities to the highest levels made possible by today's ultrafast lasers could generate pressures to surpass those in the center of our sun.

The results open a path to obtaining unprecedented pressures in the laboratory with compact lasers. The work could open new inquiries into high-energy-density physics; how highly charged atoms behave in dense plasmas; and how light propagates at ultrahigh pressures, temperatures and densities.

Creating matter in the ultrahigh-energy-density regime could inform the study of laser-driven fusion — using lasers to drive controlled nuclear fusion reactions — and further the understanding of atomic processes in astrophysical and extreme laboratory environments.

The ability to create ultrahigh-energy-density matter using smaller facilities is of great interest for making these extreme plasma regimes more accessible for fundamental studies and applications.

The CSU study has been published in the journal *Science Advances* (doi: 10.1126/sciadv.1601558).

Hyperspectral imaging system could advance remote sensing

BEER-SHEVA, Israel — Advances in spectroscopy imaging will be applied to the development of a hyperspectral/ultraspectral imaging system that will be used for remote sensing.

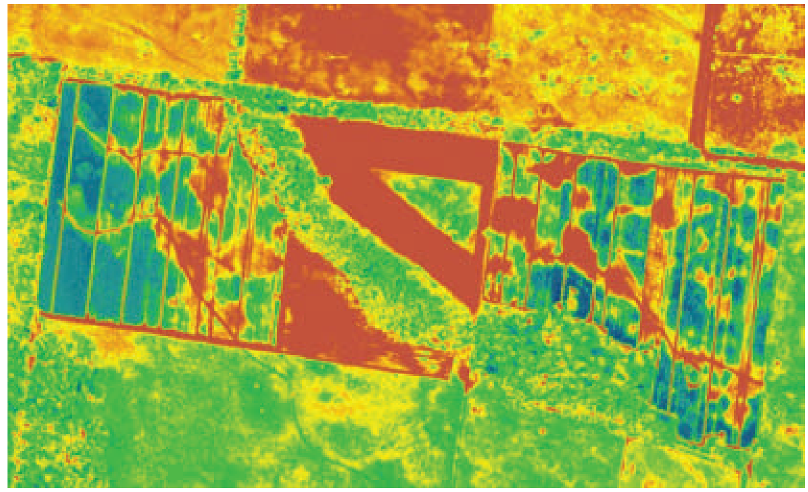
The imaging system incorporates a novel camera system that uses a compressive sensing technology. The camera, which has been significantly miniaturized, requires only one-tenth of the data traditionally needed to quickly produce high-resolution images.

The camera system is based on the work of researchers at Ben-Gurion University of the Negev (BGU), who will collaborate with ImageSat International (ISI) to develop a high-performance, high-resolution imaging system that is compact, simple to operate and cost-efficient.

Remote sensing from space or aircraft has a wide range of applications including agriculture, climate and pollution monitoring, homeland security and commodity exploration.

"This new technology based on BGU research could lead to a new generation of spectral systems for flight- and space-based remote sensing," said professor Dan Blumberg. "The collaboration between academia and industry is a sterling example of the 'NewSpace' concept, which promotes innovation and creativity in the space industry and will enable ImageSat to become the leader in the field of hyperspectral imaging."

Hyperspectral imaging sensors measure the light reflected by the earth's surface in different wavelengths, ranging from one to several hundred per pixel. This generates significant amounts of data that must be transmitted to the earth for processing, and can require enormous bandwidth.



Ben-Gurion University of the Negev

An example of hyperspectral imaging for agricultural use.

Robot with a human touch

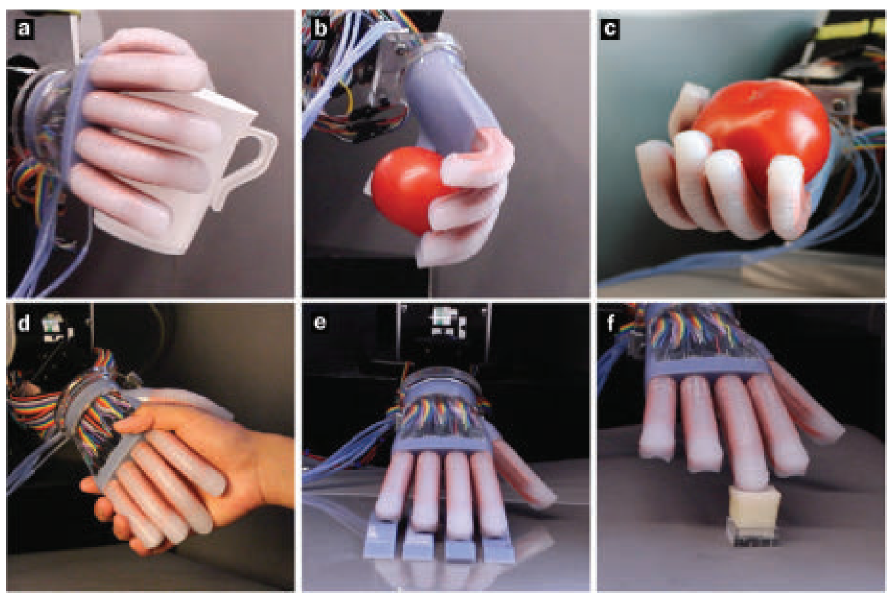
ITHACA, N.Y. — A soft robot has been created that can feel its surroundings internally, much like humans do.

Using stretchable optical waveguides as curvature, elongation and force sensors in a soft robotic hand, researchers at Cornell University have overcome the hindrances often associated with using motorized means for sensing.

"Most robots today have sensors on the outside of the body that detect things from the surface," said doctoral student Huichan Zhao. "Our sensors are integrated within the body, so they can actually detect forces being transmitted through the thickness of the robot, a lot like we and all organisms do when we feel pain, for example."

Optical waveguides have been in use since the early 1970s for numerous sensing functions, including tactile, position and acoustic. Fabrication was originally a complicated process, but the advent over the last 20 years of soft lithography and 3D printing has led to the development of elastomeric sensors that are easily produced and incorporated into a soft robotic application.

The research group led by Robert Shepherd, assistant professor of mechanical and aerospace engineering and principal investigator of Organic Robotics, employed a four-step soft lithography process to produce the core (through which light propagates) and the cladding (outer surface of the waveguide), which also houses the LED and the photodiode.



Melissa Osgood

Capabilities of the hand. Holding a coffee mug **(a)**; grasping a tomato with the palm facing down **(b)** and the palm facing up **(c)**; shaking a human hand **(d)**; lateral scanning over surfaces to detect roughness and shape **(e)**; and probing the softness of a soft sponge **(f)**.

The more the prosthetic hand deforms, the more light is lost through the core. That variable loss of light, as detected by the photodiode, is what allows the prosthesis to "sense" its surroundings.

"If no light was lost when we bend the prosthesis, we wouldn't get any information about the state of the sensor," Shepherd said. "The amount of loss is dependent on how it's bent."

The group used its optoelectronic prosthesis to perform a variety of tasks, including grasping and probing for both shape and texture. Most notably, the hand was able to scan three tomatoes and determine, by softness, which was the ripest.

The study is featured in the journal *Science Robotics* (doi: 10.1126/scirobotics.aai7529).

Optical circulator could route quantum data in integrated optical circuits

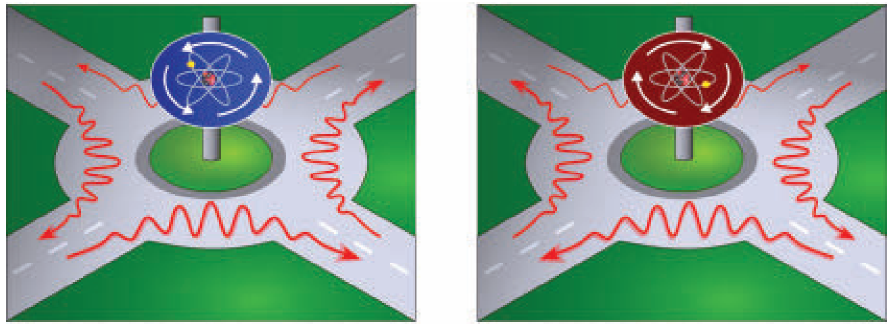
WIEN, Austria — An advance in optical signal processing uses a fiber-integrated quantum optical circulator, operated by a single atom, to control the direction of light. The nonreciprocal behavior of the circulator arises from a chiral interaction between the atom and the transversally confined light. The circulator's nonlinear response at the single-photon level enables photon number-dependent routing. Dubbed a "nano-roundabout," the circulator could be used in integrated optical chips, and would be an advance for nanotechnology where the ability to process light pulses consisting of individual photons could be useful.

To develop a means of signal processing using light, researchers at TU Wien coupled two glass fibers at their intersection point to an optical resonator, in which the light circulated in a way similar to the movement of cars in a traffic circle. The team coupled a single atom to the light field of a "bottle resonator," i.e., a microscopic glass with a surface on which the light could circulate.

The team found that when the bottle resonator was placed close to two ultrathin glass fibers, the fibers coupled. In the absence of an atom, the light changed from one glass fiber to the other via the bottle resonator; no sense of direction was defined for the circulator, which meant that light could travel both clockwise and counter-clockwise.

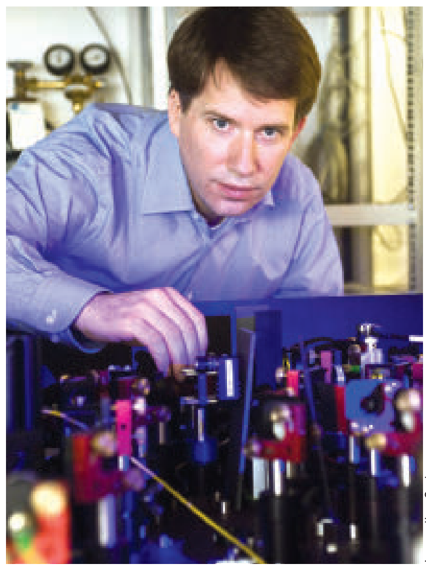
To break the symmetry between forward and backward propagation direction, the team used the polarization properties of the light. They coupled an atom to the resonator, preventing the coupling of the light into the resonator and the overcoupling of light into the other glass fiber.

The direction of circulation and the polarization of light were "locked" together; the direction of rotation depended on whether the light in the resonator traveled clockwise or counter-clockwise. When coupled to the resonator, the atom could interact differently with the light depending on the direction of circulation.



TU Wien

Functional principle of a nano-roundabout.



Jacqueline Godany

Arno Rauschenbeutel from the Vienna Center for Quantum Science and Technology at the Institute of Atomic and Subatomic Physics of TU Wien.

"The clockwise circulating light is not affected by the atom. The light in the opposite direction, on the other hand, strongly couples to the atom and therefore cannot enter the resonator," said researcher Arno Rauschenbeutel.

The asymmetry of the light-atom coupling with respect to the propagation direction of the light in the resonator allows control over the circulator operation. The circulation can be adjusted via the internal state of the atom.

"Because we use only a single atom, we can subtly control the process," said Rauschenbeutel. "The atom can be prepared in a state in which both traffic rules apply at the same time: All light particles then travel together through the circulator in both clockwise and counter-clockwise direction."

Luckily, this is impossible according to the rules of classical physics, as it could result in chaos if applied to road traffic. In quantum physics, however, such superpositions of different states are permitted, opening up exciting possibilities for the optical processing of quantum information.

The research was published in *Science* (doi: 10.1126/science.aaj2118).

Squeezing light cools microscopic drum below quantum limit

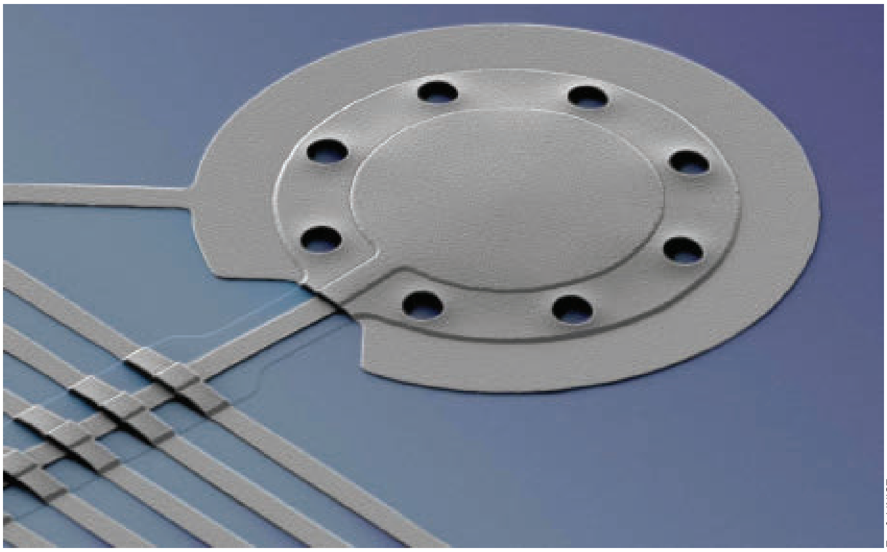
GAITHERSBURG, Md. — Using a special circuit to generate microwave photons stripped of intensity fluctuations, physicists at the National Institute of Standards and Technology (NIST) have cooled a mechanical object to a temperature lower than previously thought possible.

The new NIST theory and experiments showed that a microscopic mechanical drum — a vibrating aluminum membrane — could be cooled to less than one-fifth of a single quantum, or packet of energy.

John Teufel, the NIST physicist who led the experiment, said the new technique could be used to cool objects to absolute zero, the temperature at which matter is devoid of nearly all energy and motion.

"The colder you can get the drum, the better it is for any application," said Teufel. "Sensors would become more sensitive. You can store information longer. If you were using it in a quantum computer, then you would compute without distortion, and you would actually get the answer you want."

The drum, 20 µm in diameter and



Teufel/NIST

NIST researchers applied a special form of microwave light to cool a microscopic aluminum drum to an energy level below the generally accepted limit, to just one fifth of a single quantum of energy. The drum, which is 20 μm in diameter and 100 nm thick, beat 10 million times per second while its range of motion fell to nearly zero.

100 nm thick, was embedded in a superconducting circuit designed so that the drum motion influenced the microwaves bouncing inside a hollow enclosure known as an electromagnetic cavity.

The NIST experiment used the "squeezed light" to drive the drum circuit, ultimately moving the noise and unwanted fluctuations from a useful property of the light to another aspect that doesn't affect the experiment.

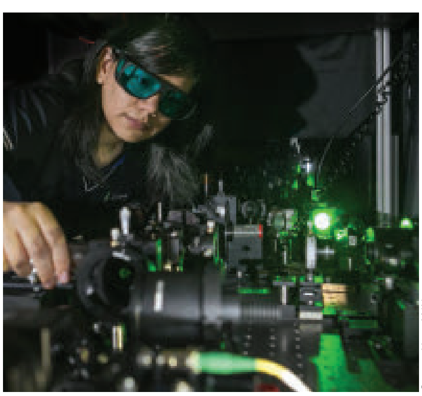
"Noise gives random kicks or heating to the thing you're trying to cool," Teufel said. "We are squeezing the light at a 'magic' level — in a very specific direction and amount — to make perfectly correlated photons with more stable intensity. These photons are both fragile and powerful."

The NIST theory and experiments indicate that squeezed light removes the generally accepted cooling limit; this includes objects that are large or operate at low frequencies, which are the most difficult to cool.

The drum might be used in applications such as hybrid quantum computers combining both quantum and mechanical elements.

The NIST study has been published in the journal *Nature* (doi:10.1038/nature20604).

Nanocrystal can transform light to visible spectrum



Stuart Hay, ANU

ANU Ph.D. student Maria del Rocio Camacho-Morales.

CANBERRA, Australia — A novel nanocrystal, 500 times smaller than a human hair, is capable of changing the intensity, shape and color of light. Developed by researchers at The Australian National University (ANU), the nanocrystal was built on glass so that light could pass through it. It could be used to convert light to the visible spectrum, enabling objects to be seen in very dark environments.

"The nanocrystals are so small they could be fitted as an ultrathin film to normal eye glasses to enable night vision," said professor Dragomir Neshev.

The researchers embedded AlGaAs nanostructures in optically transparent low-index material, which allowed for simultaneous forward and backward nonlinear emission. They demonstrated that the nanodisk AlGaAs antennas could emit second harmonic in preferential direction with a backward-to-forward ratio of up to five, and could generate complex vector polarization beams, including beams with radial polarization.

In order to measure the tiny amount of light coming through the nanostructures, the researchers had to fabricate the devices on a glass substrate, determine a way to measure the conversion of the colors from invisible to visible, and perform extensive numerical simulations to understand the physics behind the operation of the device.

"…[G]rowing a nano semiconductor on a transparent material is very difficult," said researcher Maria del Rocio Camacho-Morales.

In addition to its potential as a component in lightweight night-vision glasses, the device could be used to create security holograms in bank notes and in imaging applications.

"These semiconductor nanocrystals can transfer the highest intensity of light and engineer complex light beams that could be used with a laser to project a holographic image in modern displays," said researcher Mohsen Rahmani.

The research was published in *NANO Letters* (doi: 10.1021/acs.nanolett.6b03525).

ASU spectrometer to fly on NASA asteroid mission

TEMPE, Ariz. — A spectrometer developed by Arizona State University will fly onboard a NASA mission to Jupiter's Trojan asteroids.

The Lucy mission has been chosen under the agency's Discovery Program, a series of cost-capped exploratory missions into the solar system. Lucy will carry an ASU-designed and -developed thermal emission spectrometer that will measure surface temperatures on each asteroid the spacecraft visits.

Philip Christensen/ASU

The Thermal Emission Spectrometer for the Lucy mission will be a close copy of the OSIRIS-REx Thermal Emission Spectrometer, seen here under construction in the cleanroom on the Tempe campus. Its task in the Lucy mission will be to measure surface temperatures of primitive asteroids as a way of determining their physical properties.

"I'm really excited about this instrument, the third to be built here at SESE," said Philip Christensen, thermal emission spectrometer designer and principal investigator at ASU's School of Earth and Space Exploration.

The Lucy mission, set for a 2021 launch, was named for the iconic fossil skeleton, since it will investigate a particular collection of primitive asteroids that scientists hope may uncover fossils of planetary formation. The mission should arrive among the Trojans in 2027 and visit six asteroids by 2033.

Because Jupiter's Trojan asteroids orbit far from the sun, they all have very cold surfaces. The spectrometer's mission is to measure temperatures with great precision all over each asteroid that the Lucy spacecraft visits.

"By mapping how temperatures vary by the local time of day, we can map the surface properties of these previously unknown objects," Christensen said.

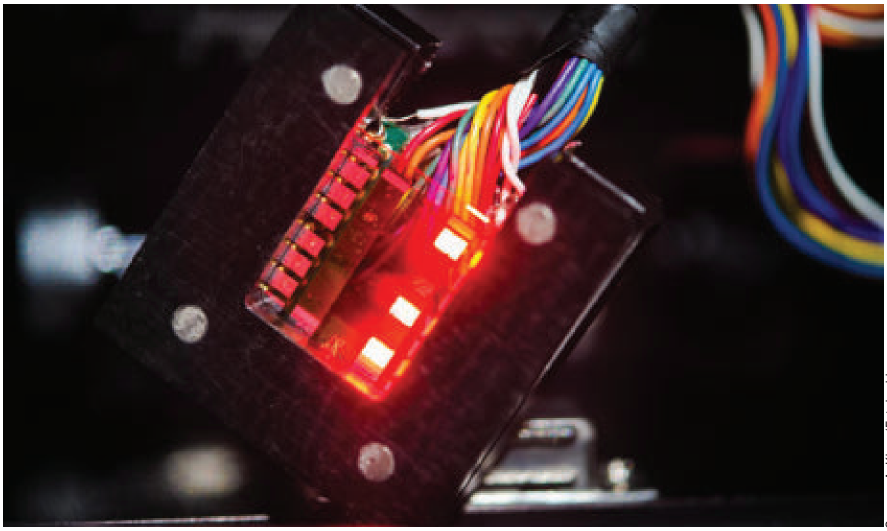
Self-assembling particles could produce lower-cost LEDs

PRINCETON, N.J. — Self-assembling nanoscale perovskite particles could be a more efficient and lower-cost alternative material for LEDs.

In the past, the inability to create uniform and bright nanoparticle perovskite films limited their potential. Now, Princeton University researchers have developed a novel self-assembling technique.

Barry Rand, assistant professor at the Andlinger Center for Energy and the Environment at Princeton, said, "Our new technique allows these nanoparticles to self-assemble to create ultra-fine grained films, an advance in fabrication that makes perovskite LEDs look more like a viable alternative to existing technologies."

LEDs emit light when voltage is applied across the LED. When the light is turned on, electrical current forces electrons from the negative side of the diode to the positive side. This releases energy in the form of light. LEDs operate best when this current can be strictly controlled. Rand, who also is an assistant professor of electrical engineering, and


Sameer A. Khan/Fotobuddy

A new type of LED is made with crystalline substances known as perovskites.

his team have created a device with thin nanoparticle-based films that allows that.

Rand's team and other researchers are exploring perovskites as a potential lower-cost alternative to gallium nitride (GaN) and other materials used in LED manufacturing. Lower-cost LEDs would speed the acceptance of the bulbs, reducing energy use and environmental impacts.

Perovskites can be either superconductive or semiconductive, depending on their structure; this makes them promising materials for use in electrical devices. Potentially, they could also serve as a replacement for silicon in solar panels, as they are cheaper to manufacture yet offer equal efficiency as some silicon-based solar cells.

Hybrid organic-inorganic perovskite layers are fabricated by dissolving perovskite precursors in a solution containing a metal halide and an organic ammonium halide. It is a relatively cheap and simple process that could offer an inexpensive alternative to LEDs based on silicon and other materials.

However, while the resulting semiconductor films could emit light in vivid colors, the crystals forming the molecular structure of the films were too large, which made them inefficient and unstable.

Rand and his team made some changes to the process using an additional type of organic ammonium halide, and in particular a long-chain ammonium halide, adding it to the perovskite solution during production. This dramatically constrained the formation of crystals in the film. The resulting crystallites were much smaller (around 5 to 10 nm across) than those generated with previous methods, and the halide perovskite films were far thinner and smoother.

This led to better external quantum efficiency, meaning the LEDs emitted more photons per number of electrons entering the device. The films were also more stable than those produced by other methods.

Russell Holmes, a professor of materials science and engineering at the University of Minnesota, said the Princeton research brings perovskite-based LEDs closer to commercialization.

"Their ability to control the processing of the perovskite generated ultraflat, nano-crystalline thin films suitable for high efficiency devices," said Holmes. "This elegant and general processing scheme will likely have broad application to other perovskite active materials and device platforms."

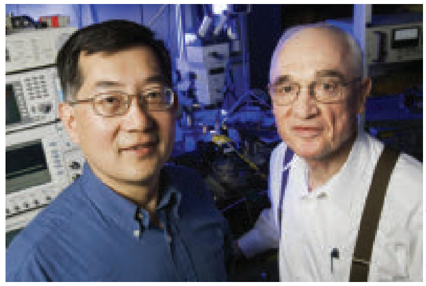
This advance could speed the use of perovskite technologies in commercial applications such as lighting, lasers and television and computer screens. The research findings have been reported in the journal *Nature Photonics* (doi:10.1038/nphoton.2016.269).

Tunneling could be key to modulating bandwidth of transistor laser

CHAMPAIGN, Ill. — Two recent studies could impact the fundamental modulation bandwidth of the transistor laser and increase its capacity for data transfer in optical and 5G wireless communications.

Electrical engineers Nick Holonyak Jr. and Milton Feng at the University of Illinois invented the transistor laser in 2004, based on their discovery that a transistor could be modulated to be a signal and a device that could harness the physics between electrons and light. The transistor laser is a three-port device that incorporates quantum wells in the base and an optical cavity for energy-efficient, high-speed data transfer. The engineers are now exploring how optical absorption can be enhanced, using an approach they have called the Feng-Holonyak Intra-Cavity Photon-Assisted Tunneling (FH-ICPAT).

"The fastest way for current to switch in a semiconductor material is for the electrons to jump between bands in the material in a process called tunneling," said Feng. "Light photons help shuttle the electrons across, a process called intra-cavity photon-assisted tunneling, making the device much faster."



University of Illinois

Milton Feng and Nick Holonyak Jr. invented the transistor laser in 2004 and continue to develop the technology for energy-efficient high-speed data transfer in optical and 5G wireless communications.

The research team explained the principles of operation for tunneling modulation of a quantum well transistor laser with current amplification and optical output via intra-cavity photon-assisted tunneling in two recent papers.

"The tunneling gain mechanism is the result of the unique transistor laser base transport properties under the influence of FH-ICPAT and base dielectric relaxation, which yields fast carrier base transport and faster recombination than the original Bardeen transistor," said researcher Curtis Wang. "The voltage and current dependence of the tunneling current gain and optical modulation have been revealed in detail. Although the analysis is carried out for the transistor laser intra-cavity photon-assisted tunneling, the operation mechanism should apply in general to tunneling collector transistors of various design configurations."

In a companion paper, the researchers explained how optical absorption and modulation in a p-n junction diode for a direct-gap semiconductor could be enhanced by photon-assisted tunneling in the presence of an optical cavity and photon-field in a transistor laser.

"In the transistor laser, the coherent photons generated at the base quantum well interact with the collector field and 'assist' optical cavity electron tunneling from the valence band of the base to the energy state of conduction band of the collector," Feng said. "The stimulated light output can be modulated by either base current injection via stimulated optical generation or base-collector junction bias via optical absorption.

"In this work, we studied the intra-cavity coherent photon intensity on photon-assisted tunneling in the transistor laser and realized photon field-dependent optical absorption. This FH-ICPAT in a transistor laser is the unique property of voltage (field) modulation and the basis for ultrahigh-speed direct laser modulation and switching.

"We remain indebted to John Bardeen, our mentor, for his lifelong continuing interest in the transistor (parallel to the BCS theory), the effect of the electron and the hole (e-h) in helping to originate the diode laser and LED, and in addition now leading to the e-h recombination (electrical and optical) transistor laser," Feng added.

The research was published in the *Journal of Applied Physics* (doi: 10.1063/1.4967922) and (doi: 10.1063/1.4942222).

Fiber innovations, along with improvements in optical transceivers and connectors, are needed to keep up with surging demands for both more data and higher bandwidth.

For **Optical Fiber**, More Bandwidth Looms

Engineering improvements to fiber, as well as enhancements to detectors and sources, aim to improve capacity for long-haul networks and data centers.

BY HANK HOGAN
CONTRIBUTING EDITOR

The world's data travels largely by fiber, with more being moved than ever before. San Jose, Calif.-based networking giant Cisco Systems forecasts that data traffic will grow 22 percent a year from 2015 to 2020.

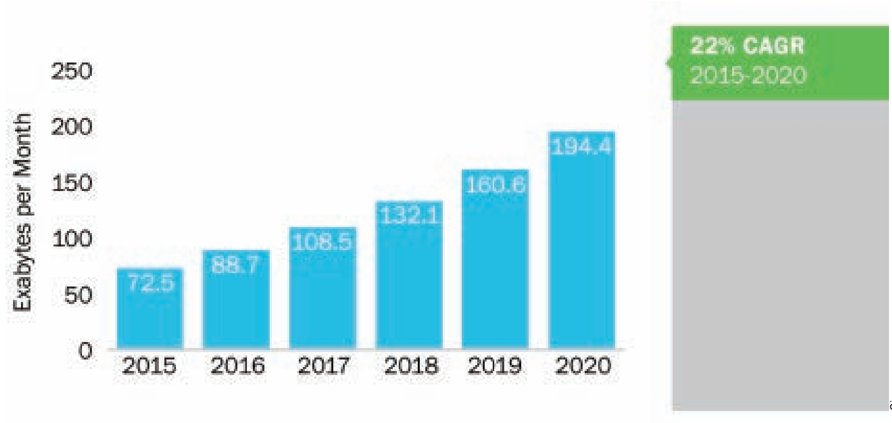
Little wonder, then, that more fiber is going in the ground, under the sea and into data centers. This year the optical fiber installed in communication networks globally will total 421 million kilometers, said Richard Mack, principal analyst with market research firm CRU International.

"This total is 10 percent more than the amount installed in 2015, and it is almost twice the amount installed five years ago, in 2011," he said.

In addition to more fiber being installed, industry and researchers are also working to boost capacity by engineering the fiber as well as improving sources and detectors. Some are looking at what could be fundamental material changes.

An example of these trends at work can be seen at Corning Inc. Based in Corning, N.Y., the company makes fiber for a wide variety of applications, said Joel Orban, product line operations manager for the

Corning Inc.



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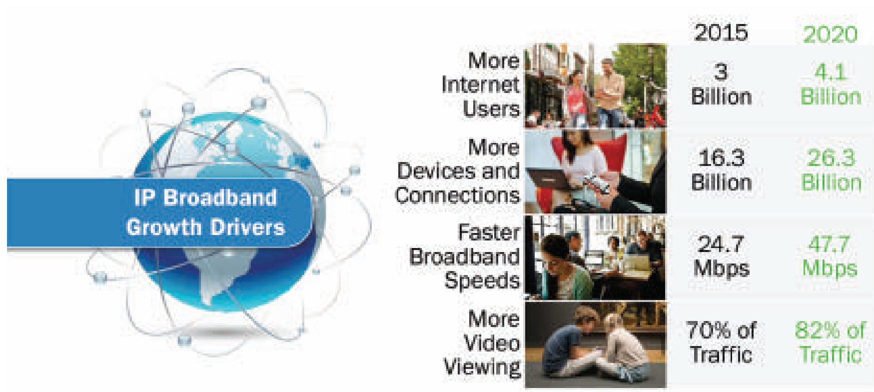


Cisco

Global data traffic, which largely travels over fiber, is projected to grow 20+ percent a year due to more users, devices and video.

single-mode and multimode optical fiber business. Single-mode fiber is often used in telecom and long-haul applications, with transmission wavelengths around 1550 nm and distances of thousands of kilometers. Multimode fiber, on the other hand, is used in shorter run applications such as data centers and elsewhere. Source wavelengths are 850 and 1310 nm.

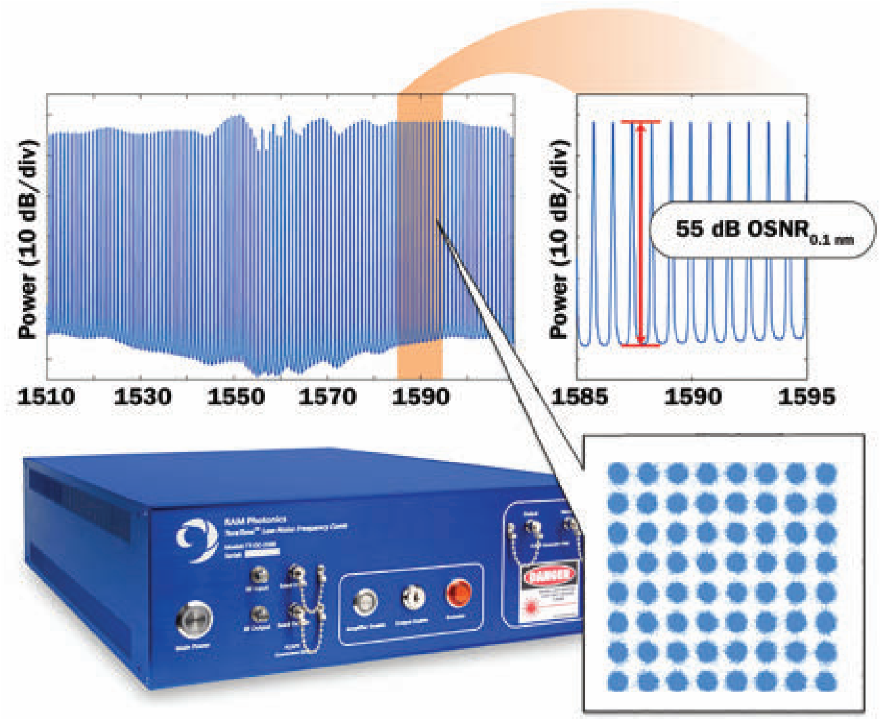
There are other differences in the cabling, driven by the differing application needs. Data centers prefer bend-insensitive cabling, the better to navigate tight confines. Telecom carriers are turning to smaller diameter optical fiber, achieved by shrinking the nonlight bearing protective coating so that the overall diameter drops from 242 to 200 µm. That smaller size enables 144 fibers to go into a standard sized cable that before held 96.

“These designs can effectively increase fiber density by 50 percent,” Orban said.

Another change involves the size of the core, the part of the fiber through which light travels. Glass fiber that is 125 µm in diameter may have a core diameter of only nine or 10 µm. Increasing that to

Corning Inc.

Mobile data traffic is one reason why fiber bandwidth demands are growing.



Stojan Radic, UCSD and RAM Photonics

A new class of laser, based on research at the University of California, San Diego, and made by Ram Photonics, uses an optical comb to provide hundreds of stabilized carriers to cancel transmission distortions on complex channel modulation, thereby increasing fiber data-carrying capacity.

Finisar

Demonstration of a pluggable 400G module, with four times the current commercially deployed connection speeds, interoperating with test equipment.

11, 12 or more lowers the power density, decreases nonlinear optical effects, reduces loss per kilometer traversed and increases the maximum bandwidth. However, such fibers can be more sensitive to bend losses.

Larger core fibers can transmit high-speed data roughly twice as far as narrower core, standard fiber, said Robert Lingle Jr., director of market and technology strategy at OFS of Norcross, Ga. OFS and its parent company, Furukawa Electric of Japan, make fiber and cable, as well as signal and pump lasers.

More wavelengths = greater capacity

Another way to raise capacity is to use more wavelengths of light. For example, one trend is to extend the 1535-to 1560-nm range C-band out to 1610 nm by adding L-band amplifiers, Lingle said. Both long-haul and data centers are interested in this for the extra capacity.

"That's a very active area and new fibers need to be designed for the C- and the L-bands," Lingle said.

He added that a large group of companies are now devising a 10-year multimode fiber road map. These guidelines will be used to develop fibers, cables and transceivers so that links can move from the current 100 Gbps commercially deployed capability to 400 and 800 Gbps. The goal of the group is to do so by employing wavelength division multiplexing over multimode fiber, thereby maintaining the cost advantage traditional for multimode fiber links, according to Lingle.

When increasing bandwidth to 400 Gbps and beyond, doing so without having to resort to more channels eliminates the need for higher density transmit/receive optical subassemblies and fiber cable connectors, said Craig Thompson, vice president of new markets at optical fiber component and module maker Finisar Corp. of Sunnyvale, Calif. The company makes transceivers, lasers and detectors for 850-, 1310- and 1550-nm wavelength bands.

Fewer channels are better because the amount of space for a subassembly or connector is largely fixed. So, if it takes eight instead of the current standard four channels to get to a given data rate, then the subassembly or connector density must be roughly doubled.

The move to 400 Gbps also presents other challenges. For instance, there is a different and more complex signaling modulation. However, those faster speeds also present new opportunities for fiber optics. The alternative, sending electrons down a conductor, is also running into problems.

"Generally, as speeds go up the possible reach in copper reduces and to get that reach you need more copper, bulkier cables and sometimes even some active components at each end of the cable," Thompson said. "We're getting to the point where copper has some real limitations."

He thinks that the 400-Gbps generation, made up of eight lanes running 50 Gbps each, will see a mix of optical and electronic transport even in the very short runs that connect a server rack together. The optical side might even be favored because it offers lower latency, or transmission lag.

In addition to increasing bandwidth demands, the age of the installed long-haul networks is also playing a role in new deployments. Many long-haul networks are decades old and may be maxed out in capacity, said Ron Johnson, director of product development at Cisco.

Beyond solving capacity constraints, putting in new fiber and associated components offers benefits. By using low-loss, large-core fiber, for instance, the distance a signal can travel before having to be regenerated can be significantly increased, cutting costs. More savings are possible by eliminating electronic components in favor of relatively new high port count reconfigurable optical add-drop multiplexers or ROADMs. Whereas previous devices might have six ports, the latest ones may have as many as 20. That makes it possible to have enough capacity at the optical switch to add and drop signals as well as transmit them on through without having to do so electronically.

Still more savings arise from other characteristics of this new generation of optical switches. "You have a much wider (spectral) band and that reduces the transmission effects, which is translated to fewer or no regeneration required," Johnson said.

Such savings lead to a lower cost per bit. That may create increased data demands, which will result in the need for more bandwidth. So, the new cables being installed typically have additional fiber built in. This provides extra capacity that could be lit when needed.

As for the future, extensive research efforts underway aim to boost the capacity of existing fiber. One such was demonstrated at University College London. In a 2015 *Nature* paper[1], the group reported on a technique that nearly doubled the length a signal could reach. They employed digital signal processing to undo the distortions introduced in the signal, using known physical parameters of the fiber to do so. One payoff is more throughput.

"You can go to higher orders of modulation to send more information over greater distances with these DSP [digital signal processing] techniques, ensuring that the ratio between your signal power and the noise remains high enough," said Robert Maher, at the time a senior research associate. He was the paper's lead author and now works for Infinera Corp, a Sunnyvale, Calif. maker of long-haul wavelength division multiplexing gear.

At the University of California, San Diego, a research group has taken another approach. As outlined in a 2015 *Science* paper[2], they passed an ordinary laser beam through a special mixer to generate hundreds of wavelengths. The sources thus produced are exceedingly stable, with relative carrier variability improved by orders of magnitude. That makes it possible to dramatically increase the bandwidth of existing fiber.

"You will more than quadruple capacity by encoding information using such a laser," said Stojan Radic, professor of electrical and computer engineering and leader of the research group.

He added that a demonstrator of the concept will be built in 2017. Commercial applications will come after that. Radic is also a technical consultant with San Diego-based RAM Photonics, which has produced a laser source motivated by the technique.

Finally, while silica optical fiber dominates today, that may not always be the case. The interaction of high-intensity light with current fiber leads to nonlinear, performance-limiting effects. Incorporating significant amounts of aluminum, barium, yttrium or combinations of these and other materials leads to glasses that exhibit much smaller nonlinear effects. Eventually, as power levels climb in response to the demand for more bandwidth, fiber may be constructed out of something other than today's silica standard.

John Ballato, a professor of materials science and engineering at Clemson University, noted that the high-power lasers now used in industrial and military applications are already at such a point. Using different, more linear core glasses makes higher operating power possible.

Such a fundamental material change is many decades off, if it happens at all. In the end, though, it may be necessary to make a clean break with the past to achieve a radical result.

As Ballato said, "The lightbulb did not arise from continuous improvements of the candle."

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Corning Inc.

Optical fiber spools.

Compact **UVC Laser** Shows Promise for Environmental Sensing

A novel solid-state laser technology for wavelengths near 220 nm overcomes limitations of current-generation UV lasers and gas discharge lamps.

BY TIM SMEETON, KARL WELNA,
EDWARD BOARDMAN, RISHANE PEREIRA,
VALERIE BERRYMAN-BOUSQUET,
SHARP LABORATORIES OF EUROPE LTD.

Advances in sensor technologies and the more widespread deployment of sensors are continually improving safety, quality of life and industrial productivity. Many of the most reliable chemical, biological and gas sensors are in some way based on light, with current technology exploiting wavelengths from deep ultraviolet to far infrared. Within this field, ultraviolet light with wavelengths between 210 and 230 nm in the ultraviolet C (UVC) spectral range has a vital role because of the strong and specific interaction between these wavelengths and many analytes, especially those measured during medical diagnosis, life sciences research, drinking water production and gas analysis.

Sensor technologies that need this ultraviolet light include instrumentation for identification and quantification of proteins and other organic molecules, sensors for organic compounds and nitrates in water, and sensors for several gases important for emissions and air quality analysis (Figure 1). These technologies rely on measurements of absorption, induced-fluorescence or scattering of the 210- to 230-nm wavelengths that, in current technology, must be generated using gas discharge lamps or complex laser systems (Figure 1, bottom). Gas discharge lamps currently dominate this field — especially deuterium lamps and xenon flash lamps, which emit a continuum of wavelengths between 200 and 400 nm and are filtered to provide emission in a specific wavelength range. Laser sources are advantageous or essential for many sensors, thanks to the high spectral purity or spatial quality of a laser beam. However, the few wavelengths available and very high cost of existing gas lasers and complex frequency-converted lasers mean that exploitation of laser-based sensors is limited to niche markets.

There is a strong pull from sensor developers to move away from reliance on gas lamps and complex laser systems and adopt more practical compact solid-state alternatives. The advantages of solid-state light sources are well known, and include lower system costs, lower total ownership costs, smaller size, improved robustness, low-voltage operation, lower energy consumption, longer lifetimes and resilience to frequent on-off cycling. These features can enable significant improvements in sensor functionality and, more importantly, enable the migration of technologies that are presently only viable in high-cost applications to more affordable and widespread use.

A recent example of the impact of new solid-state light sources on photonic sensors can be seen in technologies enabled by LEDs emitting wavelengths between 240 and 320 nm. New sensors to measure dissolved organic compounds in water using wavelengths near 255 nm and for protein analysis with wavelengths near 280 nm are evidence of the trend away from the gas lamp sources that were previously incumbent. Theoretically, similar LED technology is applicable to wavelengths below 230 nm, but severe technical challenges associated with operation at these shorter wavelengths — difficulties in semiconductor doping, in particular— have prevented viable LED operation in the 210- to 230-nm range, and laser diodes for these wavelengths seem to be, at best, a distant prospect.

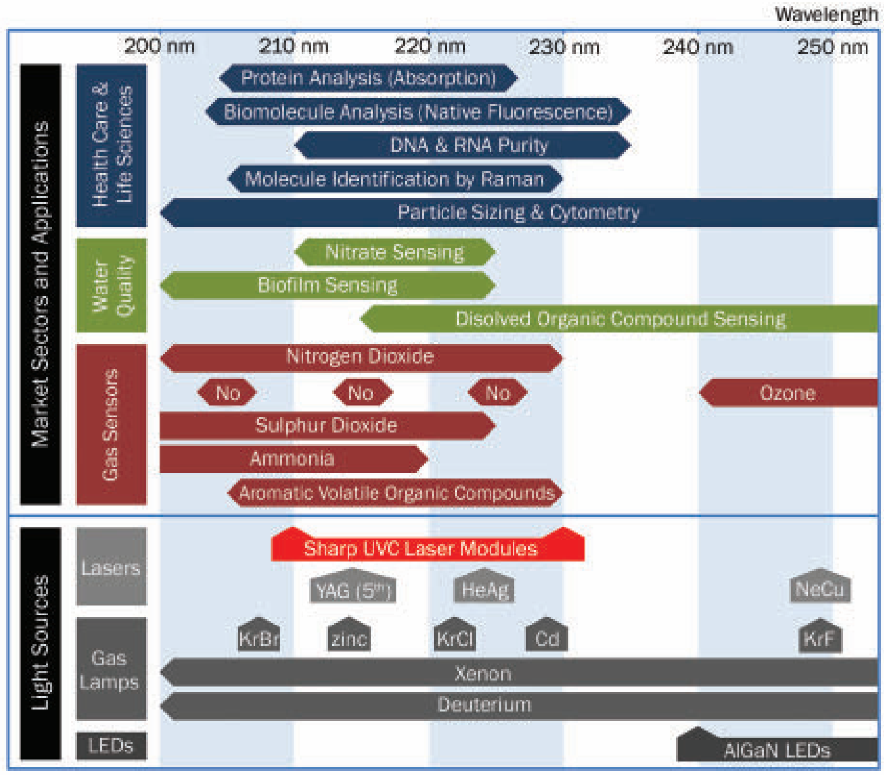


Figure 1. Wavelengths required for existing and emerging sensors based on deep ultraviolet light and available light source technology.

This leaves an unsatisfied need for a new-generation light source to bring the benefits of solid-state devices to the 210- to 230-nm wavelength range for the first time, and to enable wider penetration of laser-based sensor technologies.

Sharp Laboratories of Europe has developed a UVC laser module technology that meets these needs and creates exciting opportunities for sensor technologies based on deep ultraviolet laser light.

UVC laser module

The new laser modules provide laser emission with a wavelength near 220 nm from solid-state technology in a compact package with highly practical operating conditions. Blue light emitted from a laser diode is frequency-doubled to generate an output wavelength near 220 nm and a high-performance, compact wavelength filter ensures pure ultraviolet emission (Figure 2). A proprietary design overcomes the critical challenges associated with frequency-doubling laser diodes at these wavelengths to provide modules with high output power, excellent temporal stability and a wide operating temperature range in a compact package.

The UVC laser modules are designed to deliver technical performance meeting the requirements for sensor technologies (Table 1). Laser modules can be produced with an emission wavelength anywhere between 210 and 230 nm, enabling

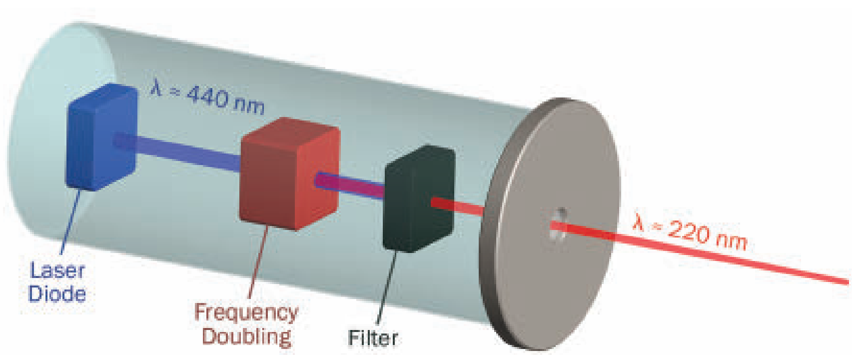


Figure 2. Underlying concept of the UVC laser module.

Wavelengths near 220 nm are essential for identifying and quantifying proteins and other biological molecules.

precise matching with the wavelengths required for specific applications (Figure 3). The emission wavelength of a module is either tuneable over ±0.5 nm through modulation of temperature or injection current, or may be fixed at manufacturing to remain within ±0.1 nm during service. The modules may be operated for modes ranging from microsecond duration pulses through to CW, providing output powers up to 0.15 mW, which are suitable for absorption, induced-fluorescence and scattering applications. The ultraviolet emission is in a linearly polarized collimated beam, enabling high-efficiency transmission through optical systems, and the beam may be focussed with simple, low-loss optical components to provide extreme power densities — for example, exceeding 100 W·cm^{-2} in a 10-µm-diameter spot. The lasers operate by direct electrical current injection for temperatures between 0 °C and 50 °C without needing any warmup time, thereby enabling simple and low-cost integration into instrumentation ready for operation in the field. The laser technology is proven to be reliable and robust, with operating lifetimes exceeding several thousand hours demonstrated. The highly compact UVC laser module package features an external volume less than 15 cm^3, similar to the size of an AA battery.

UVC laser modules have significant advantages over existing light sources for sensor technologies (Table 2), providing a unique combination of small spectral linewidth, laser beam quality, high power density, practical operating conditions and emission wavelength below 230 nm. This combination has a disruptive impact on many sensor technologies (Figure 1), creating many new opportunities.

Table 1.
Typical parameters for UVC laser modules.

Emission Wavelength		220 nm typical [210 nm min.; 230 nm max.]
Linewidth (FWHM)		<0.4 nm
Output Power	Continuous	0.05 mW
	Pulsed (µs to ms)	0.15 mW
Beam Diameter at Exit Window		<1 mm
Operating Temperature		0 °C to 50 °C
Warmup Time		None Required
Package Size		<15 cm^3
Voltage		<6 V

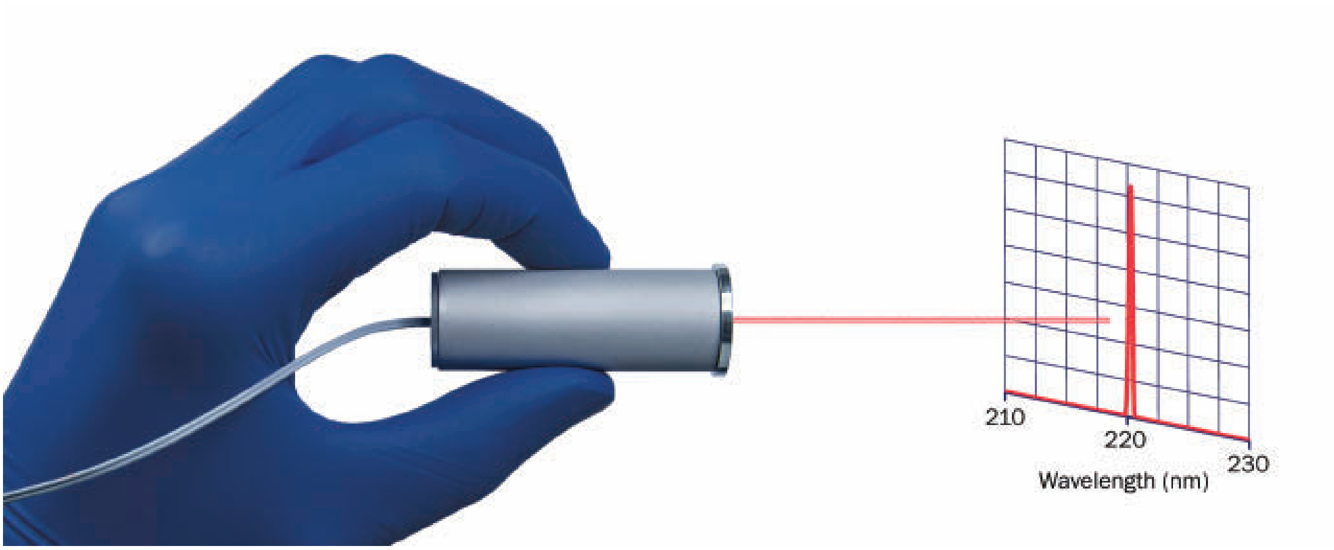
Table 2.
Comparison of properties of the Sharp UVC laser module with existing UVC lamps, LEDs and lasers.

	Sharp UVC Laser Modules	UVC Lamps	UVC LEDs	Other UVC Lasers
Solid-State & Robust	✔	✘	✔	✘
Wavelength Less Than 230 nm	✔	✔	✘	✔
Small Beam	✔ [~µm^2]	✘ [~cm^2]	✘ [~mm^2]	✔ [~µm^2]
High Power Density	✔ [>100 W·cm^{-2}]	✘ [<1 W·cm^{-2}]	✘ [<1 W·cm^{-2}]	✔ [>100 W·cm^{-2}]
Small Spectral Linewidth	✔ [<0.4 nm]	✘ [>200 nm]	✘ [~10 nm]	✔ [<0.1 nm]
Compact	✔ [<15 cm^3]	✘ [>150 cm^3]	✔ [<0.1 cm^3]	✘ [>500 cm^3]
Low Voltage	✔ [<6 V]	✘ [>100 V]	✔ [~6 V]	✘ [>100 V]

Opportunities for health care and the life sciences

Analysis of proteins and biomolecules is a cornerstone of life sciences research and health care. Wavelengths near 220 nm are essential for identifying and quantifying proteins and other biological molecules, and the UVC laser module brings new opportunities in several areas:

- High-performance liquid chromatography (HPLC) and capillary electrophoresis (CE) techniques widely use absorption of wavelengths near 220 nm for detection, generally using gas discharge lamps. Wavelengths near 214 nm are standard for protein and peptide analysis because they are very strongly absorbed, enabling at least 20 times higher sensitivity compared with 280-nm wavelengths. UVC laser modules provide opportunities for significant improvements to these systems including lower cost, smaller size, longer operating lifetime, battery operation and operation without warmup. There is also the potential for improved functionality, such as improved linearity of absorbance versus concentration thanks to the narrow spectral linewidth of the laser emission.
- Laser-induced native fluorescence (LINF) is a powerful technique for analysis of biomolecules that have not been modified by labeling with fluorescent marker molecules. Laser light with wavelengths near 220 nm induces fluorescence from these molecules almost universally, creating myriad opportunities. These are currently only



exploited in niches due to the constraints of available laser sources. UVC laser modules enable this technique to be deployed widely without reliance on bench-top laser systems.

- Point-of-care diagnosis tools for analysis of proteins or other biomolecules can exploit laser wavelengths near 220 nm for the first time with UVC laser modules. For example, deep ultraviolet absorption and fluorescence processes that are conventionally available only in laboratories may now be incorporated into emerging diagnostic technologies. This meets the trend to improve the quality and efficiency of health care with medical diagnosis at the patient point of care.

Tracking water pollutants

Chemical sensors based on optical absorption, fluorescence and scattering provide market-leading stability, accuracy and reliability for the water industry. UVC laser modules enable performance improvements and more widespread use of optical-based sensors for this sector:

• Organic pollutants in water and bio-

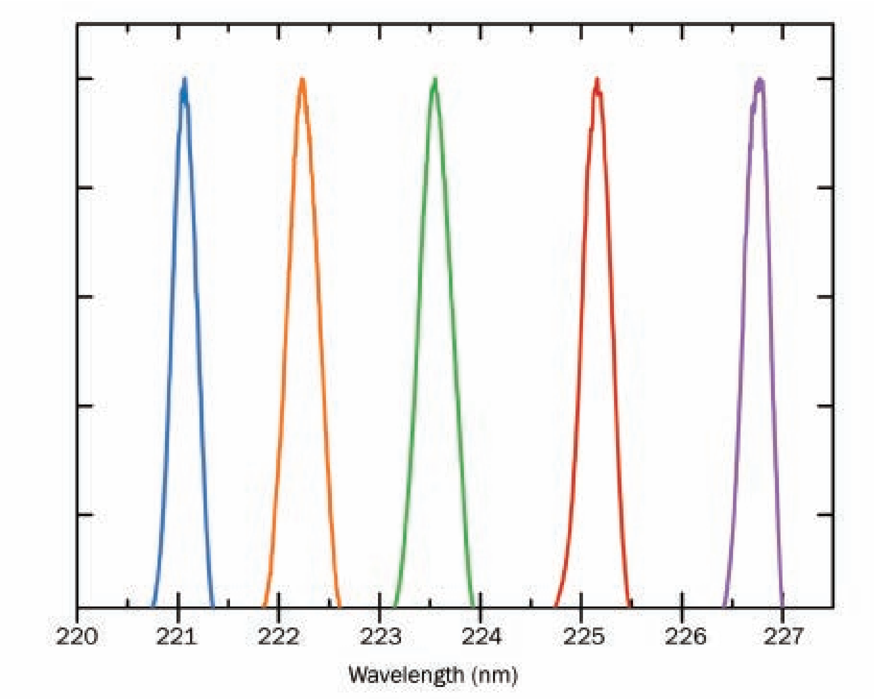


Figure 3. Laser emission spectra from five different UVC laser modules from 220 to 227 nm. Modules can be produced with an emission wavelength anywhere between 210 and 230 nm.

films on surfaces can be detected and quantified with high specificity from the fluorescence induced by ultraviolet light. The high beam quality, high power density and small spectral linewidth of laser light enable efficient fluorescence sensors with simple optical designs and with no interference from the input beam. Wavelengths near 220 nm are highly effective at inducing fluorescence and also make it possible to distinguish between families of organic molecules. For example, molecules containing many aromatic rings — polycyclic aromatic hydrocarbons (PAHs) — have characteristic fluorescence for input wavelengths in the 220- to 230-nm range. These phenomena have long been used inside laboratories, and the UVC laser modules provide an opportunity for widespread exploitation in the field.

- Nitrate sensors for water using absorption of wavelengths near 220 nm are the preferred technology in wastewater treatment, drinking water production and monitoring agricultural fertilizer pollution of natural waters[1]. Most sensors use xenon flash lamps with wavelength filters to isolate wavelengths around 220 nm. UVC laser modules enable lower manufacturing and operating costs thanks to simpler and safer optical designs and improved reliability. Furthermore, operation of UVC laser modules without warmup time enables remarkably lower power consumption suitable for battery-powered environmental monitoring. These improvements can help the water industry and environmental monitoring sectors realize their vision for much more widespread monitoring.

High-performance gas sensors

Monitoring pollutant gases is an important part of measures to improve air quality and reduce disease caused by exposure to harmful compounds in the air. Laser-based gas sensors provide sensitivity, long-term accuracy and specificity unmatched by other technologies, but require availability of lasers at specific wavelengths. These new UVC laser modules provide the first widely useable source of several wavelengths that are important for gas sensing:

- Emissions gases nitric oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ammonia (NH_3) all have strong absorption features in the 210- to 230-nm wavelength range. The narrow spectral linewidth of the UVC laser modules, and the option for modules with tuneable or fixed emission wavelength, enables precise alignment with these features. Most importantly, these laser-based sensor technologies can be deployed widely for the first time, for example for indoor air quality applications.
- Volatile organic compounds also have strong absorption for wavelengths near 220 nm, so the UVC laser module similarly enables novel sensor technologies for these, based on absorption and fluorescence.

Outlook

The UVC laser modules are the first laser sources for wavelengths in the 210- to 230-nm range that are suitable for widespread use. They also represent the first viable compact solid-state light sources of any type in this wavelength range. This technology enables a transition away from reliance on gas discharge lamps and complex laser systems in sensors and consequently creates opportunities for disruptive improvements in sensor performance. This can lead to migration of proven sensor concepts to widespread use and stimulate development of entirely new sensor technologies.

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New **4G Optics** Technology Extends Limits to the Extremes

Advances in liquid crystal and liquid crystal polymer materials have made it possible to modulate the orientation of the anisotropy axis at high spatial frequencies, ushering in the next generation of optics for space communications and intraocular lenses.

BY NELSON TABIRYAN AND DAVID ROBERTS, BEAM ENGINEERING FOR ADVANCED MEASUREMENTS
DIANE STEEVES AND BRIAN KIMBALL, U.S. ARMY NATICK SOLDIER RD&E CENTER

From the advent of the candle to the emergence the first laser diode, there have been numerous advances in light sources. After all, all materials radiate when energized one way or another.

Optics, however, have undergone a slow evolution.

There are only a few ways to control light. Isotropic materials such as glass modulate shape or take advantage of the refractive index. The first case serves as the foundation for the first generation of optics, and is still overwhelmingly in use today given the capability of strongly influencing light propagation in a broad band of wavelengths.

Weight and size, however, limit refractive lenses and prisms to applications that require relatively small optics. Gratings based on modulation of refractive index may exhibit high efficiency in thinner structures, however, compromising bandwidth.

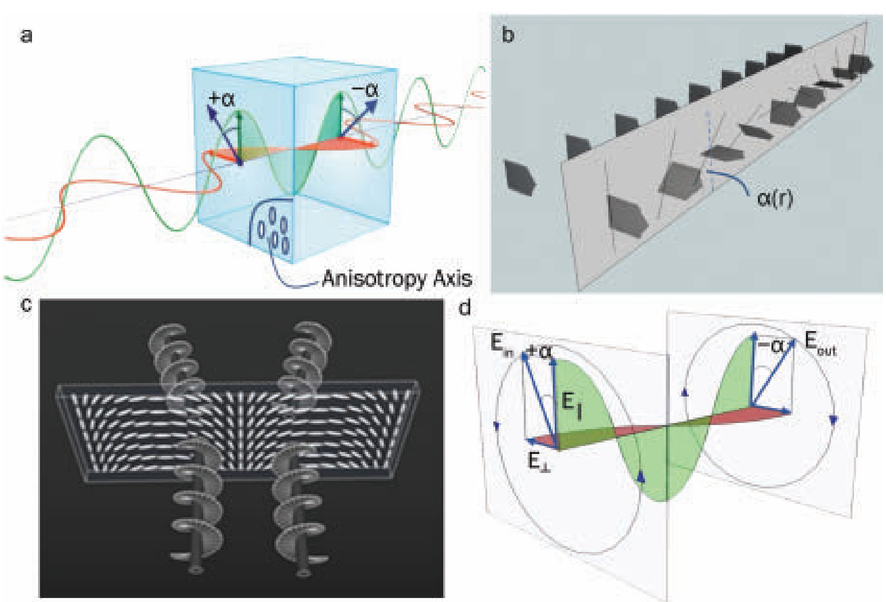

Figure 1. Modulation of optical phase due to spatial modulation of the anisotropy axis orientation of a half-wave retardation plate. Rotation of linear polarization of light upon passage through a half-wave plate **(a)**. The green and red sinusoids depict the electric field components of a beam polarized along and perpendicular to the anisotropy axis; α is the angle the linear polarization axis makes with the anisotropy axis at the entrance to the film. Modulation of light polarization by a half-wave plate with optical axis orientation angle varying along a transverse Cartesian coordinate **(b)**. Diffraction of light by a half-wave plate with linear spatial modulation of the optical axis orientation; a right- or left-circularly polarized light beam diffracts into +1st or −1st order depending on sign **(c)**. Visualization of the 2α geometrical phase-shift between input and output circular polarized beams due to passage through a half-wave plate **(d)**.

Anisotropic materials offer two more ways to control light. The modern liquid crystal display controls light by modulation of birefringence. The thickness of liquid crystal layers is limited to micrometers due to light scattering and structural defects in thicker layers. Therefore, even with huge optical anisotropy, $\Delta n = n_{\parallel} - n_{\perp} \sim 0.2$ for commercially available materials and $\Delta n = n_{\parallel} - n_{\perp} \sim 1$ for experimental compounds ($n_{\parallel}$ and $n_{\perp}$ being the principal values of refractive indices of the liquid crystal), the maximum obtainable phase modulation by a liquid crystal due to modulation of birefringence is small for developing lenses or other optical components that could challenge conventional optics.

Modulating transparent anisotropic thin films

Orientation of the anisotropy axis is the only remaining optical parameter to modulate in transparent anisotropic materials. Micrometer-thin material films engineered to have spatially varying orientation of the anisotropy axis constitute the fourth generation of optics (4G optics) that extends the limits of optical and electro-optical systems to extremes in terms of optical strength, bandwidth, aperture size and versatility.

- **Optical power** — comparable to that of glass optics.
- **Bandwidth** — encompassing wide portions all over the electromagnetic spectrum.
- **Aperture sizes** — ranging from micrometers to meters.
- **Weight** — determined essentially by substrates' weight only.
- **Manufacturing cost** — using low-cost simple equipment and procedures, al-

lowing roll-to-roll fabrication and customization in real time.

- **Material cost** — driven mostly by substrate cost.
- **Versatility** — any optical component fabricated using the same materials and processes.
- **Fabrication time** — processes that could be as fast as nanoseconds and not longer than minutes.

This is made possible due to modulation of the geometrical phase known as the Pancharatnam-Berry phase. The phenomenon, known since the 1950s, remained largely unexplored until liquid crystal and liquid crystal polymer materials made it possible to modulate orientation of the anisotropy axis at high spatial frequencies with high quality in a large area — and using technologically inexpensive processes[1,2]. Like the breakthrough in displays, liquid crystals are now driving the advances in optics and photonics while other technologies of "flat optics" remain a laboratory fascination due to complexity and cost. The success of liquid crystal technology is largely due to decades of huge investments in liquid crystal display research and development.

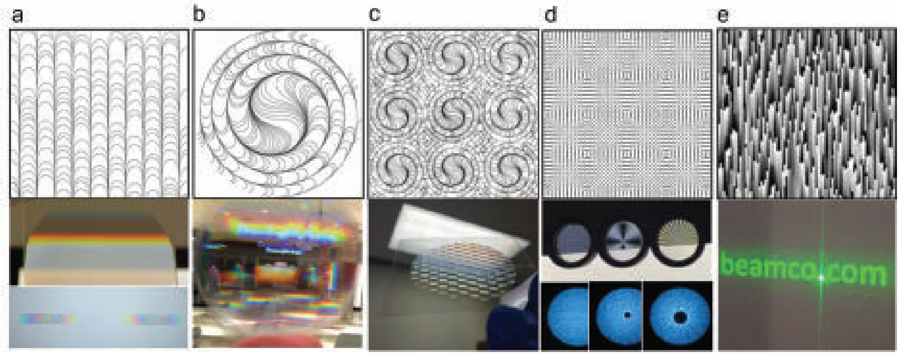

Figure 2. Examples of diffractive wave plates. **Top:** optical axis orientation patterns presented by a system of continuous lines tangential to the local orientation of the anisotropy axis **(a-c)**, as line segments **(d)**, and as a gray scale varying from 0 (white) to 180° orientation angle (black) **(e)**. **Bottom:** photographs of devices and optical effects, including a cycloidal diffractive wave plate and diffraction pattern of a black and white image of the word "BEAM" demonstrating practical absence of zero-order over visible spectrum **(a)**; a nonachromatic diffractive wave plate lens demonstrating both focused and defocused images and some zero-order **(b)**; an array of diffractive wave plate lenslets **(c)**; single vector vortex wave plates **(d)**; and a holographic beam shaper designed to convert a Gaussian beam into "beamco.com" with zero-order as the dot **(e)**.

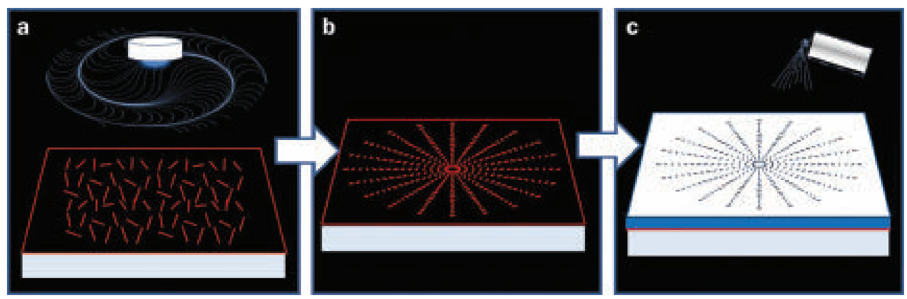

Figure 3. Main steps in the diffractive wave plate fabrication process: deposition of photoalignment material and exposure to a polarized light beam **(a)**; photoalignment obtained by spatially patterned, linearly polarized light corresponding, as an example, to the pattern for a diffractive wave plate lens **(b)**; and coating of the alignment layer with liquid crystal polymer that adopts the orientation pattern recorded in the photoalignment layer **(c)**.

Geometrical phase visualized

Half-wave retardation plates are thin anisotropic films commonly used for rotating polarization of a light beam. Choosing the film thickness according to the condition $L(n_{\parallel} - n_{\perp}) = \lambda/2$ (λ — wavelength in vacuum) ensures that the slower polarization component of the beam is delayed exactly by one half-wave compared to the faster one. Then the beam at the output of the film remains linearly polarized, making an angle $-\alpha$ with respect to the anisotropy axis, with α being the angle at the input surface (Figure 1a).

Consider now a system of half-wave retardation plates with different orientation of anisotropy axis (Figure 1b). A linearly polarized input results in an output beam with spatially varying polarization. In the case of continuous modulation, $\alpha = qx$ with $q = \pi/\Lambda$ determining the spatial period Λ, the polarization at the output with an angle 2α has a twice higher spatial frequency of $2q$. The obtained polarization pattern is remarkable; it corresponds to the field in the overlap region of two orthogonally circularly polarized beams propagating at angles of $\pm \lambda/\Lambda$ with respect to the normal to what effectively is a "diffractive wave plate." Hence, such a wave plate diffracts a linearly polarized or an unpolarized beam into orthogonal circularly polarized beams (Figure 1c).

Note now that the angle α for a circularly polarized beam is changing in time due to polarization rotation, and there is a 2α phase shift between rotation angles of the output and input beams (Figure 1d). Thus, a half-wave retardation film reverses the polarization handedness of an input circularly polarized beam while also inducing a phase equal to 2α that depends only on orientation of the anisotropy axis of the half-wave retardation film. That is the geometrical phase. A constant phase for a uniform wave plate never mattered. When modulated, though, it opens up a new frontier of optics.

The new world of optics

Simply varying the pattern of anisotropy axis orientation in a wave plate makes it possible to produce all the variety of optical components and functions. The linear modulation pattern $\alpha = qx$ is indeed the simplest and, known as cycloidal diffractive wave plate, acts as a prism (Figure 2a). A parabolic profile, $\alpha \sim r^2$, acts as a lens (Figure 2b). Note that different signs of the phase shift corresponding to different handedness of circular polarization mean different signs of the focal length of such a diffractive wave plate lens: It focuses a beam of one handedness while defocusing the beam of opposite handedness[3].

Arrays of optical elements such as lenses and vortices can be designed for which the optical axis orientation is continuous across the boundaries between array elements (Figures 2c and 2d). More complex structures corresponding to a holographic beam shaper are also possible (Figure 2e).

As wave plates, it is no more a wonder that 4G optics are broadband and can be made practically achromatic in a wide range of wavelengths using techniques

Images courtesy of Beam Co.

for fabrication of broadband wave plates[4]. The diffraction efficiency for those components can exceed 99 percent if properly designed and fabricated.

Fabrication: dielectric coatings with a twist

Forcing continuous deformation of a crystal axis in the microscale is not easy. Fortunately, it is both feasible and technologically cost-effective for liquid crystal materials due to their low elastic energy. Thin films of liquid crystal materials are obtained between substrates with conductive layers for switchable electro-optical systems or as thin polymer film coatings.

In the basis of fabrication is a process known as photoalignment. The substrate is coated by a nanometer thin film of a material (Figure 3a) that generates anisotropy when illuminated by linearly polarized light, with anisotropy axis determined by light polarization (Figure 3b). Certain azobenzene dyes with anisotropic molecules are among the most effective photoalignment materials. The molecules of azobenzene undergoing repetitive photoisomerization end up aligned predominantly perpendicular to the polarization where the absorption is minimized. This process can be induced by UV as well as by visible light of blue-green wavelengths, which is particularly important due to wide availability of high-power lasers for such wavelengths.

Due to thinness, the photoalignment layer itself does not affect the optical properties of the system; however, it proves adequate for inducing alignment of a few micrometers-thick layer of liquid crystal molecules deposited on it (Figure 3c). The thickness of the liquid crystal layer is critical for maintaining orientation patterns. Roughly, the orienting forces at the surface of the substrate can support orientation patterns modulated with a spatial period not less than half of the thickness of the liquid crystal layer. In the case of fabrication of liquid crystal polymer components, all different techniques that ensure thickness uniformity can be adapted for coating processes, including spin-coating and ink-jet printing. The fabrication process in the case of liquid crystal polymers is finished by fixing the structure by polymerization with unpolarized UV light.

The techniques for patterning light polarization are another key aspect of the technology. They include polarization holography[5], digital spatial light polarization modulation[6], and polarization lithography, wherein, for example, a linear-to-patterned polarization converter is used for printing required polarization patterns. A diffractive wave plate, generally, can serve as a polarization converter if it meets the half-wave retardation condition for linearly polarized light or a quarter-wave retardation condition for a circularly polarized recording light. The complete fabrication process, even for relatively large area components, such as a 6-in. diameter, takes only minutes. As important, the technology is adaptable for roll-to-roll production.

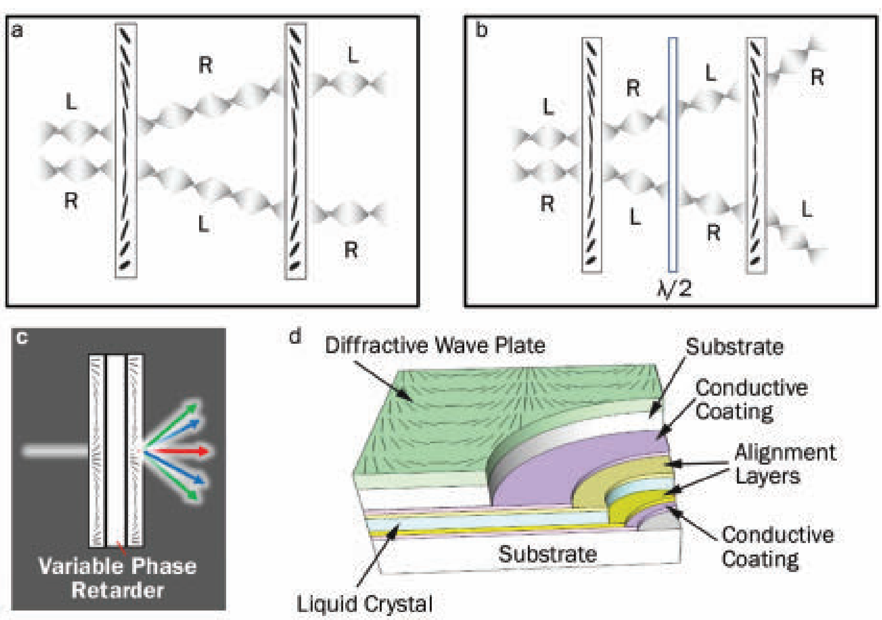

Figure 4. Switching of diffractive wave plate function using a variable phase retarder. Two identical diffractive wave plates in series with no intermediate phase retardation **(a)**. The pair of diffractive wave plates comprising an intermediate half-wave retarder **(b)**. Diffraction of a broadband beam by the system with spectrally modified zero-order transmission **(c)**. The integrated structure includes a variable phase retarder and a diffractive wave plate **(d)**.

Electro-optical systems

Liquid crystal cycloidal diffractive wave plates were originally proposed for developing polarizer-free displays. Application of an electric field erases the liquid crystal orientation pattern by switching it into a state of uniform alignment parallel to the field, thus eliminating the diffraction. A more versatile technique for controlling transmission of light through a diffractive wave plate is based on switching the polarization state of an incident polarized light beam by a variable phase retarder. A combination of diffractive wave plates may allow controlling unpolarized light (Figures 4a, 4b). Two identical diffractive wave plates arranged parallel to each other cancel the total diffraction due to switching of polarization handedness at the output of the first diffractive wave plate. In case of diffractive wave plate lenses, the combined system may have no focusing power.

Thus, the output beam may remain as collimated as the input one, and the lateral distance between the beams (Figure 4a) can be negligibly small due to the thinness of individual components. Switching polarization handedness by a variable phase retarder allows the beams to be further diffracted by the second cycloidal diffractive wave plate (Figure 4b). In the case of spectrally broadband beams, the half-wave retardation condition can be produced for a narrow range of wavelengths allowing some of the spectral components of the beam to transmit through the system (Figure 4c).

A useful combination is one that integrates a diffractive wave plate, such as a cycloidal diffractive wave plate with a liquid crystal variable phase retarder (Figure 4d). In this case, the phase retarder serves as a substrate for the liquid crystal polymer diffractive wave plate. The system is essentially an elementary stage that can be further integrated with additional such stages for all electronic multi-angle steering of a light beam and/or focusing the beam into multiple positions. The number of steering points, focal points, topological charges or beam shapes grows as 2N where N is the number of stages (Figure 5).

Note the lack of chromatic effects due to a relatively large f-number (~ 8) for an electrically switchable liquid crystal diffractive wave plate lens (Figure 5a). The first image is not visible, and the effect of the defocused light is revealed as a slight haze only.

Systems of variable phase retarders with liquid crystal polymer cycloidal diffractive wave plate overcoats allow various optical effects for an incident unpolarized white light (Figures 5b, 5c). Such devices act as a tunable filter or a broadband variable transmission system with no polarizers due to the variable phase retarder providing desired spectral modulation of the polarization state of the light at different voltage values.

An all-electronic beam steering device (Figure 5d) comprising multiple stages of liquid crystal polymer cycloidal diffractive wave plates and variable phase retarders is of particular interest due to large angle random access fast beam steering with no moving parts, and for large-area high-power laser beams. A generator of different topological charges for laser beams is just another example of numerous unique opportunities on the path to developing ultimately agile photonics systems (Figures 5e, 5f).

4G optics is of great value for infrared due to the transparency of liquid crystal materials for near-IR, mid-IR, and even longer IR wavelengths. Thus, any thin flat substrate for infrared optics is readily transformed into a thin-film lens, a prism or a beam shaper (Figure 6).

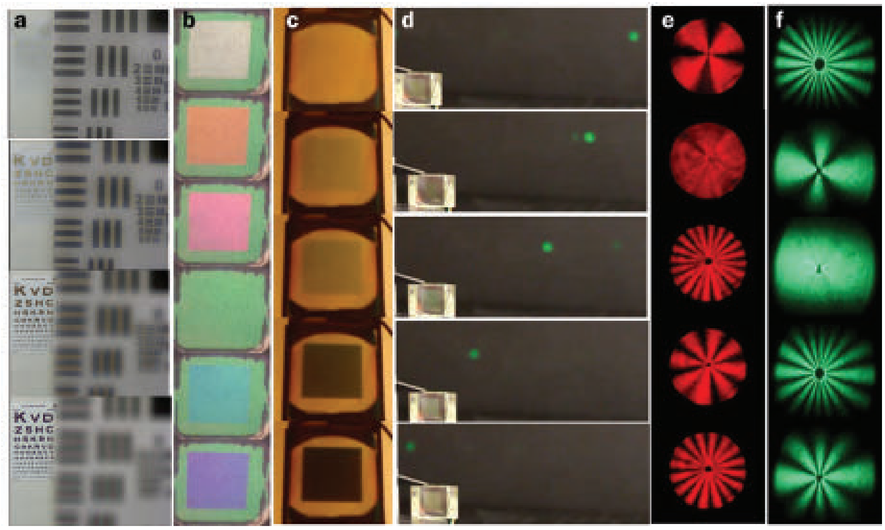

Figure 5. Switchable diffractive wave plate systems. Imaging with a diffractive wave plate lens switched between focusing and nonfocusing states **(a)**. An electrically tunable filter **(b)** and a broadband variable transmission system **(c)** based on a variable phase retarder with liquid crystal polymer cycloidal diffractive wave plate overcoats — images correspond to an unpolarized white light input at various voltage settings. An all-electronic beam pointing with three stages of cycloidal diffractive wave plates paired with variable phase retarders **(d).** Visible and infrared light of various topological charges produced by a system of liquid crystal polymer vector vortex wave plates controlled with variable phase retarders **(e, f)**.

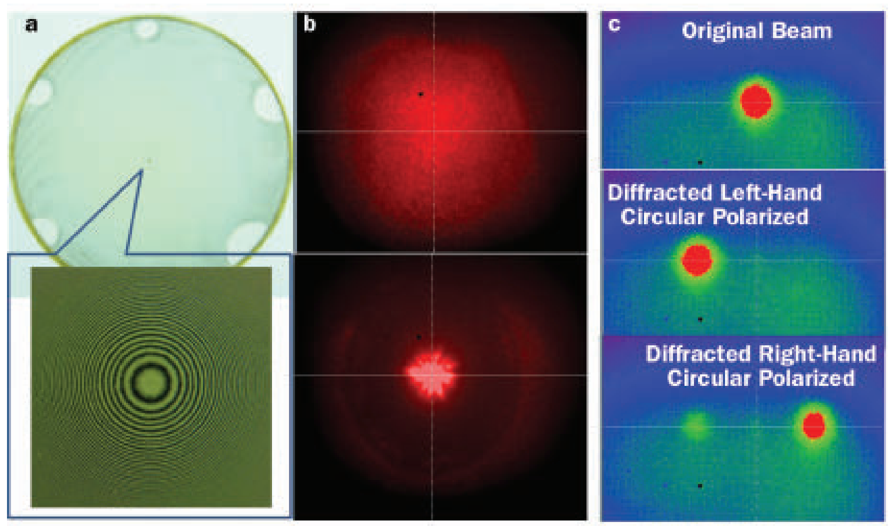

Figure 6. Diffractive wave plates for infrared, designed for and operating at 10.6-µm wavelength: A lens of f-number approximately 1 showing expanded view of center region between crossed linear polarizers **(a)**; defocusing and focusing of a laser beam when switching circular polarization handedness **(b)**; pointing a cycloidal diffractive wave plate when switching the sign of circular polarization of the input infrared beam **(c)**.

A glance into future

The word "liquid" in "liquid crystals" may create an impression of something fragile or unstable. The properties of liquid crystal polymers are nearly unaffected by temperature; due to the achievements of liquid crystal display industry, the operation range of many liquid crystals spans from −40 °C to over 100 °C. What is compromised at low temperatures is the switching speed.

Therefore, many applications are on the horizon, among the most exciting being the prospect of very large ultralight lenses for space telescopes, deep space communications, solar concentration and, here on Earth, ophthalmic lenses, including intraocular ones, with adaptive multipoint focusing capability. The 4G lenses and prisms may likely define the future of virtual reality and displays. For photonics, electrically switchable 4G optical components make feasible the fastest switchable lenses with the largest change in focusing power; all-electronic large-angle beam steering with thin and compact systems of low-power consumption; and generating beams of record-high topological charge for next-generation ultrafast optical communication, to name a few.

The seeds of those future applications are being planted now with concepts in development for polarization-insensitive imaging systems, with demonstrations of diffractive wave plates on flexible polymer films (Figure 7a); with technology tests for very large optics (Figure 7b); designs of large broadband imaging systems (Figure 7c); adapting material basis for using advanced production techniques such as inkjet printing; and laying grounds for fabrication of large space optics where it belongs: in space[7]!

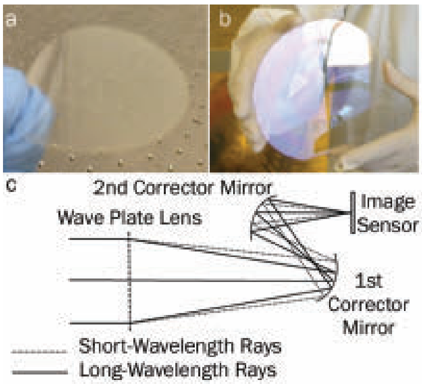

Figure 7. Preparing for the future: fabricating diffractive wave plates on plastic substrates **(a)**; testing large area component technology using a 6-in. diameter diffractive wave plate lens on glass substrate **(b)**; design concept of a space telescope of 20-m diameter with a primary diffractive wave plate lens — a system of small aspheric corrector mirrors with diffractive wave plate coatings allows diffraction-limited imaging in a wide spectral bandwidth **(c)**.

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CAOS Smart Camera Captures Targets in Extreme Contrast Scenarios

A new camera technology working in unison with CMOS sensors smartly extracts extreme scene contrast pixel light intensity information using time-frequency coding of selected agile pixels.

BY NABEEL A. RIZA
UNIVERSITY COLLEGE CORK

Imaging electromagnetic radiation is of fundamental importance to a number of fields, from medicine and the biological sciences, to security and defense. Often, demanding contrast imaging scenarios arise that call for a high instantaneous linear dynamic range (HDR) — in certain cases reaching 190 decibels (dB) — and the ability to achieve extremely low interpixel crosstalk. Other requirements include secure camera operation to curtail the misuse of raw data output; adaptable spectrum usage; high camera speed; and the ability to achieve pixel selection and time integration control as well as adaptive spatial resolution.

For applications such as security and surveillance, achieving true image scene pixel information, as opposed to slowly collecting high-resolution pixel information with absent scene zones, is vital.

This has led to an increasing demand for a smart camera that can achieve true vision for a pressing imaging scenario through highly directional and adaptive image pixel sifting for specific regions of interest with high-value targets. A survey of today's multipixel CMOS and CCD camera technologies reveals that photo detector array (PDA) sensors in general support around 60-dB-level linear dynamic ranges. Using custom design techniques, 120-dB higher dynamic ranges have been reached. These methods involve hardware modifications in the sensor chip aimed at increasing pixel size, often via a deeper quantum well and by controlling pixel integration time through the creation of pixel resets giving a piece-wise linear response or by using log or linear-log response CMOS sensor chip design technologies. Additionally, multi-image capture processing has been deployed where multiple images are captured at various optical filter attenuation- or integration-time settings, and software estimates the final HDR image.

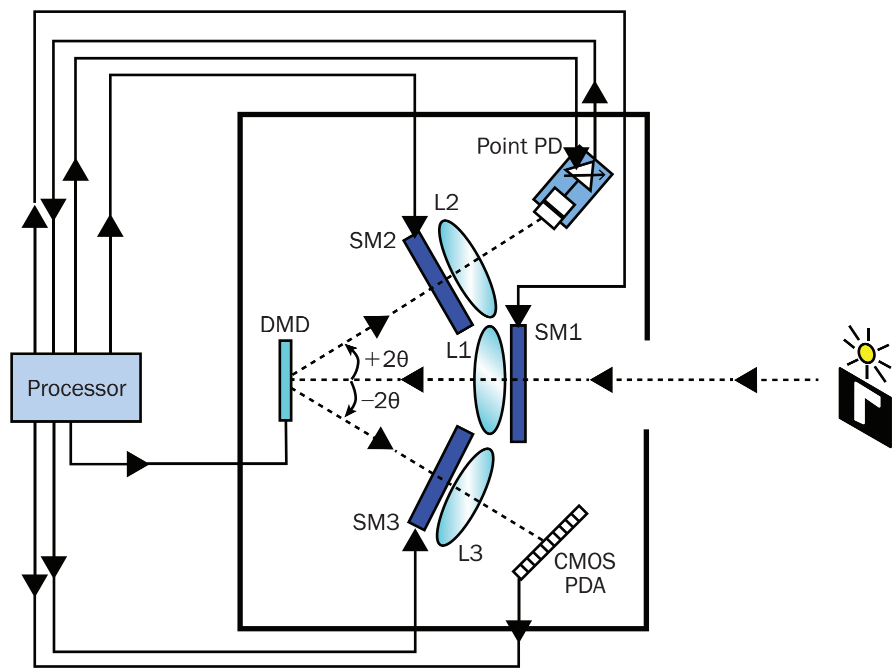

Figure 1. Shown is the CAOS smart camera design using a CMOS photodetector array (PDA) as the Hybrid (H) hardware element. L1,L2,L3: Lenses. SM1,SM2,SM3: Smart modules for light conditioning. PD: Photodetector with amplifier.

Fundamental limitations

Although these sensor technologies and techniques have their unique merits, they each have certain fundamental limitations. For instance, time-sequential multi-image capture processing works best when the camera is on a stationary tripod and the viewed scenes are static, or else ghosting appears. For the best results, a small camera aperture with a large depth of field is needed; otherwise, the multi-image processing technique produces image artefacts, particularly for scenes with a shallow depth of field.

Log CMOS sensors generally have limited color reproduction, sensitivity and signal-to-noise ratios (SNRs) at the lower light level regions of signal log response compression operation. This leads to a nonuniform imaging performance with stronger fixed pattern noise and longer response times. When compared to an all-linear response CMOS sensor that provides a linear mapping over the entire contrast range of the incident image spatial space,

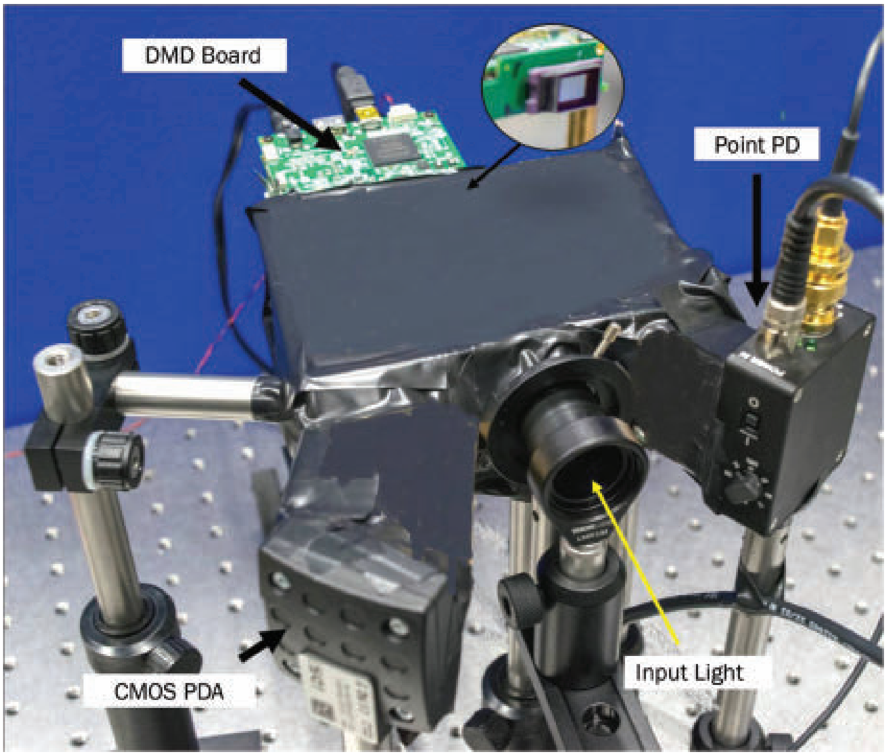

Figure 2. Laboratory prototype of the CAOS smart camera using a CMOS photodetector array (PDA) as the H (Hybrid) hardware element in the overall camera design.

the typical lin-log and piece-wise linear (or overall nonlinear response) CMOS sensors have lower SNRs. The log and lower slope response region of operation for detection of the brighter pixels in these two types of sensors produces reduced gray-scale levels due to voltage swing compression. This leads to lower contrast images and limited color reproduction. Therefore, varying image quality across the detected image zone depends on which response curve — linear or log or high slope or low slope — is used in sensing the light irradiance levels for the sensor pixels. To put things in context, see sidebar, "CMOS Sensor Dynamic Range Ratings."

For the reasons above, there remains a challenge for cameras to reach extreme all-linear, instantaneous dynamic ranges approaching 190 dB with multicolor smart capture of targets of interest within extreme contrast images. This is a requirement in diverse scenarios from natural night scene settings to complex biological materials, to hostile terrains such as deserts, snow and outer space. One can also think of this challenge as enabling the smart and intrinsically secure capture of spectral and spatial signatures of targets of interest to empower higher reliability pattern recognition and classification of sought-after high-value targets observed by the camera.

Inspiration from multiple access RF signal wireless

A new type of camera technology — the coded access optical sensor (CAOS) smart camera — addresses these shortcomings, working in unison with CMOS, CCD and focal plane array (FPA) camera sensors to extract previously unseen images.

The premise behind CAOS borrows from the advanced device and design radio frequency (RF) multiple access wireless network technologies that can detect very weak information signals at specific radio frequencies. With CAOS, agile pixels of light are captured from the target region of interest of an incident image in the camera and are rapidly encoded like RF signals. This encoding is done in the time-frequency domain using an optical array device such as a multipixel spatial light modulator. The encoded optical signals are then simultaneously detected by one point optical-to-RF detector/antenna. The output of this optical detector undergoes RF decoding via electronic wireless-style processing to simultaneously recover the light levels for all the agile pixels in the image.

On the contrary, CCD/CMOS/FPA cameras simply collect light from an image, so that photons are collected in the sensor buckets or wells and are transferred as electronic charge values. There is no deployment of spatially selective time-frequency content of the photons. CAOS, therefore, represents a seismic shift in imager design, made possible by modern-day advances in wireless and wired devices in the optical and electronic domains using extremely large time-bandwidth product time-frequency domain signal processing. Notably, the spatial size, location and shape of each agile pixel in the smart pixel set that is sampling the incident image region of interest in the CAOS camera is controlled using prior or real-time image application intelligence. This data gathered by the CAOS-mode imaging works in unison with other classic multipixel sensors and computational imaging methods operating within the CAOS hardware platform.

The CAOS smart camera forms a hybrid imaging platform where the agile pixel acquires a kind of space-time-frequency representation. Limited dynamic range image intelligence, for example, can be quickly gathered using classic compressive sensing. This computational technique is based on image spatial projections data combined with numerical optimization

CMOS Sensor Dynamic Range Ratings

State-of-the-art performance numbers available in 2016 by leading commercial CMOS sensor vendors are as follows: Omnivision CMOS sensor linear instantaneous DR = 94 dB and a dual exposure DR = 120 dB; New Imaging Technologies (NIT) log CMOS sensor with log response DR = 140 dB; Photonfocus LinLog CMOS sensor with linear operation DR = 60 dB and LOG response DR from 60 dB to 120 dB; Melexis-Cypress-Sensata Autobrite CMOS sensor with piece-wise linear DR = 150 dB.

Images courtesy of Nabeel A. Riza.

processing; it also uses the same CAOS hardware platform. Other linear spatial transform computational methods can also be deployed within the CAOS smart camera by appropriately programming spatial masks, such as 2D spatial codes, on the spatial light modulator. These space-focused, spatial code-based methods are unlike the CAOS-mode that, instead, engages time-frequency coding of agile pixels in the image space.

Summarizing, the CAOS smart camera is, intrinsically, a hybrid camera that works together with the CMOS/CCD/FPA sensor and computational imaging methods to extract smarter image information — where smarter refers to better spatial and spectral selectivity, faster speed, higher targeted pixel dynamic range and larger or more diverse spectral bands. The smarter concept extends to more optimized agile pixel shape, location, size, time duration, plus better camera security, and higher robustness to bright source blinding of scenes as well as improved fault tolerance through the hybrid dual channel camera design.

Incorporating digital micromirror device technology

A version of the CAOS smart camera called the CAOS-CMOS camera (Figures 1, 2) has been built and demonstrated[1] using Texas Instrument's Digital Micromirror Device (DMD) spatial light modulator as the CAOS-mode time-frequency agile pixel encoder. To start the imaging operation, the DMD is programmed to direct the incident light to the camera arm with the CMOS photodetector array to gather initial scene intelligence information that is used to program the DMD in the CAOS-mode to seek out the desired pixel high dynamic range regions of the scene. This visible band camera demonstrated a 31-dB improvement in camera linear dynamic range over a typical commercial 51-dB linear dynamic range CMOS camera when subjected to three test targets that created a scene with extreme brightness as well as extreme contrast (>82 dB) high dynamic range conditions.

These controlled experimental hardware settings were deliberately chosen to allow the research team to clearly demonstrate the features of the smart design CAOS camera, such as when the limited linear dynamic range and noise floor of a deployed CMOS sensor cannot allow imaging beyond a certain scene contrast level. When this occurs, the CMOS sensor providing limited dynamic range image is used to guide the CAOS-mode of the smart camera to successfully see the high dynamic range regions of the scene that were unseen by the CMOS sensor. Therefore the 82-dB dynamic range for the CAOS camera was set by the highest contrast scene that could be produced in the lab environment for this first-time experiment.

The CAOS camera in the first incoherent light imaging experiment was subjected to a sample target on the left edge of the image view that is extremely bright (Figure 3). The two targets on the right of the bright target were extremely dim targets, near the noise floor of the demonstrated camera. Yet the CAOS smart camera was able to correctly see all three targets without any attenuation of the incoming light from the imaged scene (Figure 3b).

Note that any attenuation of the light to eliminate saturation of the CMOS sensor sent the weak light image content into the noise floor of the CMOS sensor, making it impossible to see the weak light targets. In a second CAOS camera experiment, the team used a visible laser beam with a 10,000,000:1 gradual linear optical attenuation control to generate a 140-dB extreme linear dynamic range image pixel contrast target incident on the camera imaging plane. Using this new extreme contrast test target and improved electronic signal capture and digital signal processing methods, the CAOS camera was able to successfully detect the target over a 136-dB camera linear dynamic range, showing a 40-dB advance in instantaneous

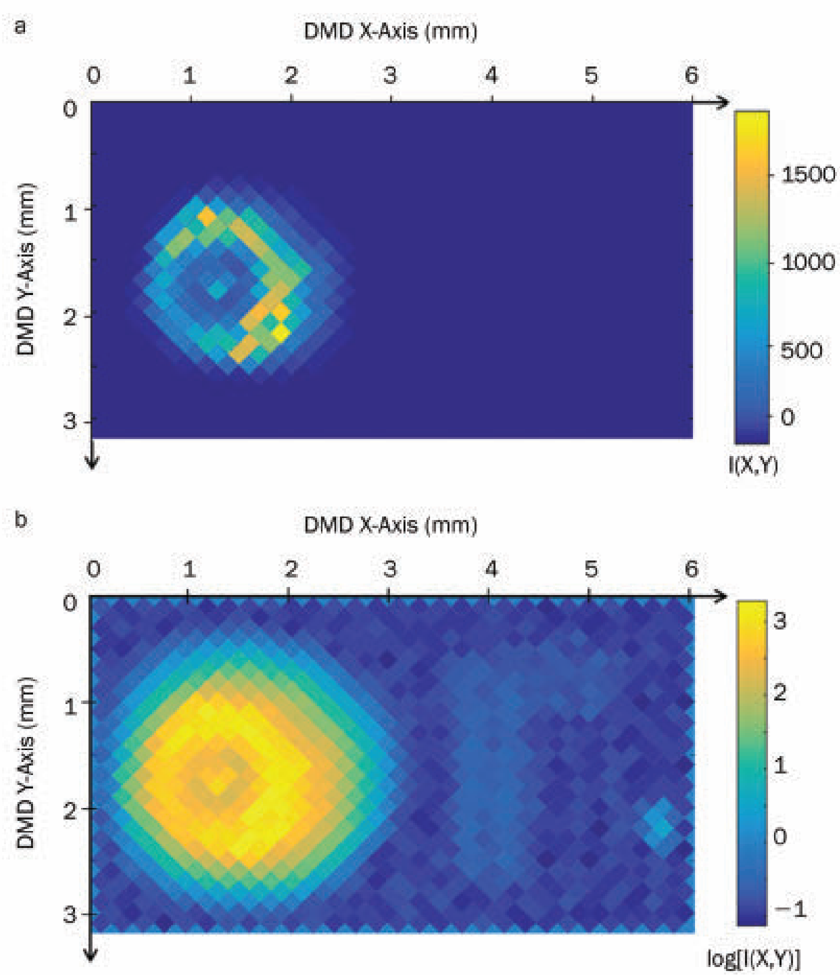

Figure 3. An 82-dB high instantaneous linear dynamic range-scaled irradiance map of the CAOS-mode-acquired image in a linear scale (two faint targets not seen) **(a)** and logarithmic scale (all three targets seen) **(b)**.

linear dynamic range when compared to the 2016 best state-of-the-art 94-dB linear dynamic range CMOS sensor. The camera also demonstrated dual-band imaging with better than −60 dB interband crosstalk when using a visible shortwave-IR (SWIR) test target made up of a 2 × 2 array of three visible and one SWIR LED[2] (Figure 4).

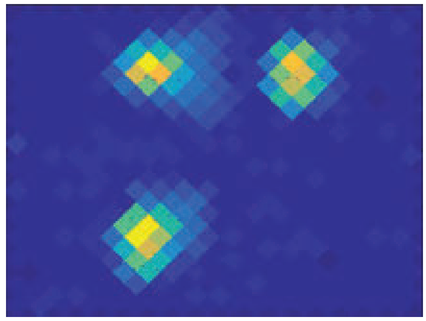

Figure 4. The visible band image captured by the dual-band CAOS camera using three visible LEDs and one shortwave-IR (SWIR) LED target scene with LEDs arranged in a 2 × 2 formation. The SWIR LED, as expected, is missing from the camera visible channel created image.

Multiple time-frequency coding modes

Complete electronic programmability allows the CAOS camera to perform as a smart spatial sampler of irradiance maps and also for electronic processing for high-performance encoding and decoding of the agile pixel irradiance map. Much like wireless and wired communication networks, the agile pixel can operate in different programmable time-frequency coding modes such as code division multiple access (CDMA), frequency division multiple access (FDMA) and time division multiple access (TDMA)[3]. CDMA and FDMA will produce spread spectrum radio frequency signals from the point photodetector (PD) while TDMA is the staring-mode operation of the CAOS imager, one agile pixel at a time producing a direct current signal.

For full impact, agile pixel codes should include CDMA, FDMA or mixed CDMA-FDMA codes that produce not only PD signals on a broad radio frequency spectrum but also engage sophisticated analog, digital and hybrid information coding techniques to provide isolation and robustness among time-frequency codes used for optical array device pixel coding. The camera also uses advanced coherent electronic signal processing, such as digital signal processing (DSP) implemented time-frequency transforms to produce noise suppression. DSP also furthers signal gain for the point PD signal leading to extreme contrast optical irradiance agile pixel decoding. Do note that agile pixel space-time-frequency coding creates a highly secure image that only the authorized recipient can see. In addition, the CAOS camera inherently makes the best and most efficient use of the relatively large full quantum well capacity of the point detector. Such is not the case in prior-art PD-array-based cameras where an incident bright extreme contrast image in most designs causes the many high-spatial-resolution smaller capacity quantum wells to be partially filled while many other quantum wells in the PD array are over-filled and create spillover to nearby wells, thus causing pixel saturation and interpixel crosstalk noise. In short, CAOS is also quantum well capacity efficient.

The speed of image acquisition by the CAOS-mode is limited mainly by the optical array device/spatial light modulator speed. Currently, the Texas Instruments' DMD technology has a 32-KHz frame refresh rate giving a code bit time of 31.25 microseconds. When encoding the agile pixels with CDMA/FDMA techniques, instantaneous simultaneous capture and processing of all agile pixels is implemented to enable faster image generation. A basic design example using a 14-bit CDMA code per agile pixel used for 1000 simultaneous agile pixels (called a CAOS frame) with 10 code lengths oversampled PD integration time of 4.375 ms plus 10 ms for data processing creates a 14.375-ms image frame time or near 70 frames/s output indicating that the CAOS camera can be currently designed to register real-time 60 CAOS frames/s video.

Furthermore, the camera can be designed for faster than real-time video rates using customized agile pixels, codes and signal processing hardware. Imaging resolution of the CAOS camera depends on the size of the agile pixel deployed and can be as small as the SLM pixel — for example, the size of the single micromirror in the DMD, which is near seven microns in scale. The number of simultaneous agile pixels, crosstalk, dynamic range, signal-to-noise ratio and speed are interrelated parameters; the imaging platform needs to be carefully optimized for a particular smart imaging scenario keeping in mind that CAOS works with — and not in competition with — existing PDA sensors within the CAOS smart camera unit.

Today, the smart camera platform is undergoing research and technology development with design optimizations for specific commercial applications[4], opening up a world of the as yet unseen as diverse as automobile machine vision systems for enhanced driver and road safety; security and surveillance; and inspection of medical, food and industrial specimens and products to foster a safer, longer and better human life.

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Optical Metrology Techniques Harness Structured Light Beams

This approach holds promise for advancing laser remote sensing, fluid dynamics and profilometry.

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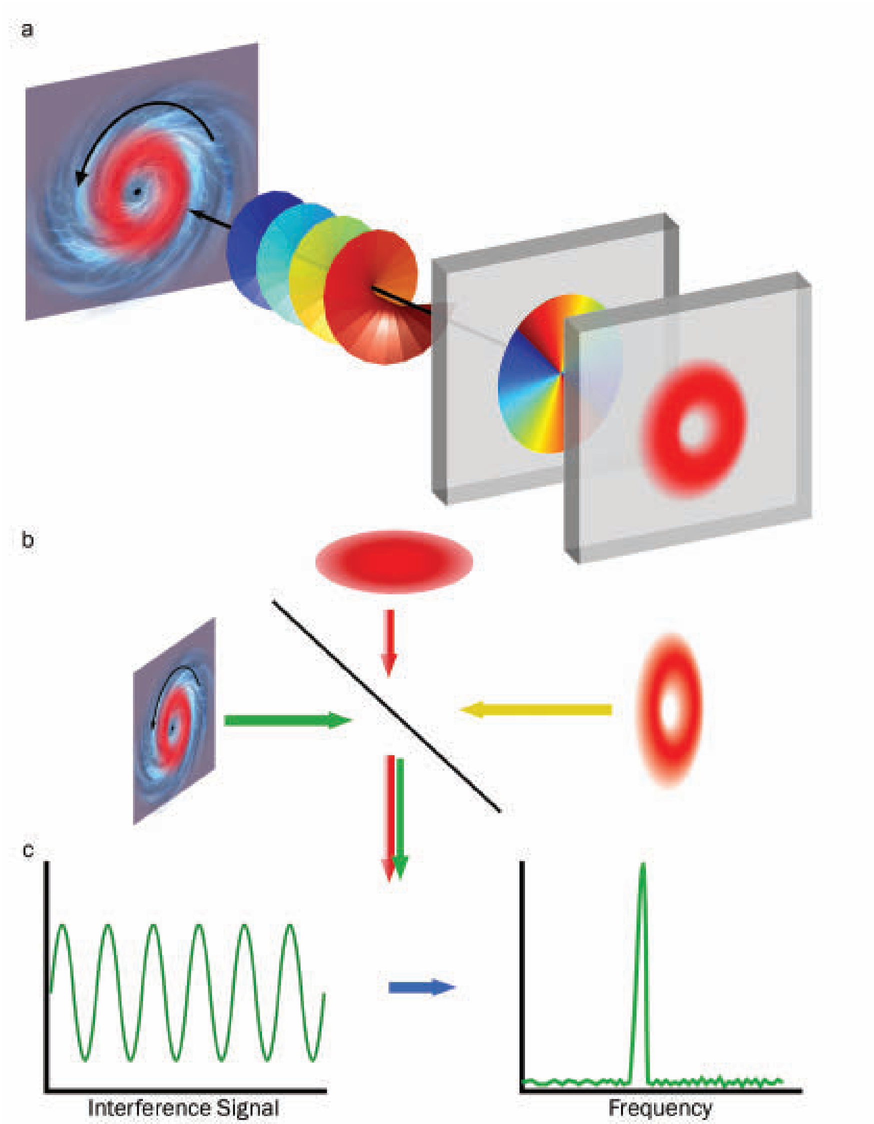

Figure 1. The angular velocity of targets describing a circular motion can be measured directly with a vortex beam **(a)**. The backscattered signal is interfered with a reference signal (a Gaussian beam, for example) to extract the desired information **(b)**. The interference signal is Fourier transformed to obtain a frequency peak that is directly related to the target's velocity **(c)**.

As a result of technological advances in recent years, researchers have at their disposal devices capable of tailoring — with almost unlimited freedom — the shape of beams of light. Computer-controlled spatial light modulators (SLMs) and digital micromirror devices (DMDs) are some of the most popular devices with such capabilities. They are invaluable tools in the generation of optical beams with a transverse varying phase structure, otherwise known as structured, sculpted or engineered fields. Two examples of these structured fields are Laguerre-Gauss and Hermite-Gauss beams.

Structured beams are routinely used in many different fields of science and technology[1,2]. In optical microscopy, optical vortices are a convenient way to shape the light beams as required by some super-resolution techniques capable of reaching resolutions far beyond the diffraction limit[3]. In the field of optical tweezers, the great diversity of existing structured fields have made it possible not only to trap, but also to guide micron-sized particles along various 2D and 3D trajectories[4]. The use of optical beams with different spatial shapes as information carriers provides a way to explore new avenues for increasing the bit rate of optical communications systems[5,6]. The potential advantages of using beams with a tailored complex wavefront for measuring velocities and fluid vorticity have broad applications in laser remote sensing — to measure velocities and fluid vorticity — and in the high-resolution profilometry — to measure surface profiles.

The Doppler effect, the frequency shift that acquires a light beam when scattered back from a moving object, is a well-known technique used to monitor the position and speed of moving targets. The Doppler effect observed when the illumination source is a Gaussian beam with nearly a flat wavefront provides information on the velocity of the target along the direction parallel to the beam's propagation axis — that is, the direction of the energy flow (Poynting vector) of the optical beam.

Some approaches to overcome this drawback have been developed, such as considering multiple Gaussian beams propagating along different directions to measure the corresponding velocity components. In general, these schemes require the use of several light sources, or fast mechanical realignment of the direction of propagation of the laser beam, which makes its implementation cumbersome.

On the contrary, when using structured light as the illumination source, the light reflected from the target can also carry information about the velocity of the target in the transverse plane. This is due to the fact that tailoring phase gradients in the optical beam corresponds to the additional introduction of flows of energy perpendicular to the direction of propagation of the optical beam[7].

That information is reflected in the appearance of what can be called a transverse Doppler frequency shift associated with the presence of a transverse component of the Poynting vector[8], or in other cases, the change of position of the target in the plane perpendicular to the propagation axis of the illuminating beam.

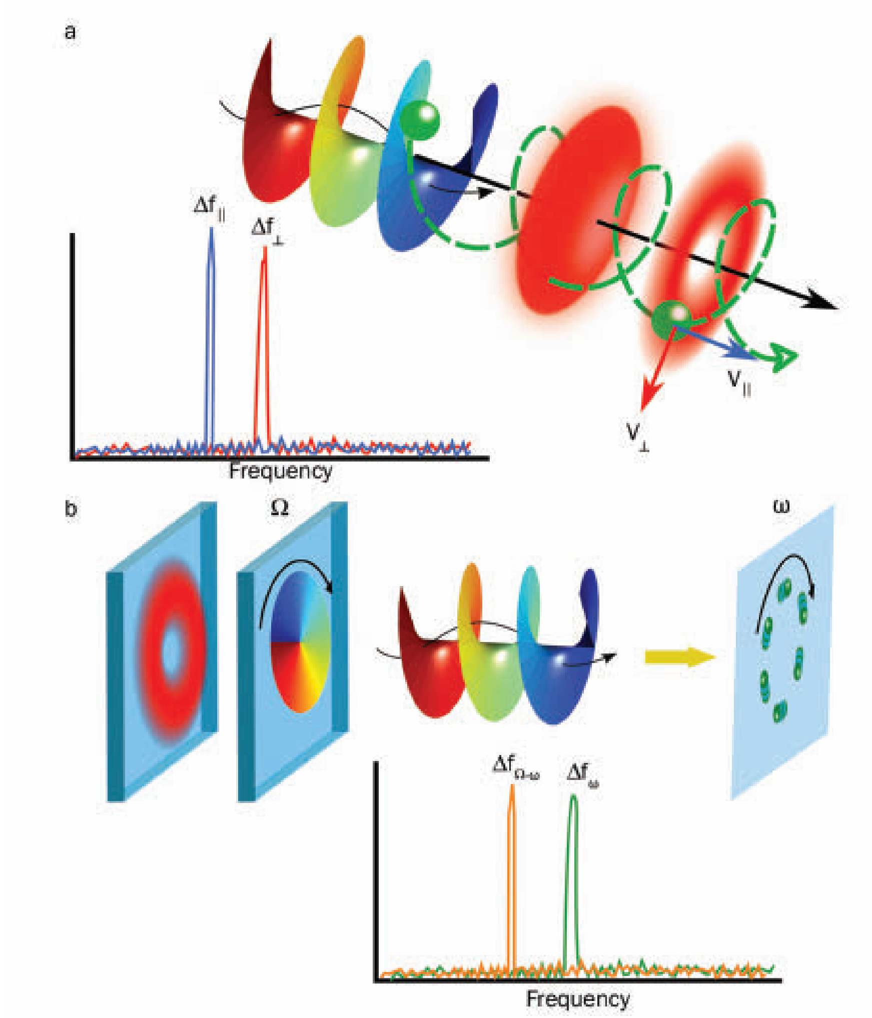

Figure 2. A particle moving in a 3D helical motion can be interrogated simultaneously with a vortex and a Gaussian beam **(a)**. As a consequence, a longitudinal and a transverse Doppler shift will appear. A rotating phase profile illuminating a rotating particle will upshift or downshift the Doppler frequency corresponding to the particle's motion, which can be used to determine its direction of motion **(b)**.

Measuring the interference signal

The relationship between this transverse Doppler shift and the transverse component of the velocity allows the unique determination of the full value of the velocity. In principle, the illumination beam can take any structured phase profile; however, information about the type of movement can help to tailor the most appropriate phase profile[7,9].

For instance, for targets rotating at constant angular velocity, azimuthally varying phases such as those present in Laguerre-Gaussian vortex beams adapt perfectly to their motion (Figure 1a). To extract the desired information, the backscattered light is made to interfere with a reference beam (Figure 1b). The intensity of the interference signal is measured and Fourier transformed to obtain a frequency peak (Figure 1c) from which the transverse component of the velocity can be easily obtained.

One can envision complex systems based on structured light beams capable of measuring simultaneously all components of velocity, longitudinal ($\nu\|$) and transverse ($\nu\perp$). The basic idea has been demonstrated recently in a proof of concept experiment[10]. Here, particles in a 3D helical motion were illuminated sequentially with a Gaussian and a vortex beam (Figure 2a) to determine the full velocity vector. In this scheme, the Gaussian beam is used to measure the longitudinal component and the vortex beam is used to measure the transverse component of the velocity, in this case the angular velocity. Moreover, spatial light modulators can also be used to actively change from one hologram to another, a feature that can be exploited to determine the direction of motion. Currently this measurement is done through the use of acousto-optic modulators, electro-optic frequency shifters or rotating waveplates, which are commonly restricted to particular beam sizes and specific frequencies. Here, the concept is to actively change the holograms displayed on the spatial light modulator to upshift or downshift the Doppler frequency generated by the moving target[11]. The direction of motion would be determined after comparison of both frequencies, since a downshift will be observed if the target moves in the same direction of the dynamic phase (Figure 2b).

Images courtesy of **Carmelo Rosales Guzmán**.

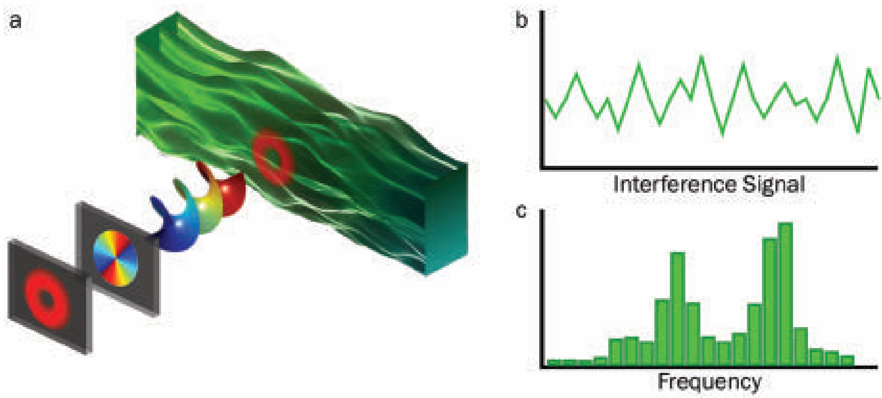

Figure 3. Schematic representation of a vortex beam illuminating a fluid to obtain information of its vorticity **(a)**, the interference signal of the backscattered light and a reference beam **(b),** and the frequency spectrum from which the vorticity can be measured **(c)**.

Measurement of fluid vorticity

The method described above could impact other areas of research such as in fluid dynamics, where it offers the possibility to measure in a direct way the vorticity in fluids[12]. Vorticity is a vector field that contains information about the tendency of a fluid to rotate. Well-established techniques for estimating the vorticity are based on computing the curl of the velocity vector. In this approach, uncertainty errors on the velocity affects directly the accuracy of the vorticity. Furthermore, determining the full velocity vector represents a cumbersome task. In contrast, when a certain region of the fluid is illuminated with a vortex beam, the backscattered light generates a spectrum of frequency shifts that contains information about the velocity at every point along the ring of light (Figure 3a). Again, to obtain the desired information, the backscattered light is made to interfere with a reference beam and the interference signal is measured with a photodetector. The measured signal in this case is a mixture of different frequencies (Figure 3b). Hence, its Fourier transform forms a histogram of Doppler frequency components (Figure 3c), whose centroid is directly related to the vorticity of the fluid.

Accurate measurement of a submicron surface's profile

The thickness of very thin layers is commonly measured using a common path interferometer[13,14]. In this configuration, the sample is placed over an engineered ridge with specific width and height. The width is such that half of the illuminating beam straddles the ridge and the other half its base. As a result, two beams traveling along the same path produce a stable interference pattern in the far field, which is due to the difference in height of the surface. The on-axis intensity varies sinusoidally with the height of the ridge, reaching maximum sensitivity for heights equal to 1/8 of the illuminating wavelength (λ). This forces the height of the ridge to be an integer multiple of λ/8, known as the quadrature condition. The sample thickness is determined from the intensity changes it introduces when placed over the ridge (Figure 4a). Unfortunately, the need to fulfill the quadrature condition by constructing a physical ridge limits the use of this technique to certain wavelengths. A method in which the quadrature condition is not imposed by a ridge but rather is passed on to the signal reflected from the sample was recently proposed[15]. The main idea consists in projecting the reflected light onto appropriately tailored structured light in which the quadrature condition is encoded (Figure 4b). Such projection can be efficiently made with SLMs.

DMDs and diffractive optics hold promise

Structured light beams are invaluable tools that allow the development of new solutions and applications in a great vari-

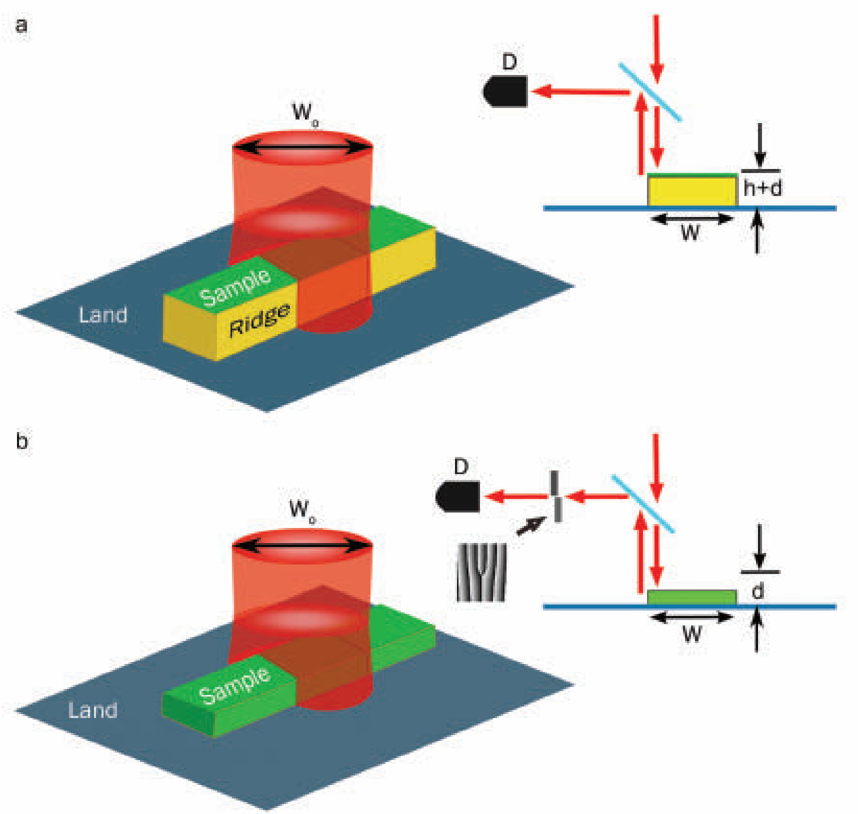

Figure 4. Implementation of the quadrature condition through the construction of a physical ridge **(a)** by means of projecting the light reflected directly from the sample onto a specifically tailored beam **(b)**.

ety of fields such as laser remote sensing, optical communications and superresolution microscopy, to mention just a few.

Here the authors presented novel techniques that could potentially impact the fields of laser remote sensing, fluid dynamics and profilometry. Most of the success of using structured light beams comes from the development of spatial light modulators that have paved the way toward the generation of almost arbitrary structured light beams. However, at present day, the core technology of a spatial light modulator, the liquid crystal, severely limits the use of novel ideas in solutions outside of the lab. For example, their refresh rate is very low (~60 Hz), they are sensitive to polarization, their damage threshold power is low and the wavelength at which they operate can be an issue.

An alternative to the spatial light modulator is the digital micromirror device technology. A DMD consists of an ensemble of several hundred thousand microscopic mirrors, arranged in a rectangular fashion, and integrated in a chip. Each mirror of this ensemble can be rotated digitally to an on or off state, −12° or +12°, respectively. DMDs are cheaper, polarization insensitive and can reach a refresh rate grater that 4 KHz. DMDs are becoming popular and have already demonstrated their potentiality in generating structured light beams. Another option is the use of diffractive optical elements, which can be cheaper and mass produced. The biggest challenge is how to bring these ideas from the lab to real applications and how to combine with current systems to broaden their range of applications.

Meet the authors

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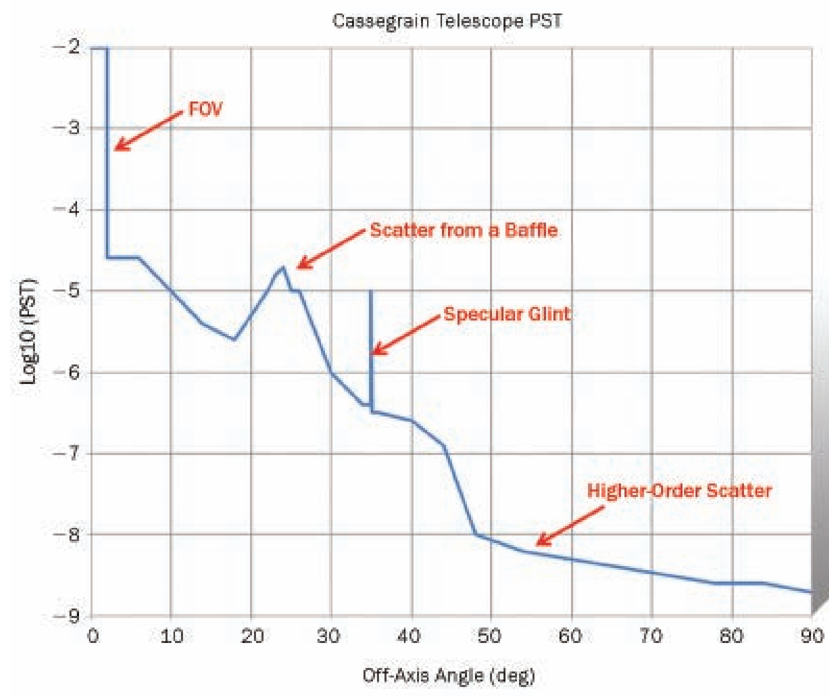
Optical System Optimization
Analyzing the Effects of Stray Light

Stray light can impede the performance of any optical system. With a deeper understanding of stray light, and the right tools, optical engineers can predict and compensate for its effects in order to improve quality.

Richard Pfisterer
Photon Engineering LLC

Electrical engineers are very familiar with the effects of shot noise, thermal noise, flicker noise and crosstalk, and recognize how these effects can reduce the signal-to-noise ratio (SNR) in their systems.

Most optical engineers, on the other hand, frequently fail to appreciate the effects of optical noise in their systems, leading to non-optimal performance. This can be particularly significant in astronomical observations, low-light level signal detection and medical imagery, where every signal photon counts. Furthermore, optical engineers may not understand how stray light propagates through their systems or how optical surfaces and painted baffles scatter light. Fortunately, the field of stray light analysis is mature, the software is capable and our understanding of scatter processes continues to grow. Today, the tools and understanding needed to predict stray light levels, identify sources of stray light and confidently recommend design/implementation changes to improve the quality of the optical instrument exist.



A plot of the point source transmittance (PST) can graphically indicate scatter from internal structures, specular glints and higher-order scatter effects.

Sources of optical noise

Diffraction is considered a stray light mechanism because it produces a distribution of energy that extends well beyond what would be expected from geometrical considerations; for example, a circular aperture, when illuminated by coherent light, produces an Airy distribution that can cover the area of the detector. Since diffraction irradiance is proportional to the wavelength of light, it is rarely a significant stray light contributor in the UV and visible, but can become very significant in the longwave IR, dominating the effects of optical surface scatter.

Ghost images can result when light incident on a surface is divided into reflected and transmitted components and both continue to propagate; ultimately some portion of the light reaches the image plane. Since ghost images are specular, they can retain coherence and polarization properties of the incident light; it is not uncommon in high-powered laser systems for ghost images to sum coherently to produce high fluence levels capable of shattering an optical element.

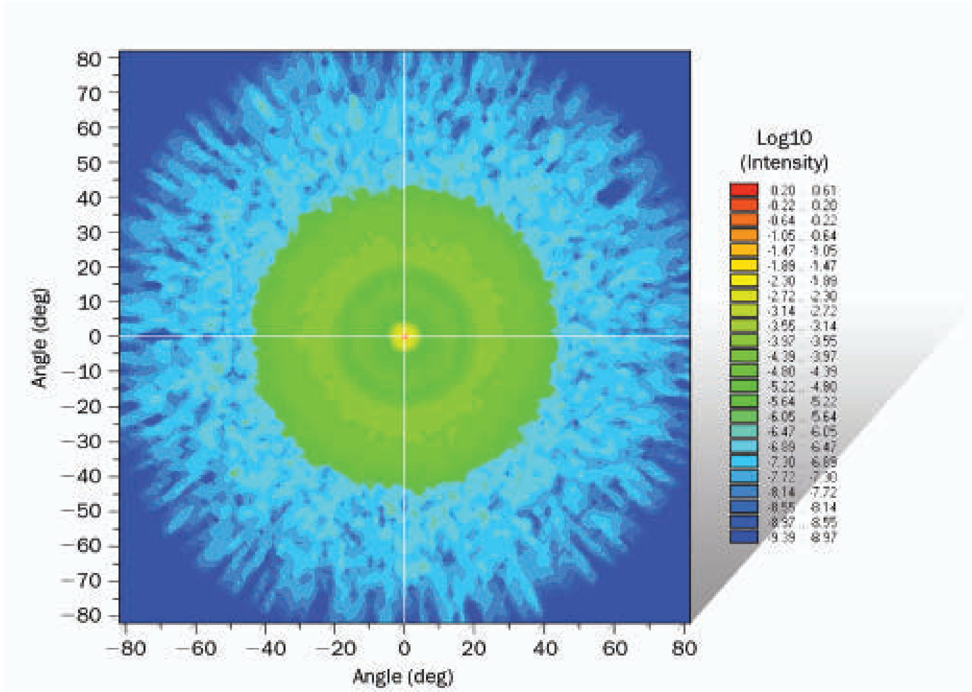
Diamond-turned surfaces that are not post-polished typically contain residual periodic grooves left over from the turning process that can act like a diffraction grating. Incident light is diffracted into multiple unintended orders that propagate through the system.

The grinding and polishing processes leave a residual microroughness on an optical surface as well as subsurface damage. A small amount of the light incident on an optical surface is scattered into an angular (typically Lorentzian) distribution centered on specular direction and continues to propagate. At the image plane, the scatter distributions from all of the surfaces add incoherently to create a composite scatter field.

Dust, with its ability to scatter light, is ubiquitous in virtually all environments. The exact distribution of scattered light is a function of the wavelength of light, the complex refractive indices of the particulates and their size population on the surface. While totally unrelated mathematically to surface roughness, particulate scatter distribution is also manifest as a Lorentzian function.

Recognizing the very wide variation in composition, it is not surprising that paints and surface treatments — such as anodization or texturing — can produce very diverse distributions of scattered light. Analysts classify paints and surface treatments into four broad categories: diffuse (matte) finishes, specular (glossy) finishes, hybrid finishes that can vary from diffuse to specular depending upon the angle of incidence of light onto the surface, and "other," which includes carbon nanotube technology, the "blackest" materials that we know of. Paints and surface treatments can be very effective at controlling stray light but they can also cause unwanted side effects such as outgassing and particulate generation (flaking).

All structures radiate thermal energy according to their temperatures and emissivities. However, the magnitude of this thermal radiation is usually significant only in the longwave IR (8 to 12 µm) where the peak of the blackbody curve corresponds to room temperature. Unfortunately this is exactly where many types of instruments operate, so designers of thermal IR seekers, medical imaging devices — for breast and skin cancer diagnoses, for example — and other thermal detection systems must consider how the thermal self-emission of the instrumentation can degrade the contrast of the thermal signal they are trying to image.



A plot showing the percentage stay light calculation as an intensity plot in object space.

Stray light metrics

Just as a lens designer might use encircled energy or root-mean-square (rms) wavefront error to characterize the performance of an optical system, stray light analysts use several different metrics for describing the stray light characteristics of an optomechanical system.

Point source transmittance (PST) is the oldest stray light metric dating back to the 1970s and is conceptually very simple: Following from linear system theory, PST is simply the ratio of some measure of energy on the detector to the energy incident into the system, as a function of angle of incidence. This very general definition is frequently made more specific by expressing the PST as the ratio of the irradiance incident on the detector to the irradiance incident on the entrance aperture. Regardless of the definition, the PST has value as a diagnostic tool — by identifying at which angle(s) stray light effects become significant, which leads to the recognition of the responsible stray light mechanism(s) — as well as a comparative tool. By comparing the PSTs of two different systems, the analyst can immediately quantify how the hardware differences affect the stray light characteristics.

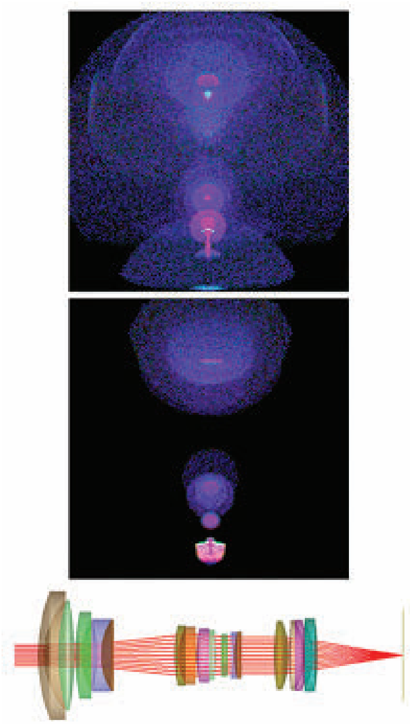
"Percent stray light" captures the stray light characteristics of a system as a single number; it is the ratio of the optical noise power from every conceivable stray mechanism to the signal power from the intended target. In other words, it is essentially the reciprocal of SNR expressed as a percentage. In a well-baffled system, the percent stray light is typically on the order of a few percent. This particular stray light metric is commonly used in applications such as orbiting Earth-resource satellite cameras where the field-of-view is very small and the Earth as a stray light source subtends a large solid angle.

Ghost image calculations are very often used in the development of photographic and cellphone lenses to identify "sensitive" surfaces that can cause artifacts when illuminated under specific conditions. The calculation, while ray intensive, is straightforward and can include the effects of source spectral bandwidth, coating sensitivity to variations in angles of incidence on each surface, material absorption, detector responsivity and so on.

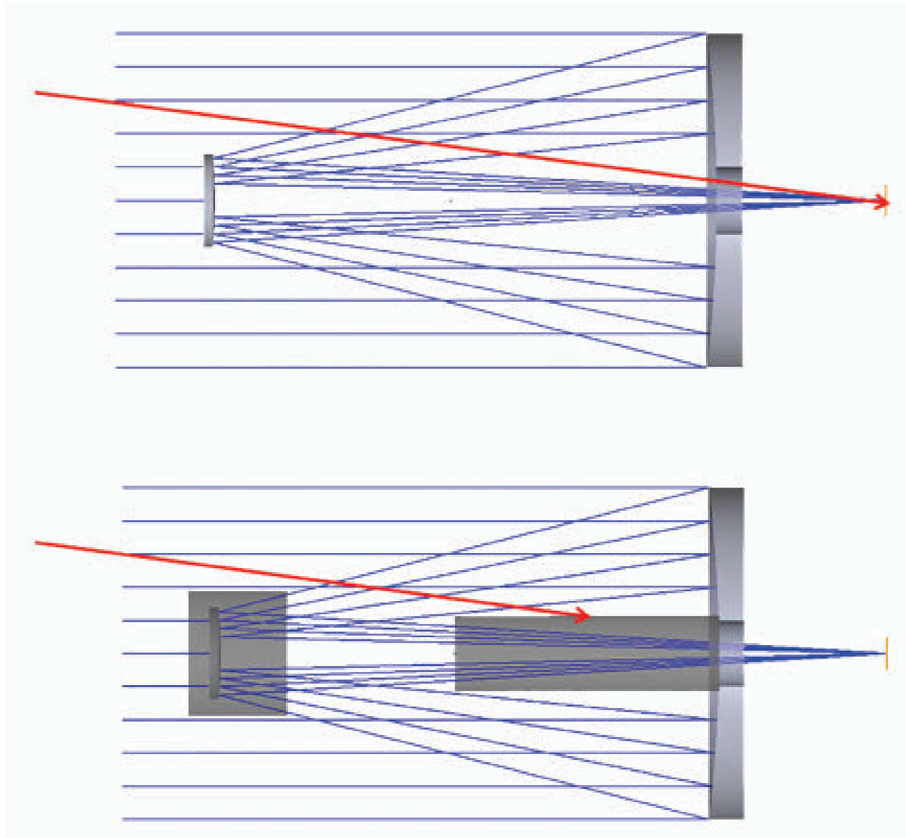
In longwave-IR imagery applications, the thermal self-emission is calculated using a clever approach developed in the 1980s: Rays traced backward from the detector determine the geometrical configuration factor (GCF) — the projected solid angle divided by pi — for each component. Once the GCF is known, standard radiometric equations can be used to determine the thermal self-emission contributions usually reported in watts or photons/area/sec. The tremendous advantage of this technique relative to previous ones is that the accuracy of the calculation is determined by the number of rays traced, which is decided by the analyst.

Baffles design

Baffles, stops and vanes all work to control the propagation of unwanted light through an optical system. Most optical designers are familiar with field stops to block out-of-field stray light; however these are not always effective in reflective systems where the optical path "folds" onto



The morphology of a ghost can change dramatically over the field of view of a system. Upper plot: polychromatic ghost image at 41 degrees off-axis, Middle plot: polychromatic ghost image at 47 degrees off-axis, Lower plot: Axial ray trace of camera optics.



Sometimes light does not propagate the way the lens designer intended. Baffles can prevent unwanted light from reaching the detector.

itself. Lyot stops are stops placed in a conjugate plane to the entrance pupil and are used primarily to block diffraction effects originating from the edge of the pupil.

Baffles tubes containing vanes are commonly used to shadow an optical system from direct illumination at high off-axis angles and to control the number of scatter events prior to light reaching the optical system. (Since scatter is an inefficient method of energy propagation, sometimes it only takes a few interactions of stray light with vanes along a baffle in order to adequately suppress the stray light.) They are also used in dewars and other detector assemblies to limit illumination of the detector from stray light.

Not all vanes are overt. Sometimes a very shallow vane is used to suppress a grazing incidence reflection off of the side of a telescope tube.

Rarely is there a single best or optimum approach to baffle implementation in a real-world system. Baffles add weight and cost to a system, and stray light control is simply one of many considerations when building hardware.

Capabilities of modern analysis software

Modern stray light analysis software has benefited from almost 40 years of continual development and comparisons with actual hardware, and has therefore matured greatly. In many ways, the software is very much like commercial CAD software in that it can define and subsequently edit complex geometries. Unlike lens design software that typically describes systems with, say, fewer than 100 surfaces, stray light analysis software may need to describe hundreds of thousands of surfaces literally modeling each "nut and bolt."

Where stray light software departs from CAD is in the specification of the specular and scatter properties of the components. In order to perform even the most rudimentary stray light calculations, the optical coating (specular) information must be specified as well as the scatter models; the latter are described by BSDFs (bidirectional scatter distribution functions). BSDFs can become extremely complex to define as they are functions of both 3D specular and scatter angles, and frequently there are additional dependencies on wavelength and polarization. Finding a complete specification of the BSDF of a paint or surface treatment in the open literature is oftentimes impossible and so it is common to send samples to measurement laboratories that have multiwavelength scatterometers to characterize the BSDF.

A single ray incident on a surface assigned an optical coating will generally create two rays: a reflected ray and a transmitted ray whose fluxes are determined from the properties of the coating, the wavelength and polarization of the ray, and the ray's angle of incidence with the local surface normal. This process is called "ray splitting" and is the basis of all ghost image calculations.

A single ray incident on a surface assigned a scatter model will generate a distribution of scattered rays whose flux values are determined by the BSDF. While scatter physically radiates into 2π sr relative to the local surface normal, it is computationally inefficient to generate scattered rays in software into so large a scatter angle. Consequently scattered rays are typically "aimed" into specific directions of interest, such as toward a detector or image of a detector. This is referred to as "importance sampling".

Once the geometry is defined and the specular and scatter models (including importance sampling) are specified, performing a stray light calculation involves defining a source with the correct radiant, spectral and coherent properties and then propagating those rays nonsequentially through the system. Various thresholds are set so that rays whose fluxes drop below some predetermined level are terminated. Given the complexity of the systems and the number of rays ultimately traced, it is not uncommon for a given calculation to run for several hours, several days, or even longer. In recent years, the accessibility of distributed computing networks has made it possible to tremendously reduce the run times of stray light calculations.

In the early days of stray light analysis, the sole output of a lengthy calculation was a single number: the total stray light level on the detector. While this was certainly useful information, it didn't suggest to the analyst what needed to be done to make the system perform better. However with modern stray light software, the analyst has access to numerous calculations that can provide insight into how stray light is propagating. For example, in addition to irradiance plots of the signal and stray light at the detector, the analyst can peruse tables of individual surface stray light contributions, lists of ray paths that describe the exact trajectories of stray light through the system, and graphical representations of how surfaces are illuminated. Based on these outputs, the analyst can decide which surfaces require better baffling, upgraded AR coatings, a different type of paint and so on. Hamming's oft-quoted statement that "the purpose of computing is insight, not numbers" very much describes the value of modern stray light software[1].

Under the relentless pressure to make optomechanical systems smaller yet more sensitive, instrument designers, systems engineers and stray light analysts work to make every photon useful. While there are theoretical limits on how smooth a surface can be manufactured or how black a paint can be, very often extreme measures are not required to make a system work. Sometimes it is simply a matter of correctly positioning a single vane in a baffle or keeping internal surfaces "clean enough" that makes the difference between unacceptable and near-optimum performance.

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Asia-Pacific
Special Section

As the **Asia-Pacific** region continues its rapid expansion in the global market, some experts are calling it the "largest and fastest growing market for photonics."

In this special section, *Photonics Spectra* takes a look at the current state of the **Asia-Pacific** photonics market and gets firsthand insights into what is happening there from several industry authorities.

Asia-Pacific Eyes Photonics Market Growth

The ongoing development of manufacturing and telecommunications technologies, among others, is thrusting the industry to the top of the global goods market. Asia-Pacific, in particular, is expected to grow quickly and steadily.

BY JUSTINE MURPHY
SENIOR EDITOR

The global photonics market will continue its fervent growth in the coming years, according to a number of reports, as technology advances industry-wide. Progressing the most is the telecommunications sector, which is expected to become the largest end-use industry for photonics because of rising demand for fiber optics components and systems. The manufacturing sector is booming, too, as lasers and other photonics-related technologies are replacing traditional machines and tools.

While this growth is occuring around the world, the Asia-Pacific (APAC) region is expected to see the fastest expansion.

Lasers grow in manufacturing sector

Parallel to widespread technological evolution, the photonics market is demonstrating robust growth in manufacturing, telecommunications and consumer electronics, and specifically in the APAC region.

Several market research companies attribute this robust development, in part, to advances in and demand for technologies in the manufacturing sector. Laser components and systems increasingly are finding manufacturing applications,

APAC Market Flourishing in the Wake of Global Uncertainty

Industry experts focus on several key factors to explain growth in the region.

As part of our look at the Asia-Pacific photonics market, *Photonics Spectra* spoke with photonics industry experts — Wenko Sueptitz, head of the photonics division for Spectaris (a German high-tech industry association), and Mike Bähren, head of the association's market research division — about the current trade market, as well as what the future holds. PS also spoke with Herman Chui, senior director of product marketing at Spectra-Physics, for his insight on the APAC market and what the industry can expect for the years ahead.

Q: Which APAC regions and market sectors have seen the most growth in the photonics market in recent years? To what can this market growth in APAC countries be attributed?

Chui: Korea and especially China have experienced the most growth in photonics and lasers in recent years. This again is tied to the major shift in manufacturing to this region and especially these countries; consumer electronics, automotive and industrial manufacturing have been in particular among the faster-growing market sectors.

The photonics and lasers market growth in APAC is due primarily to three factors: faster economic growth in APAC than other regions of world, shift in manufacturing to APAC, and an increasing usage of lasers for manufacturing.

Bähren: East Asia has become the center of the global photonics industry. Very strong are China, Korea, Taiwan and Japan. The growth rates differ — China and Korea are further gaining market share. In Japan and Taiwan, the revenues are more flat or even declining.

One of the reasons for this dynamic is the strong governmental support of the photonics industry in China and Korea. In Korea, the photonics industry gets the highest governmental support, followed by China. Europe is lagging behind, despite Horzion2020 and other national initiatives. In Taiwan and Japan, we see a strong influence of price decline of the flat-panel displays. Additionally, in Japan [we see] the declining demand for photo cameras due to the omnipresence of smartphones.

Overall, the Asian countries are very strong in the communication-related photonic applications like displays, optical communication and information, but also in solid-state lighting. One major reason is the cost-efficiency and the fast ramp-up toward the mass production of new optoelectronic goods in these countries.

Q: What is the state of manufacturing in Europe in regard to the loss of manufacturing to companies in APAC? In your experience, what trends are you seeing globally in trade that relate to this concern?

Bähren: [We are seeing] the companies in the Asia-Pacific region expand their global according to the market research firm Reportlinker, with demand from APAC contributing to global market growth. Specifically, laser technology has begun replacing traditional machine tools in manufacturing applications, as low-cost fiber lasers and industrial pulse lasers are being developed.

The projected expansion in the next several years of telecommunications into the largest end-use sector of the photonics industry can be attributed to a rising demand for optical fibers. Optical fibers are quickly becoming more popular than traditional metallic wires, as they demonstrate greater safety and security, and telecommunications and information technology is prompting new developments in regions such as China and India.

The 3D imaging market's anticipated boom in the Asia-Pacific region comes from continuing advances of this technology and from demand for security and defense applications such as facial identification, and weapons and explosives detection. Health care applications are also a top user of 3D imaging technology. Compared to traditional imaging methods, 3D imaging is "faster and easier to read," according to Massachusetts General Hospital. Mass General said that this technique is able to extract data from exams to create "precise anatomical visualizations with added benefits for radiologists, referring physicians and patients." It also can reduce costs for the health care system.

Growing investment in R&D across APAC is helping to drive the microscopy devices market, as is the growth of universities and research institutions there. An increased focus on nanotechnology research has become a driving factor in this market segment, and growth of the electronic and renewable energy industries has boosted the demand for microscopy devices in semiconductor applications. The high resolution capacity of such devices is leading R&D advances in cell biology and neurology. The increasing use of electron and scanning probe microscopes is further propelling the microscopy devices market segment.

3D imaging market gains traction

Within a five-year span (2016-2021), the global photonics market should witness a nearly 10 percent compound annual growth rate (CAGR). By 2021, a late-2016 report by Research and Markets notes this market is expected to reach $724 billion (USD). Propagating the fastest will be the Asia-Pacific region. The report also projects that China will be the largest market for photonics in the region into the near future. The market in India is surging, as well, putting it in a prime position to exhibit the fastest growth among APAC nations.

Over the next three years the global 3D imaging market is expected to reach $16.6 billion, growing by more than 27

market position; [we are seeing advances] in research-intensive areas and application fields, which requires a close cooperation or development partnership between the photonics manufacturer and the industry customer [and that] still offer good opportunities for European companies. Currently there are around 5000 European companies (mainly SMEs) with around 370,000 employees active in the photonics sectors. There are high market shares between 30 and 55 percent of European companies, especially in the fields production technology, optical components and systems, measurement and automated vision, medical technology, and life science.

Europe, and Germany in particular, continues to be very strong in manufacturing of complex high-end laser, med-tec, machine vision and sensor solutions. One of the main reasons of this strength is the high density of young, as well as experienced, engineers and skilled workers, a close network of companies in photonics, electronics and precision engineering, and major application markets like automobile, medtec, manufacturing equipment nearby.

Q: What are your thoughts on the current state of global trade relations? Are there changes anticipated for the future?

Sueptitz: Optical solutions for autonomous traffic is something to watch growing rapidly over the next few years. Overall, the global photonics industry is doing very well. The outlook for 2017 is as similarly sunny as it was for 2016. Despite political changes in the U.S. and possibly also in Europe over the year, we do not see a significant influence on the forecast of the photonics industry ... yet.

Q: Which sectors of the photonics market are expected to see the most growth in APAC in the next five to 10 years?

Chui: APAC has become the manufacturing center for the world. Everything from consumer electronics to automobiles to solar cells has seen a dramatic shift in manufacturing output to APAC over the past years, and this trend is expected to continue as APAC economies rise and the consumer demand for manufactured goods accelerates in APAC. Photonics and lasers are increasingly becoming a critical part of manufacturing processes as the cost per throughput improves and quality requirements tighten. As a result, we expect photonics and lasers for manufacturing to see the most growth in APAC over the next five to 10 years. We are also seeing growing demand in other areas, such as research, and life and health sciences, where APAC economies are growing faster than other regions of the world. For example, if we assume research funding remains a constant percentage of [gross domestic product], we would expect some continuing slow growth in this area.

percent annually, according to MarketsandMarkets, with Asia-Pacific expected to experience an increase in market traction. Allied Market Research anticipates significant growth, as well, in the 3D imaging sector, predicting this segment to hit $21.3 billion by 2022, and APAC countries offering significant opportunities.

APAC is also expected to be a powerhouse player in the microscopy devices market, encompassing optical, electron and scanning probe microscopes; this market is projected to top $9.7 billion by 2020. The region held the largest share of this market in 2013 (nearly 50 percent), according to Transparency Market Research. Market analysts expect this trend to continue, namely in China, which is expected to dominate the APAC region within this segment of the market through 2020.

Photonic sensors is another fast upward market segment globally. The global market is expected to reach $18 billion by 2021, noted a report by Allied Market Research. The sensor market in APAC has an anticipated annual growth of nearly 23 percent, according to KBV Research. KBV also said that within APAC, China dominated this growth in 2015, while this segment in Japan is expected to reach $1.1 billion by 2022. However, it is India that will see the most significant advances through 2022, growing annually by about 25 percent.

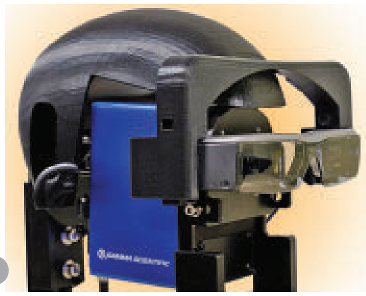
Fiber optic sensors specifically dominated the sensors segment in APAC throughout 2015, and should continue its upward momentum over the next several years at a yearly growth rate of about 21 percent.

The market for photonic integrated circuits (PICs) is swiftly emerging as a major industry sector. The groundbreaking technology is revolutionizing optical networks worldwide. Globally, MarketsandMarkets expects this segment to reach $1.5 billion within the next five years. And while North America held the reins for the PIC segment in 2015, APAC has emerged as a strong region with quick market growth anticipated by Stratistics Market Research Consulting. According to MarketsandMarkets, APAC should become the PIC market leader by 2022, growing annually by 26 percent.

The IR detector market is another in which APAC should see fast, significant growth over the next five years. Allied Market Research found that China, in particular, has the biggest market for IR detector manufacturers and consumers. Overall, the market in APAC is being fed by security concerns, manufacturing industry activities and increased expenditures in emerging markets such as Japan and India.

From bio and medical applications to defense and security, the photonics market in all fields is surging, as the Asia-Pacific region becomes the "largest and fastest growing market for photonics," according to market experts. And there are no signs it will slow down anytime soon.

justine.murphy@photonics.com



1 Measurement System

The Near Eye Display (NED) measurement system from **Gamma Scientific** is intended to aid manufacturers of head-mount and head-up displays for entertainment, medical, avionics and military applications in the development and production of higher-quality and more consistent products. The system incorporates compact imaging optics that feed both an integrated camera viewing system and a low-noise, high-accuracy spectroradiometer. An LED spot projector, viewed using the camera, enables the operator to point the optics at a precise position within the display field. Selection of the appropriate aperture permits measurements over fields of view ranging from 0.1 to 5°.

contact@gamma-sci.com

2 Optical Fault Isolation Tool

The Meridian 7 optical fault isolation tool from **Thermo Fisher Scientific Inc.** is designed to provide the resolution needed for nondestructive localization of electrical faults at sub-10-nm nodes. The device provides visible laser voltage imaging and probing and dynamic laser stimulation. By avoiding a requirement for ultrathin substrates, it preserves the integrity and functionality of the device under test to provide a reliable and practical production solution.

www.thermofisher.com

3 Acrylic Longpass Filters

Midwest Optical Systems Inc. has announced acrylic longpass filters to shield lenses and lighting from damage or to economically control the wavelength emission in large-area, broad spectrum light sources. Frequently used as enclosure windows, the filters are commonly used in FDA- and European Food Safety Authority-regulated applications where exposed glass over the inspection area is not permitted. Anti-abrasion, anti-reflection coatings are offered, which can also withstand harsh solvents such as acetone. High transmission ranges from 90 to 98 percent. The acrylic filters are available in threaded mounts, sizes M13.25 to M105, as well as slip mounts.

www.midopt.com/filters/acrylic

4 Ultra-Black Surface Coating

The Vantablack S-VIS ultra-black surface coating technology from Surrey NanoSystems Ltd. is being offered by **Santa Barbara Infrared Inc.**, improving IR emissivity in the midwave-IR (MWIR) and longwave-IR (LWIR) spectral wavelengths. Vantablack is the world's blackest surface coating material for the UV to far-IR spectrum. It employs an innovative nanomaterial structure that absorbs virtually all incident light. Developed for spaceborne imaging applications, it offers high IR absorption and excellent thermal, mechanical and environmental stability. In the MWIR range of 3 to 5 µm, emissivity is >99.8 percent. In the LWIR range of 8 to 12 µm, emissivity is >99.5 percent. Emissivity levels on a flat-plate blackbody source provide improved radiometric accuracy for the calibration of IR cameras.

sales@sbir.com

5 High-Power Laser Modules

The ML2040 Series of high-power laser modules from **Frankfurt Laser Co.** are designed for use in harsh environments. The system features an output power of 2 W and is offered with wavelengths ranging from 405 to 1060 nm. The housing is electrically isolated and keeps protection class IP65 conditions. TTL modulation up to 1 MHz and analogue modulation up to 100 kHz are optionally available. The power stability is <1 percent over 24 hours. Apart from round and line beam, other beam shapes like grids, circles or line and dot arrays are available.

sales@frlaserco.com

6 Photoacoustic Product

The Phocus OEM from **Opotek Inc.** is the newest addition to the Phocus family line of products designed for photoacoustic applications. The Phocus OEM is a mobile unit that incorporates all the system components in an extremely small and robust package, measuring 22 × 24 × 14 in. The system includes the pump laser, the power supply and cooling unit, the optics, and the optical parametric oscillator (OPO). The ring oscillator OPO generates peak energy of more than 50 mJ at 20 Hz. The entire system is computer controlled. Access to laser wavelengths at 1064 and 532 nm is available.

opo@opotek.com

10-kW Laser Optics

II-VI Inc. has announced a new line of optics designed for 10-kW class fiber and direct-diode lasers. The optics are made from low-absorbing fused silica substrates. They undergo magneto rheological finishing to achieve $<\lambda/10$ of surface irregularity and <1 nm of roughness. With a high-performance, proprietary ion beam sputtering coating, they achieve <10 ppm of total absorption loss. The 10-kW optics are available in many complex shapes used in today's high-power beam-shaping applications such as aspheres, axicons and high aspect ratio lenses. Improved lens quality enables the lasers to maintain high reliability at high power levels and over long periods of time. The next-generation fiber and direct-diode lasers can be used in metal cutting and welding, as well as additive manufacturing.
info@iiviinfrared.com

Benchtop Laser System

The EasyJewel bench-top laser system from **Rofin-Baasel Lasertech GmbH & Co. KG** and **Coherent Inc.** is designed for marking and engraving tasks. The system also cuts metal sheets of up to a 1.2-mm thickness with high accuracy and perfect edge quality. It efficiently replaces a manual task and can be used in a multitude of ways. The laser system is especially designed for circumferential, seamless designs. The VLM Easy-GUI software guides the operator automatically through the input program and requests all necessary information in order to avoid input error. Only minimum input is required to set up the marking process.
sales-micro@rofin.de

Dispensing System

The preeflow eco-duo330 from **Intertronics** is designed for micro-dosing two-component systems, providing dosages as small as 0.2 to 32 ml/min with complete repeatability, precisely mixed and with exceptional control. Dosing quantities of 0.005 ml/shot is achievable, irrespective of temperature, time, pressure and viscosity — dosed as a dot or bead — so the smallest quantities can be created as required. The microprocessor-controlled system creates a dosing accuracy of ±1 percent and repeatability of over 99 percent in a reliable, reproducible process. Dependant on application, the mixture ratio between the two input materials can be easily adjusted from 1:1 to 10:1 using the intelligent control via a graphical interface. The dosing of dots, as well as bead applications, can be subjected to a continuous quality check thanks to the integrated pressure monitoring. Applications include the fields of medical device manufacturing, optics, photonics, electronics assembly, biochemistry and semiconductors, where the ability to meter and mix small volumes is necessary.
info@intertronics.co.uk

Circular Polarizer Filter

American Polarizers Inc. has announced a new circular polarizer filter with a 50 percent transmission level. Whereas most circular polarizers have maximum transmission levels of around 42 percent, these polarizers assure that more light is transmitted through the filter to the viewer, resulting in a brighter display. The filters are available in standard sheet sizes from 8×10 in. up to 18×24 in., as well as custom sizes. To accommodate requests for specially shaped filters, in-house laser cutting and waterjet technology can fabricate circular polarizer filters in custom shapes specified by the customer.
sales@apioptics.com

Optical to Electrical Converter

The o2e direct-current-coupled optical to electrical converter module from **Coherent Solutions** has a bandwidth of 25 GHz. The amplified output of o2e makes it a perfect match for real-time oscilloscopes. The versatile o2e has a multimode input that accepts both multimode and single-mode input fibers, and a broad 830- to 1600-nm wavelength coverage makes it compatible with a wide range of applications. The o2e enables optical R&D engineers to unleash the power of real-time oscilloscope measurement for PAM4 intensity modulated optical signals, as it lets them measure streaming, nonrepetitive data without the need for a trigger signal.
info@coherent-solutions.com

Thermal Imaging Technique

The UltraMax thermal imaging technique from **Flir Systems Inc.** combines the information from multiple original thermal images into an image with higher resolution and less noise. UltraMax images produced on Flir Tsc-series cameras are clearer and larger, enabling better thermal analysis of even small details. Because the technique generates an increased number of pixels covering the same target area, UltraMax also decreases measurement spot size. As a result, users can achieve greater measurement accuracy, particularly on small details. UltraMax uses natural movement to capture an image set in which each image is slightly offset from the others. The data is combined to form an image that includes many more pixels of the target, resulting in a resolution greater than that of the original thermal imaging camera detector. The data is also used to create a clearer image, since pixel noise can be reduced through comparing similar points in multiple images. UltraMax technology is able to capture 16 thermal images in less than one second. These are stored on a Flir thermal imaging camera as a single .jpg file, and will appear as one image when viewed on the camera or in software.
research@flir.com

Time-of-Flight Sensor

The ELISA 3DRanger from **Heptagon Micro-Optics Pte Ltd.** is a 5-m Time-of-Flight smart sensor. When integrated with a smartphone camera, ELISA enables new applications like a virtual measuring tape, security features, people counting, augmented reality and enhanced gaming. The range extension also improves autofocus applications. Other new features include SmudgeSense, the company's proprietary active smudge detection and resilience technology, and a two-in-one proximity mode, adding near distance ranging functionality that enables the use of ELISA in front-facing applications with very limited real estate impact. This supports applications like real-time video chat filters or automatic selfie zoom adjustment. For power-sensitive Internet of Things applications, ELISA includes an "Always On" continuous measurement feature. The sensor is able to continue capturing measurements even if the host processor goes into sleep mode. It can then wake the host processor once an object is detected, helping conserve power at the system level.
sales-asia@hptg.com

Hexapods

The HXP200 series of hexapods from **Newport Corp.** can position loads up to 50 kg on six axes with precision, speed and accuracy. The HXP200 features a ±59-mm travel range, an 81-mm/s speed and excellent stiffness and stability. The HXP200S is a wider and stiffer version of the HXP200, capable of handling loads up to 85 kg. The HXP200 is ideal for complex motion applications in alignment and bonding, material analysis or sensor calibration and simulation. It can also be used in many other applications that require high-precision motion with six degrees of freedom such as work-piece positioning in automotive manufacturing and movement of large telescope mirrors. The HXP200 comes with dedicated software that makes programming of complex motion simple through automatic calculation of all coordinate transformations. All HXP hexapods feature two software-defined virtual centers of rotation as well as RightPath trajectory control for minimal runout along a continuous multidimensional motion path.
www.newport.com

Signal Quality Analyzer

The Signal Quality Analyzer MP1800A Series 100G-EPON Test Solution from **Anritsu Corp.** is a bit error rate test solution for 100-G Ethernet passive optical networks. The 100G-EPON Application Software MX180014A and Signal Quality Analyzer MP1800A support bit error rate measurements of optical line terminals and optical network units for the latest 100G-EPON standard. It measures a wide range of interfaces up to multichannel 64 Gbps. The MP1800A signal-source multichannel synchronization and skew adjustment functions are optimal for Oracle Load Tests requiring high-accuracy timing setting.
www.anritsu.com

NIR Spectroradiometer

The SR-6500 NIR spectroradiometer from **Spectral Evolution** covers the UV/VIS/NIR range from 350 to 2500 nm. The device features ultrahigh resolution and very stable performance with three high-density thermoelectrically cooled photodiode arrays. The SR-6500 is also calibrated to NIST-traceable radiometric calibration standards. Resolution is achieved using three high-density solid-state thermoelectrically cooled photodiode arrays. Applications include mineral identification and analysis, soil, vegetation, solar radiance and microbial diversity studies.
sales@spectralevolution.com

Beamsplitter

The High Efficiency Double Spot (HEDS) beamsplitter from **Holo/Or Ltd.** is a subaperture-based diffractive optical element. The system is capable of splitting a beam into two spots with 97 percent efficiency and almost no power in undesired orders. Beamsplitting is useful for applications including lithography, perforation, cutting and other material processing applications. For sensitive applications, a novel diffractive HEDS is also available.
sales@holoor.co.il

Happenings

MARCH

● **LASER World of PHOTONICS CHINA (March 14-16)** Shanghai. Contact Katrin Hirl, +49 89-949-20324, katrin.hirl@messe-muenchen.de; www.world-of-photonics-china.com.

● **Image Sensors Europe 2017 (March 14-16)** London. Contact Smithers Apex, +44 1372-802000, info@smithersapex.com; www.image-sensors.com.

Lamdamap 12th International Conference & Exhibition 2017 (March 15-16) Wotton-Under Edge, England. Lamdamap 12th International Conference & Exhibition on Laser Metrology, Coordinade Measuring Machine & Machine Tool Performance. Contact euspen, +44 1234-754023; www.euspen.eu.

● **OFC 2017 (March 19-23)** Los Angeles. The Optical Fiber Communication Conference and Exhibition. Contact OSA, +1 202-416-1907, custserv@osa.org; www.ofcconference.org.

● **International Laser Safety Conference (ILSC) (March 20-23)** Atlanta. Contact Laser Institute of America, +1 407-380-1553; www.lia.org/conferences/ilsc.

ARABLAB 2017 (March 20-23) Dubai, United Arab Emirates. Contact The Arablab Group, + 971 4-397- 5418, info@arablab.com; http://arablab.com.

FCMN 2017 (March 21-23) Monterey, Calif. 2017 International Conference on Frontiers of Characterization and Metrology for Nanoelectrics (FCMN). Contact Della Miller, +1 530-896-0477, della@avs.org; http://www2.avs.org.

● **SPIE Smart Structures NDE 2017 (March 25-29)** Portland, Ore. Contact SPIE, +1 360-676-3290, customerservice@spie.org; www.spie.org/x88673.xml.

APRIL

● **OSA Biophotonics Congress: Optics in the Life Sciences (April 2-5)** San Diego. Contact The Optical Society, +1 202-223-8130, info@osa.org; www.osa.org/en-us/meetings/osa_meetings/optics_in_the_life_sciences/.

● **AUTOMATE 2017 (April 3-6)** Chicago. A3 Association for Advancing Automation. Contact +1 734-994-6088, info@automateshow.com; www.automateshow.com.

European Conference on Integrated Optics (ECIO) 2017 (April 3-5) Eindhoven, Netherlands. Contact Jakajima B.V., +31 40-2952135, info@jakajima.eu; https://ecio-conference.org.

● **WCX17: SAE World Congress Experience (April 4-6)** Detroit. SAE World Congress and Exhibition is now WCX17: Sae World Congress Experience. Contact SAE International, +1 877-606-7323 (U.S. & Canada), +1 724-776-4970 (Outside U.S. and Canada), customerservice@sae.org; www.wcx17.org.

PAPERS

ECOC 2017 (Sept. 17-21) Gothenburg, Sweden
Deadline: Abstracts, April 28
ECOC welcomes and encourages the submission of original, unpublished, clear and relevant papers in any of the following topic areas: fibers, fiber devices and fiber amplifiers, integrated optoelectronic devices and optical processors, digital techniques for optical communication systems, transmission subsystems and optical network elements, datacom and computercom hardware, point-to-point transmission links, core, metro, and data center networks, access, local area and indoor networks. Contact Sweden MEETX, +46 31-708-86-90, ecoc2017@meetx.se; http://ecoc2017.org/authors.

Nanophotonics and Micro/Nano Optics International Conference 2017 (Sept. 13-15) Barcelona, Spain
Deadline: Papers, June 28
Topics include: photonic and plasmonic nanomaterials, optical properties of nanostructures, nonlinear nano-optics, quantum dots and color centers, strong light-matter interactions at the nanoscale, metamaterials, enhanced spectroscopy and sensing, nano-optomechanics, quantum nano-optics, nanoscale photothermal effects, and nanomedicine. Contact Organizing Committee, +337 81-20-1182, nanop2017@premc.org; www.premc.org/conferences.

● **ASLMS 2017 (April 5-9)** San Diego. 37th Annual Conference of the American Society for Laser Medicine and Surgery. Contact ASLMS, +1 715-845-9283, information@aslms.org; www.aslms.org/annual-conference.

● **SPIE Defense + Commercial Sensing t(April 9-13)** Anaheim, Calif. Contact SPIE, +1 360-676-3290, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/defense--commercial-sensing.

● **SPIE Technologies and Applications of Structured Light (April 18-21)** Yokohama, Japan. Part of Optics & Photonics International Congress 2017. Contact SPIE, +1 360-676-3290, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/structured-light.

● **OPIE 2017 (April 19-21)** Yokohama, Japan. Optics & Photonics International Exhibition. Contact OPIC; www.opie.jp/en/index.php.

● **SPIE Optics & Optoelectronics (Apr. 24-27)** Prague. Contact SPIE, +1 360-676-3290 or +1 888-504-8171, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/optics-and-optoelectronics.

● **IS Auto 2017 (April 24-26)** Dusseldorf, Germany. Image Sensors Automotive 2017. Contact Smithers Apex, +44 1372-802000, info@smithersapex.com; www.image-sensors.com.

Ukiva Machine Vision Conference & Exhibition 2017 (April 27) Milton Keynes, England. UK Industrial Vision Association. Contact Chris Valdes, +44 020-8773-5517, chris.valdes@ppma.co.uk; http://ukiva.org/mvc.

MAY

● **Design & Manufacturing New England 2017 (May 3-4)** Boston. Contact UBM Canon, +1 310-445-4200, UBMCanonConferences@ubm.com; www.design-manufacturing-new-england.designnews.com.

● **LIGHTFAIR International 2017 (May 7-11)** Philadelphia. Contact LIGHTFAIR International, +1 877-437-4352, info@lightfair.com; www.lightfair.com/lightfair/V40/index.cvn?id=10000.

Quantum 2017 (May 7-13) Turin, Italy. From Foundations of Quantum Mechanics to Quantum Information and Quantum Metrology & Sensing. Contact Marco Genovese, +39 011-3919-253, quantum2017@unito.it; www.quantum2017.unito.it.

● **RAPID + TCT 2017 (May 8-11)** Pittsburgh. Contact SME, +1 800-733-4763 (U.S. and Canada), +1 313-425-3000 (outside U.S. and Canada), service@sme.org; www.rapid3devent.com/.

● **Control Stuttgart (May 9-12)** Stuttgart, Germany. Contact Messe Sinsheim GmbH, +49 726-16-890, info@messe-sinsheim.de; www.tradefairdates.com/Control-M129/Stuttgart.html.

● **CLEO 2017 (May 14-19)** San Jose, Calif. Conference on Lasers and Electro-Optics. Contact The Optical Society, +1 202-416-1907, info@cleoconference.org; www.cleoconference.org/home.

● **EASTEC (May 16-18)** West Springfield, Mass. Contact SME, service@sme.org; www.easteconline.com.

● **Display Week 2017 (May. 21-26)** Los Angeles. Contact Society for Information Display, mhardcastle@mcapr.com; www.displayweek.org.

Bio-IT World Conference & Expo '17 (May 23-25) Boston. Co-located with Medical Informatics World Conference. Contact Cambridge Healthtech Institute, +1 781-972.5400, chi@healthtech.com; www.bio-itworldexpo.com/.

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Lidar yields clues into Native American history

Archaeologists have been using lidar to advance investigations of the past, primarily in areas where there were known large-scale civilizations in dense forested settings, such as Mayan areas in Central America and Angkor Wat in Cambodia.

For smaller archaeological explorations, most surveys are not as sophisticated and the brunt of the work has to be done on foot. In northern Michigan, for example, Meghan Howey, a researcher and associate professor of anthropology at the University of New Hampshire, has been leading students and volunteers around Douglas and Burt Lakes — near the University of Michigan Biological Station — for eight years in the pursuit of Native American cache pits.

In those eight years, Howey and her team discovered 69 clusters, typically containing 15 to 25 pits each. Lined with birch bark, these underground "old-fashioned refrigerated" storage pits, usually three to four feet deep, were used between A.D. 1200-1600 by Native Americans in low-density mixed hunter-gatherer-horticulturalist communities.

Howey recently teamed up with Michigan Statewide Authoritative Imagery & LiDAR (MiSAIL), a program that assists the state with its geospatial data needs through high-resolution digital aerial photography.

"Working with my collaborators and developing this innovative use of lidar, we found in that same area close to 150 high-potential cache pit clusters in a matter of about a week or two of work," said Howey.

The MiSAIL program uses a Leica ALS70-HP, high-pulse-rate airborne lidar for its topographical maps. The lidar data is computed using range and return signal intensity measurements recorded in flight, along with position and altitude measurements from an airborne GNSS/inertial subsystem.

Two students mapping a pit profile to record how they were built and how they were filled in, capturing the life history of the cache pit.

Using the raw lidar data, the team created a one-foot resolution digital terrain model (DTM) and then innovated a suite of detection routines targeted to the cache pits. This gave Howey access to a much larger spatial scale than she was able to get as a pedestrian.

"I had always focused my survey around the high terraces near the inland lakes," she said. "We were able to see cache pits in interesting locations away from the lakes; we would never have found these, ever, without lidar. We now have the potential to find many more cache pit sites across the Great Lakes, potentially transforming our understanding of the archaeological record of the region."

The cache pits Howey and her team have found are primarily empty, as the native peoples would leave items in the pits while they went on hunting and gathering missions and return later to gather them. For Howey it's not about the contents.

"This is really making us realize late precontact indigenous communities modified, shaped and engineered their landscape much more than we previously realized and they did so with a sophisticated knowledge of their entire landscape," she said. "So while these communities may not have left a large-scale signature on the land like the Maya or such, they were constantly modifying their surroundings and we have underappreciated this fact and have much more to learn!"

Modifying her own techniques with the use of lidar, Howey plans to continue her journey across the Great Lakes.

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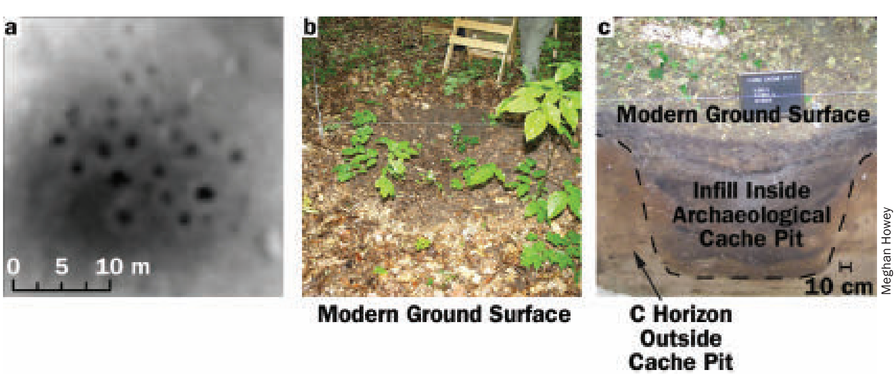

A high-resolution digital terrain model (DTM) of one previously field-identified cache pit cluster **(a)**. A cache pit with leaf litter cleared for cross-section excavations showing current appearance of these as archaeological features **(b)**. Cross-section excavation showing the full profile of an archaeological cache pit **(c)**.