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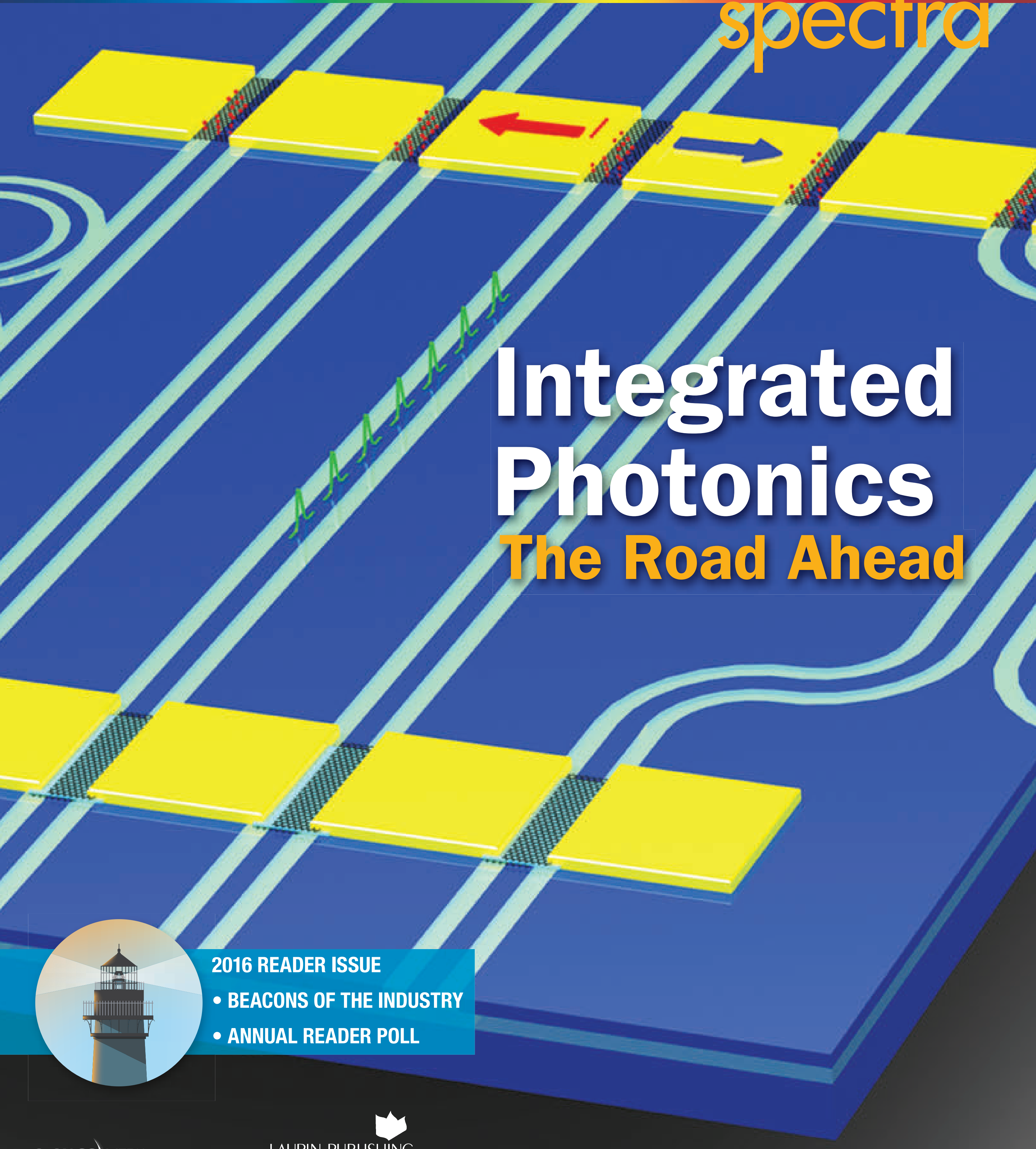

Integrated Photonics
The Road Ahead

2016 READER ISSUE
- **BEACONS OF THE INDUSTRY**
- **ANNUAL READER POLL**

PHOTONICS MEDIA

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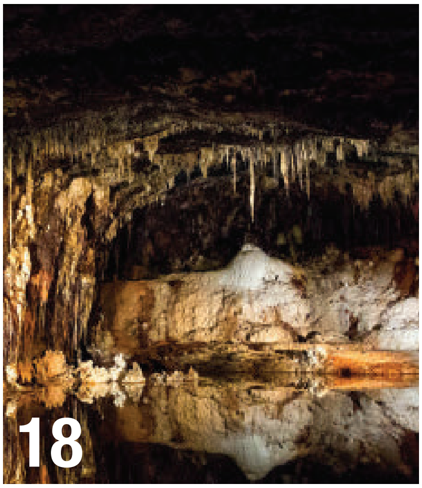
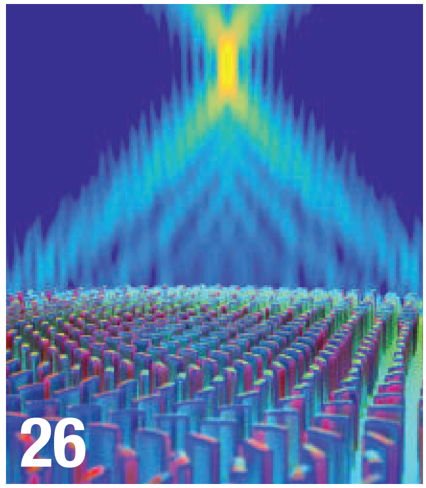
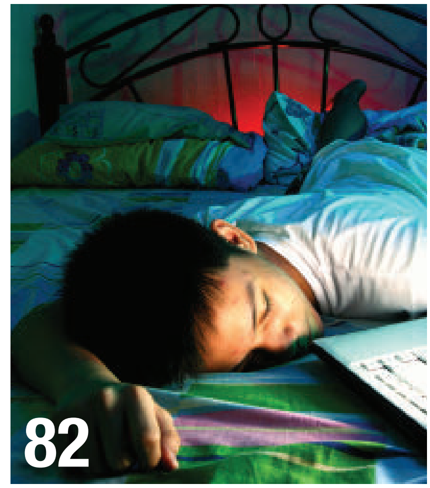
Content

AUGUST 2016 www.photonics.com VOLUME 50 ISSUE 8



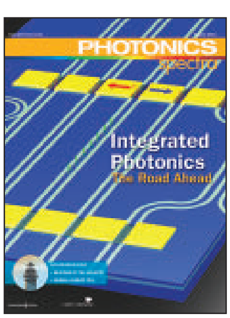




Departments & Columns

2016 READER ISSUE

THE COVER
Graphene is being developed for components on photonic integrated circuits. Courtesy of R.J. Shiue and Dirk Englund. Cover design by Senior Art Director Lisa N. Comstock.



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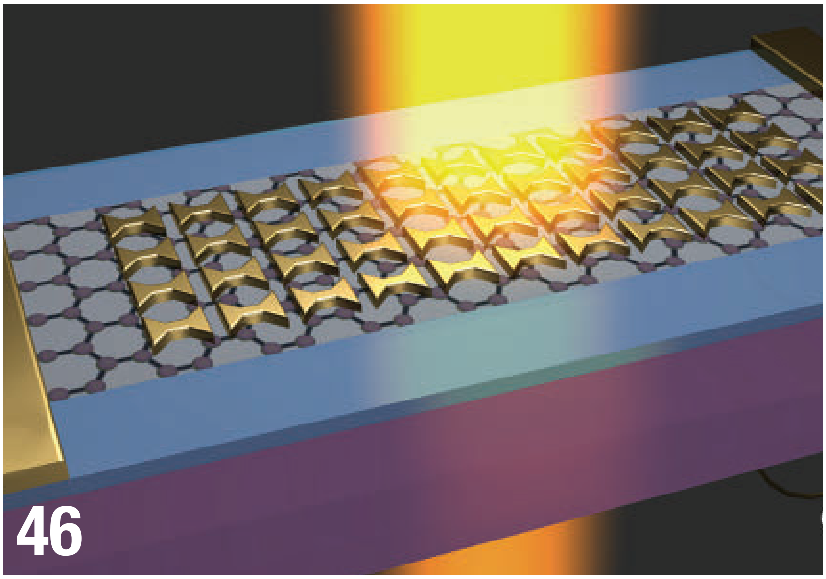
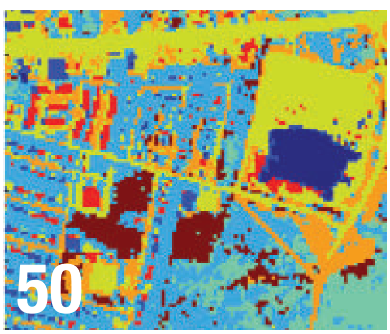
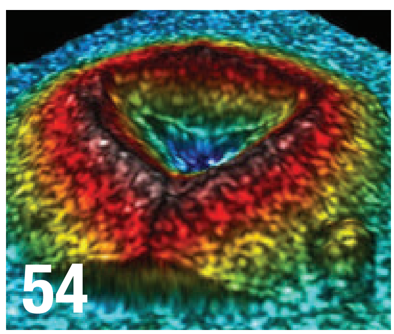
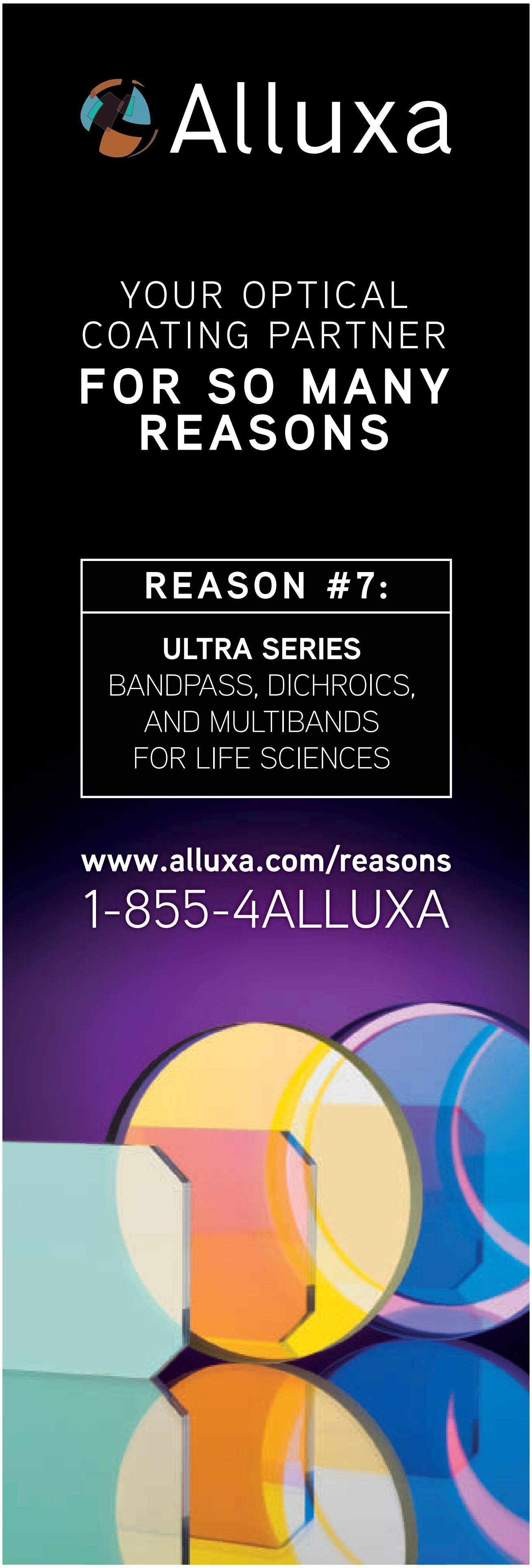
PHOTONICS: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing.







Features



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2016

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editorial COMMENT

Integrated photonics, infinite possibilities

Disruptive technologies such as self-driving cars, optical computers and ultrafast telecommunication networks all require one thing to come to fruition: more complex integrated photonic circuits. For that to happen, researchers must continue to push the limits of materials used to fabricate waveguides, filters, couplers and modulators found on the circuits.

In our cover story, “For Integrated Photonics, a Tale of Two Materials” on page 38, we chronicle efforts to integrate III-V materials onto silicon wafers, and highlight recently commercialized components from the likes of Kaiam and Mellanox, and the potential role of graphene for use in high-speed optical modulators and detectors.

Not surprisingly, this versatile 2D material has applications beyond integrated photonics, among them the potential to replace indium tin oxide as the material of choice in plasmonics. Comsol Inc.’s Valerio Marra examines simulation and modeling techniques for optimizing designs in “Simulation, Experiment Unite Graphene and Plasmonics” on page 46.

Moving from the world of plasmonics to the evolving field of image processing, we take a closer look at its two branches: embedded and deported processing. Contributing editor Marie Freebody’s “Image Processing Interprets the Modern World” starts on page 50.

With the diffraction limit no longer the cutoff for optical measurement, superresolution techniques now allow optical metrology well below that point in the XY direction. Contributing editor Hank Hogan’s “Optical Metrology Breaks Barriers” begins on page 54.

Key components Pockels cells and Faraday isolators get a fresh look in “Innovations Make Ultrafast Lasers Even Faster,” by Markus Fegelein of Qioptiq Photonics, on page 59.

Finally, we chose the August issue to unveil a new recognition program called “The Beacons,” starting on page 63. Selected from reader nominations, the distinction is reserved for those in the photonics industry who’ve made significant contributions in the areas of entrepreneurship, research and education.

Among this year’s class of Beacons you’ll find a high school science teacher from Rochester, N.Y., who was inspired to build an ophthalmology lab to create glasses for students who couldn’t afford them and ended up creating a very popular precision optics fabrication program. And, in a nod to those with an entrepreneurial vision, we feature the co-founder of one of Germany’s pre-eminent machine vision companies, whose contributions to object recognition software can be seen in thousands of manufacturing facilities worldwide.

We hope you find inspiration in this issue.

Michael D. Wheeler

michael.wheeler@photonics.com

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PHOTONICS spectra

CONTRIBUTORS

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Markus Fegelein earned his Diplom degree in physics from the Swiss Federal Institute of Technology in Zurich (ETHZ). During his tenure at Linos and later at Qioptiq, Fegelein has served as product manager for Faraday isolators, Pockels cells and electro-optic modulators. Page 59.

Valerio Marra
Valerio Marra is the marketing director at Comsol, where he leads the technical marketing group. Marra has a Ph.D. in fluid machines and energy systems engineering. Page 46.

Marie Freebody
Regular contributing editor Marie Freebody is a freelance science and technology journalist with a master's degree in physics, with a concentration in nuclear astrophysics, from the University of Surrey England. Page 50.

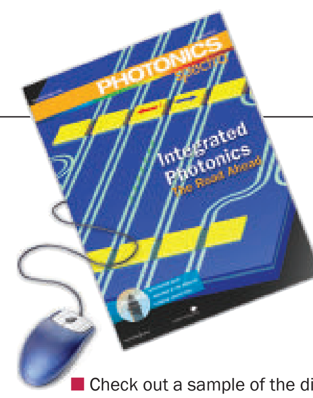
Michael D. Wheeler
Michael D. Wheeler is Photonics Media managing editor with direct responsibility for *Photonics Spectra*. In addition, he is responsible for the editorial direction of *BioPhotonics*, *EuroPhotonics* and *Industrial Photonics*. Page 38.

Hank Hogan
Regular contributing editor Hank Hogan holds a Bachelor of Science degree in physics from the University of Texas at Austin. He worked in the semiconductor industry and now writes about science and technology. Page 54.

In the September issue of
Photonics Spectra...

- **Advances in Linear Variable Filters for Microspectroscopy**
- **Positioning Samples for Raman Imaging**
- **Comparing Aspheric Metrology Methods**
- **Pushing the Boundaries of Excimer Laser Systems**
- **Innovations in MEMS Displays**

You'll also find all the news that affects your industry, from tech trends and market reports to the latest products and media.



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PS

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Controlling Quality in Advanced Optics Manufacturing

Presented by Particle Measuring Systems

Tuesday, Aug. 23, noon EDT

Advanced optics manufacturing now requires much cleaner environments than were necessary in the past. John Davis of Particle Measuring Systems will provide an overview of particle generation sources, control methods and ISO standards, to help you achieve a clean environment that maximizes productivity.

This webinar addresses performance trends in the optics industry that are driving manufacturers to reduce the contamination levels to which a component is exposed during the manufacturing process, including during cleaning, handling, coating and assembly. It covers the ways in which quality control can be compromised through component exposure to particulate and molecular contamination; and the effects of contamination on laser damage thresholds in coatings and on yields in nano-optics and LED production.

Davis will discuss the advantages of continuous monitoring with laser particle counters and provide several examples of particle excursions in the optics industry that have been found and fixed, illustrating the types of improvements that can be made through contamination control.

To register for this free webinar visit www.photonics.com/webinars.

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Coming in October

A free webinar with David Bruce of FANUC America Corp. on Vision Guided Robotics (VGR). VGR has quickly become an enabling technology used across a range of industries to automate many different processes. In this webinar, Bruce will discuss the two subsets of VGR, 2D and 3D, and will go over the proper techniques for selecting and implementing a vision guidance system that includes the latest advances in the technology. For more information and to register, visit **www.photonics.com/webinars**.

NEW! Available on demand:

Robotic Collision Avoidance: When Accidents Are Not an Option

Tim Dykstra, Product Sales Manager for Concept Systems Inc., provides a detailed overview of the technologies and systems that can be used to avoid dangerous collisions between robots and their environment as well as robots and humans in a dynamic manufacturing environment. He discusses the role of vision systems and sensors in collision avoidance; how to select and integrate technologies; the role of a collision avoidance module (CAM); and the future of path planning and collision avoidance. For more information and to watch this webinar and other past presentations, please visit **photonics.com/webinars**.

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Planetary Resources secures funding for earth observation

Asteroid mining company Planetary Resources Inc. of Redmond, Wash., has secured $21.1 million in Series A funding to deploy and operate Ceres, an advanced Earth observation business. Ceres is set to use the first commercial IR and hyperspectral sensor platform to better understand and manage natural resources. It will leverage Planetary Resources' Arkyd spacecraft to deliver affordable, on-demand Earth intelligence of natural resources on any spot on the planet. While typical satellite imagery provides only a picture, Ceres will provide actionable data with higher spectral resolutions by measuring thermographic properties and detecting the composition of materials on Earth's surface.

The funding was led by Bryan Johnson and the OS Fund, joined by Idea Bulb Ventures, Tencant, Vast Ventures, Grishin Robotics, Conversion Capital, The Seraph Group, Space Angels Network and Larry Page.

Planetary Resources

Planetary Resources' president and CEO Chris Lewicki with the Arkyd 6 spacecraft before delivery to the launch pad. A rendering of the Arkyd 6 spacecraft in orbit **(inset)**. The mission will validate the thermographic sensor and supporting technologies for the company's prospecting missions.

Amerlux equips LA with LEDs

Amerlux

The Avista LED light engine for exterior lighting was installed throughout downtown Los Angeles.

Energy-efficient lighting provider Amerlux LLC of Oakland, N.J., has supplied the City of Los Angeles with its Avista LED light engines as part of a major downtown retrofit project. Before the retrofit project, the city illuminated its streets with 250-W high-pressure sodium lamps at a 25-ft mounting height with a 100-ft spacing. Amerlux placed 600 60-W Avista LED luminaires, saving taxpayers almost 80 percent in energy costs and providing better color rendering for enhanced visibility, safety and security.

Amerlux is a designer and manufacturer of energy-efficient lighting systems for supermarket, retail, commercial and architectural projects.

$16.4B

— projected value of the global surface vision and inspection market by 2022, as reported by Grand View Research Inc.

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Soraa LEDs illuminate Saalfeld Fairy Grottoes

The LED lamps of lighting technology provider Soraa of Fremont, Calif., have been installed to illuminate the mineral formations of Saalfeld Fairy Grottoes in Thüringen, Germany. Through Soraa LEDs and lighting artist Rolf Zavelberg's approach to lighting design, thousands of visitors can now see the subtleties in the stalagmite colors within the underground caverns.

The different color temperatures and optics from Soraa's LED lamps enabled the caves at Saalfeld Feengrotten to produce a very detailed and sophisticated lighting production that does not alter the character of the grottoes. The caves at Saalfeld Feengrotten are illuminated using Soraa's Violet-Emission 3-Phosphor (VP3) LED technology. Utilizing every color in the rainbow, the lamps accurately render warm tones, achieving a color-rendering index of 95 and deep red rendering of 95. Unlike blue-based white LEDs without any violet emission, the lamps have violet emissions to properly excite fluorescing brightening agents including paper and natural objects.

Soraa develops LEDs based on pure gallium nitride substrates.


Gordon Axmann

Soraa's LED lamps have been installed to illuminate the natural beauty of the Saalfeld Fairy Grottoes in Thüringen, Germany.

Gamaya lands $3.2M in financing

Hyperspectral agricultural imaging and diagnostic provider Gamaya of Lausanne, Switzerland, has raised $3.2 million (equivalent to about $3.2 million CHF) in its first series of financing.

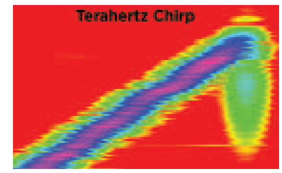
The Gamaya system includes a drone-mounted hyperspectral camera integrated with an analytical platform that automatically translates the data into actionable information for farmers using a simple, scalable and cost-effective methodology. Agronomy-driven information is delivered through maps and recommendations, such as weed or disease maps, so that a farmer can easily take action in the field. The action maps are integrated into farm management platforms and can be easily relayed to field machinery for the necessary treatment, such as the spraying of chemicals or the distribution of fertilizers.

37% — fiber lasers' share of the global laser materials processing market in 2015, up 7% from the previous year, as reported by Optech Consulting

This month in history

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

2011



A chirping sensor developed at the National Institute of Standards and Technology was used to rapidly detect trace gases with greater sensitivity and speed than existing technologies. The device was built from off-the-shelf technology and used terahertz frequencies for molecular detection.

2006

A portable ytterbium fiber laser enabled conservators to clean the 3,300-year-old tomb of Egyptian scribe Neferhotep. The laser system removed dirt without damaging the underlying paint and subsurface.

1996

The U.S. Air Force Phillips Laboratory in New Mexico successfully tested a laser-light active tracking system on a booster theater missle traveling at about 100 m/s. The laser tracked out to a range of about 50 km.

1986

AT&T Bell Laboratories was constructing a 450K-sq-ft, $50M R&D center focused on fiber optics in Upper Macungie Township, Pa., to support its manufacturing plant in Allentown.

Nüvü’s cameras head into space

With the support of the Canadian Space Agency, Montreal-based Nüvü Camēras’ CCD Controller for Counting Photons (CCCP) now features passive heat dissipation for space travel.

Expanding the frontiers of detection in near complete darkness, the cooling innovation dissipates emitted heat without the use of air, an essential requirement when air is absent from the environment or when access to air circulation is limited. The innovation, spurred by space exploration, also pioneers new developments in electron-multiplying CCD (EMCCD) cameras to benefit human lives through hospital center systems.

With the goal of inclusion on a future major space mission, a TRL-5 (technology readiness level 5) version of the CCCP will be designed to withstand the harsh environment of space. This space technology has the potential to revolutionize the imaging of exoplanets, asteroid research and space debris monitoring.

Nüvü’s development road map toward space qualification has been laid out for the Canadian Space Agency. The company develops ultrasensitive EMCCD products.

Phoenix, Sandia to collaborate on PIC

Micro- and nanotechnology provider Phoenix Software BV of Enschede, Netherlands, and Sandia National Laboratories in Albuquerque, N.M., have partnered to facilitate the design and fabrication of photonic integrated circuits.

The collaboration aims to develop a photonics process design kit for Sandia’s silicon photonics manufacturing process. The combination of Phoenix’s suite of photonic design tools and Sandia’s foundry services enable photonic designers to innovate in the field of integrated photonics.

In July 2015, the U.S. Department of Defense’s Manufacturing Technology Program established the American Institute for Manufacturing Integrated Photonics (AIM Photonics) to develop an end-to-end integrated photonics ecosystem in the U.S., underscoring the importance of photonics in the future of the U.S. economy and national security.

Phoenix Software provides products and services for integrated photonics. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corp. for the U.S. Department of Energy’s National Nuclear Security Administration.

DARPA grants $1.3M for IR detection

DARPA has awarded a $1.3 million grant to a team led by University of Central Florida (UCF) researcher Debashis Chanda in Orlando, to fund the development of a next-generation IR detector that could be used in night vision, meteorology and space exploration.

DARPA is funding the UCF team's research for three-and-a-half years. Portable IR cameras have long been used by law enforcement, soldiers, firefighters and others to see in the dark or locate people by their body heat. But the blurry images those devices produce are sometimes nothing more than indistinct colored blobs. More powerful infrared detectors that produce more detailed images, ones typically used by NASA and defense agencies, are large, expensive and can only function at ultralow temperatures.

"The biggest problem is that most IR detectors need cryogenic cooling, and in most cases you can't carry a big cooling tank with you," Chanda said.

The team is working on an entirely new type of detector that relies on thin graphene, a one-atomic-layer thick, 2D material. Chanda envisions an IR detector that is small, portable and doesn't need to be cooled, and produces high-resolution images.

DARPA is an agency of the U.S. Department of Defense, responsible for the development of emerging military technologies.


University of Central Florida

Debashis Chanda, assistant professor at the University of Central Florida's NanoScience Technology Center.

The DSP-HD electro-optical/IR camera.

Controp fills international helicopter camera orders

Controp Precision Technologies Ltd. of Hod Hasharon, Israel, said it has filled several orders for its DSP-HD high-definition electro-optical/IR camera payloads in helicopters. The systems were supplied for installation on the United Nations' Mi-17, Mi-24, Bell 407 and Eurocopter EC-145 helicopters. The system was also supplied to an undisclosed customer in Asia.

Controp provides camera systems for air, land and sea surveillance, defense, and homeland security applications.

$5.8B

— value of the global microscopy market by 2019, as projected by MarketsandMarkets

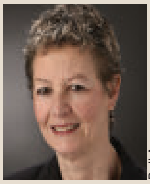
Sydor awarded $1M DOE grant

Sydor Instruments of Rochester, N.Y., has been awarded a $1 million Small Business Technology Transfer Phase II grant from the U.S. Department of Energy.

Sydor will use this grant in collaboration with Cornell University in Ithaca, N.Y., to further advance the commercialization effort of the Keck-PAD fast-framing hybrid x-ray pixel array detector to meet immediate and future detector needs for the emerging applications in the study of material behavior. The Phase II program will advance the Phase I detector design for manufacturing, and produce two beta prototypes for testing.

Sydor develops high-speed imaging and diagnostic solutions.

PEOPLE IN THE NEWS



Ball Aerospace

The Rocky Mountain Section of the American Institute of Aeronautics and Astronautics has named **Lisa Hardaway**, of Ball Aerospace & Technologies Corp. in Boulder, Colo., Engineer of the Year for 2015 to 2016. The organization cited the wide-ranging impact her work has had in the aerospace industry, as well as her mentorship of women undergraduates in aerospace engineering. Hardaway joined Ball Aerospace in 1995, and was program manager for the company's Ralph instrument aboard NASA's New Horizons mission. The spacecraft completed a flyby of Pluto in July 2015, during which Ball's Ralph camera returned the closest images ever seen of the dwarf planet.

CoolLED

Following the company's recent purchase by the Judge Scientific Group, LED illumination system developer CoolLED Ltd. of Andover, England, has promoted **Jim Beacher** from sales and marketing director to managing director. Beacher received his bachelor's degree from Strathclyde University. He has years of experience in the materials research and thin-film coating industries.

Swiss Center for Electronics and Microtechnology

Professor Christophe Ballif of the École Polytechnique Fédérale de Lausanne (EPFL) has won the 2016 Becquerel Prize for his achievements in solar technology research and industrialization. The award — named for French physicist Alexandre Edmond Becquerel, who discovered the photovoltaic effect — was created by the European Commission to recognize outstanding contributions by an individual to the development of solar power. Ballif has conducted research on high-efficiency crystalline heterojunction solar cells and multijunction cells. His work ranges from materials science and interfaces in different types of solar cells to manufacturing and production processes. He has also worked on the development of reliable solar modules with architectural appeal. Ballif heads EPFL's photovoltaics laboratory in Neuchâte and the Swiss Center for Electronics and Microtechnology's photovoltaic center.

Light Speed

MOVES AND EXPANSIONS

Quantum Materials Corp. of San Marcos, Texas, has announced the completion of its initial development phase with display film partners, and is entering into a preproduction phase, committing to an accelerated sample optimization and delivery schedule for its cadmium-free quantum dot (QD).

Quantum Materials has begun shipping additional deliveries of cadmium-free QD samples to its partners and is scheduled to increase shipment quantities as development reaches precommercial scale later this year. The company anticipates that commercial quantities of a high-performance, cadmium-free QD film will be available to display manufacturers in early 2017. Increasing concern over the use of cadmium in consumer displays has been driven by restriction of hazardous substances directives and heightened corporate environmental responsibility.

Quantum Materials develops and manufactures QD and nanomaterials for use in medical, display, solar energy and lighting applications through its patented volume production process.

The Jenoptik Group, headquartered in Jena, Germany, is investing $15 million in its Rochester Hills, Mich., location, creating a modern technology campus for metrology and laser machines in the automotive industry. The new facility is the largest single investment made by the company. The building will be equipped with modern systems and materials for energy-efficiency including sensor-controlled office and plant LED lighting, as well as special energy-saving heating, ventilating and cooling systems. Relocation is expected to take place in 2017, with the whole campus covering an area of 16 acres.

Jenoptik cited average annual growth of U.S. markets of 13 percent since 2009, with high demand for metrology and laser machines, especially from the auto industry. The location will also provide area and expansion options for other Jenoptik activities such as the defense, civil systems and health-care divisions.

Jenoptik is a manufacturer and designer of optical lens assemblies, optical components, refractive and diffractive micro-optics.

PRNewsFoto/Metamaterial Technologies Inc.

George Palikaras, founder and CEO of MTI **(left)**, is greeted by Boris Kobrin, founder and CEO of Rolith Inc.

Smart material and photonics technology developer **Metamaterial Technologies Inc. (MTI)** of Halifax, Nova Scotia, has acquired the business of nanotechnology provider Rolith Inc.

The business includes Rolith's proprietary manufacturing technology, rolling mask lithography (RML), NanoWeb products, intellectual property, proprietary tools and R&D facilities specific to Rolith's large surface area lithography platform and key employees. Metamaterials aims to create the next generation of smart, multifunctional materials to change the way consumers use, interact with and benefit from light.

MTI Founder and CEO George Palikaras described the acquisition as strategic, and a move that the company expects will help it overcome what Palikaras described as the industry's biggest challenge, the absence of viable manufacturing tools to produce large-scale, high-volume optical metamaterial products. He said Rolith's patented RML lithographic technology will allow the company to scale-up manufacturing to meet demand.

• Optical communication manufacturer Finisar reports 2016 revenue of $1.26B •

NPI recommends high-power laser office

WASHINGTON, D.C. — Members of the National Photonics Initiative (NPI) High Power Lasers (HPL) Task Force — comprising leading defense contractors, commercial laser companies and academia — announced recommendations to improve U.S. defense operations and manufacturing capabilities. The recommendations call for the establishment of a directed energy program office to coordinate domestic manufacturing of high-power lasers.

The program office would ensure the domestic supply of critical components required for high-power lasers for defense, and also support commercial technology applications such as cutting, welding and additive manufacturing.

NPI HPL reported that volume manufacturing of high-power lasers is moving offshore, where technology transfer enables foreign defense threats that erode the U.S. industrial base. At the same time, foreign competition has expanded rapidly, particularly in China and Russia. A directed energy program office will also serve to enhance policies that intelligently protect critical technologies while not inhibiting the success of U.S. exporting companies.

Eugene Arthurs, co-chair of the NPI HPL Task Force and CEO of SPIE, the International Society for Optics and Photonics, cited declining funding for high-power laser programs over the last decade, while the technology itself is "on the cusp of practical implementation for the warfighter."

The NPI partnered with the Directed Energy Professional Society to establish the HPL Task Force and produce recommendations. The NPI HPL Task Force report is available online.

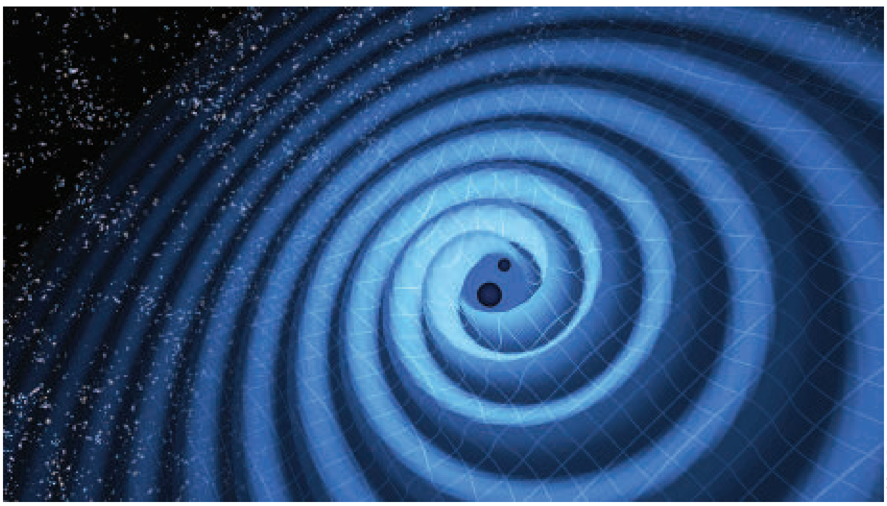
• Kinestral Technologies, AGC Group partner to commercialize fast-switching dynamic glass •

LIGO identifies second gravitational wave event

LIVINGSTON, La., and HANFORD, Wash. — The LIGO Scientific Collaboration has reported identification of a second gravitational wave event in the data from Advanced LIGO detectors.

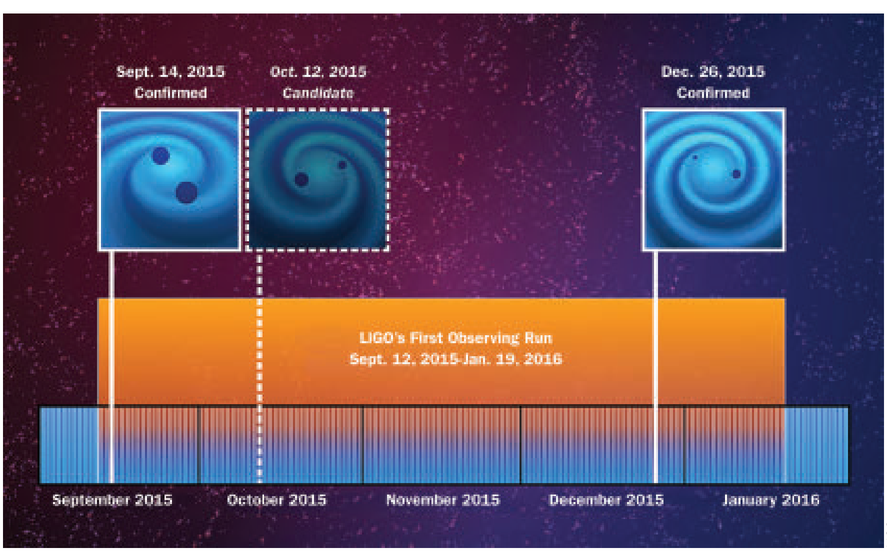
On Dec. 26, 2015, at 3:38:53 UTC, scientists observed gravitational waves — ripples in the fabric of spacetime — for the second time. The waves were detected by both of the twin Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors. Physicists have concluded that these gravitational waves were produced during the final moments of the merger of two black holes — 14 and 8 times the mass of the sun — to produce a single, more massive spinning black hole that is 21 times the mass of the sun.

"It is very significant that these black holes were much less massive than those observed in the first detection," said Gabriela González, LIGO Scientific Collaboration (LSC) spokesperson and professor of physics and astronomy at Louisiana State University. "Because of their lighter masses compared to the first detection, they spent more time — about one second — in the sensitive band of the detectors. It is a promising start to mapping the populations of black holes in our universe."



LIGO/T. Pyle

This illustration shows the merger of two black holes and the gravitational waves that ripple outward as the black holes spiral toward each other. The black holes — which represent those detected by LIGO on Dec. 26, 2015 — were 14 and 8 times the mass of the sun, until they merged, forming a single black hole 21 times the mass of the sun. In reality, the area near the black holes would appear highly warped, and the gravitational waves would be difficult to see directly.



LIGO

This timeline shows the dates for two confirmed gravitational-wave detections by LIGO and one candidate detection, which was too weak to unambiguously confirm. All three events occurred during the first four-month run of Advanced LIGO — the upgraded, more-sensitive version of the facilities.

During the black hole merger, which occurred approximately 1.4 billion years ago, a quantity of energy roughly equivalent to the mass of the sun was converted into gravitational waves. The detected signal comes from the last 27 orbits of the black holes before their merger. Based on the arrival time of the signals — with the Livingston detector measuring the waves 1.1 ms before the Hanford detector — the position of the source in the sky can be roughly determined.

The discovery was published in *Physical Review Letters*. The LIGO Observatories are funded by the National Science Foundation, and were conceived, built, and are operated by the California Institute of Technology and the Massachusetts Institute of Technology.

Photonics Media reported on the first detection of gravitational waves, announced on Feb. 11, 2016, which was a milestone in physics and astronomy, confirming a major prediction of Albert Einstein's 1915 general theory of relativity, and marking the beginning of the new field of gravitational-wave astronomy.

Advanced LIGO's next data-taking run will begin this fall. By then, further improvements in detector sensitivity are expected to allow LIGO to reach as much as 1.5 to 2 times more of the volume of the universe. The Virgo detector, a third interferometer located in Cascina, Italy, is expected to join in the latter half of the upcoming observing run.

The web version of this story features an animation showing the merger of two black holes and the gravitational waves that ripple outward during the event: **www.photonics.com/A60792**.

Novel design increases optical efficiency in graphene OLEDs

Korea Advanced Institute of Science and Technology and Pohang University of Science and Technology

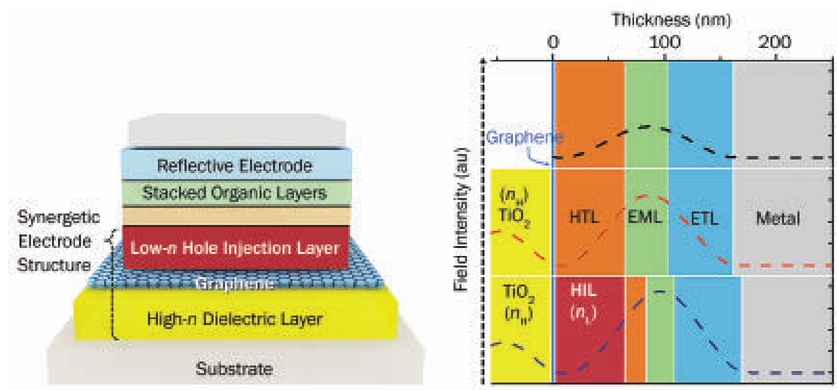
Application of graphene-based OLEDs. This picture shows an OLED with the composite structure of TiO_2/graphene/conducting polymer electrode in operation. The OLED exhibits 40.8 percent of ultrahigh external quantum efficiency and 160.3 lm/W of power efficiency. The device prepared on a plastic substrate shown at right remains intact and operates well even after 1,000 bending cycles at a radius of curvature as small as 2.3 mm.

DAEJEON, South Korea — Graphene-based OLED efficiency and flexibility have been shown to increase through a novel approach that uses graphene as a transparent electrode (TE) placed between titanium dioxide (TiO_2) and conducting polymer layers.

To improve the efficiency of graphene-based OLEDs, researchers from Korea Advanced Institute of Science and Technology (KAIST) and Pohang University of Science and Technology (POSTECH) fabricated a transparent anode in a composite structure in which graphene electrodes were sandwiched between a TiO_2 layer with a high refractive index (high-*n*), and a hole-injection layer (HIL) of conducting polymers with a low refractive index (low-*n*).

This optical design induced a synergistic collaboration between the high-*n* and low-*n* layers to increase the effective reflectance of TEs. As a result, the enhancement of the optical cavity resonance was maximized, improving the efficiency and color gamut in OLEDs. At the same time, the loss from surface plasmon polariton (SPP), a major cause for weak photon emissions in OLEDs, was reduced due to the presence of the low-*n* conducting polymers.

Graphene-based OLEDs that were developed using this approach exhibited ultrahigh external quantum efficiency (EQE) of 40.8 and 62.1 percent (64.7 and 103 percent with a half-ball lens) for single- and multijunction devices, respectively. Further, the OLEDs remained intact and operational even after 1,000 bending cycles at a radius of curvature as small as 2.3 mm, partly due to the TiO_2 layers withstanding flexural strain up to 4 percent. Oxides are typically brittle and prone to bending-induced fractures even at a relatively low strain. However, the research team discovered that TiO_2 has a crack-deflection toughening mechanism that tends to prevent bending-induced cracks from forming easily, enabling OLEDs to be highly flexible as well as efficient.



Korea Advanced Institute of Science and Technology and Pohang University of Science and Technology

Schematic device structure of graphene-based OLEDs. This picture shows the new architecture to develop highly flexible OLEDs with excellent efficiency by using graphene as a transparent electrode.

"What's unique and advanced about this technology, compared with previous graphene-based OLEDs, is the synergistic collaboration of high- and low-index layers that enables optical management of both resonance effect and SPP loss, leading to significant enhancement in efficiency, all with little compromise in flexibility," said KAIST professor Seung-hyup Yoo.

Graphene-based OLEDs have emerged as a key element in next-generation displays and lighting, mainly due to their promise as highly flexible light sources. Graphene's atomic thinness leads to a high degree of flexibility and transparency, making it an ideal candidate for TEs. Nonetheless, the efficiency of graphene-based OLEDs reported to date has been, at best, about the same level of indium tin oxide-based OLEDs.

The research was published in *Nature Communications* (doi: 10.1038/ncomms11791).

Capasso Lab reports planar metalens

CAMBRIDGE, Mass. — Materials science has made a great leap forward toward replacing glass lenses with metasurface materials that are practical to manufacture and produce aberration-free, subwavelength-resolution images. The planar metalens could replace traditional optics in smartphones, digital cameras and microscopes to enable further miniaturization of those devices.

The work was performed in the lab of Harvard University physics and applied engineering professor Federico Capasso, whose contributions to the field of photonics, in addition to metasurface research and development, include the quantum cascade laser. He discussed the technology with Photonics Media before the study's release.

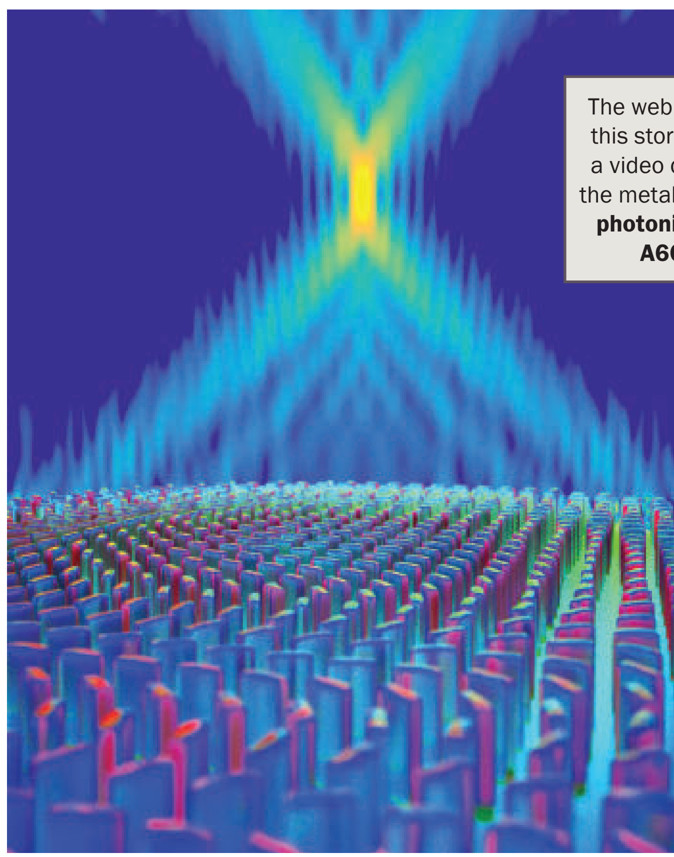
"We are reporting planar lenses … that operate at visible wavelengths, and the potential, we think, is huge to replace conventional lenses in a lot of applications," said Capasso, who described the metalens as the culmination of five years of focused research.

The metasurface lens features towers of titanium dioxide — about 600 nm in length — which focus light based on their patterning, enabling a uniform-thickness component. In the metasurface lens, the towers bend light toward the focal point; the researchers reported the metalens achieved the same resolution and magnification as a traditional glass lens 5 to 6 cm in length.

Capasso also said that fabrication of the planar lenses could become highly cost-effective, due to the technology's compatibility with memory and microprocessor chip foundries. The planar lenses could be fabricated similarly to integrated circuits and do not require polishing or complicated post-processing steps, as glass optics do.

Julia Germaine, News Editor
Julia.Germaine@photonics.com

The web version of this story features a video describing the metalens: **www.photonics.com/A60737**



Peter Allen/Harvard John A. Paulson School of Engineering and Applied Sciences

Schematic showing the ultrathin metalens. The lens consists of titanium dioxide nanofins on a glass substrate. The metalens focuses an incident light, entering from bottom and propagating upward, to a spot **(yellow area)** smaller than the incident wavelength.

Widely tunable MIR QCL eyed for spectroscopy, chemical sensing

EVANSTON, Ill. — A broadband-tunable IR laser has demonstrated the ability to capture the unique spectral fingerprints of gases. The monolithic laser technology is compact, and is expected to have applications in spectroscopy and chemical sensing.

The laser only has one moving part — a fan for cooling purposes — which Northwestern University professor Manijeh Razeghi cited as a major advantage over existing systems. Most such lasers require mechanical parts to achieve tuning. It operates in the 6.2- to 9.1-µm wavelength range with a single emitting aperture by integrating an 8-laser sampled grating distributed feedback laser array with an on-chip beam combiner, and its gain medium is based on a 5-core heterogeneous quantum cascade laser wafer.

Razeghi and her team integrated the laser into a system that contains all of the laser driver electronics and tuning software necessary for integration into a spectroscopy system. It produces a stable, single-aperture spot less than 3 mm in diameter that is suitable for standoff detection and is capable of linear or random access scanning with stabilization times of less than 1 ms per wavelength.

Initial results were published in *Scientific Reports* (doi: 10.1038/srep25213).

The laser system R&D is the culmination of more than 18 years of quantum cascade laser development work at Northwestern's Center for Quantum Devices, which Photonics Media has covered continuously. The work was supported by the Department of Homeland Security Science and Technology Directorate, the National Science Foundation, Naval Air Systems Command, DARPA and NASA.

Pryometric imaging system captures explosion parameters

ADELPHIA, Md. — A technique involving high-speed, high-fidelity imaging with optical filtering and signal processing techniques may make setting off explosives and capturing the data in real time a reasonable alternative to developing theoretical simulations to test explosives.

Research chemist Kevin McNesby and colleagues at the U.S. Army Research Laboratory, Lawrence Livermore National Laboratory and Los Alamos National Laboratory have developed an optical technique to image explosions in high resolution at costs approaching computer simulations. The researchers cited increasingly fast cameras and light sensors as key enablers of high-resolution experimental imaging.

The imaging system produces information about explosive behavior by capturing multiple variables during an explosion — pressure, temperature and chemical species maps — rather than a single point measurement, requiring additional shots for each variable.

Information gathering involved pyrometry, a technique for estimating temperature of incandescent bodies based upon their spectra of emitted thermal radiation. The experimental setup, which is specific to the type of explosive being investigated, employed a two-color imaging pyrometer comprising two monochrome cameras filtered at 700 and 900 nm, and a full-color single pyrometer that achieved wavelength resolution with a Bayer-type mask covering the sensor chip.

For each of their rigs, the framing speeds were 20,000 to 40,000 fps at a resolution of approximately 400 × 500 pixels with an exposure per frame of one to tens of µs.

The pyrometers were also able to capture the air shock structure of the detonation event, allowing for simultaneous measurement of temperature and pressure. Information regarding the chemical species was similarly captured via measuring the emission spectrum of each targeted molecule. The setup allowed a spatial resolution for a 1-kg explosive charge down to the 1-mm scale.

However, the researchers said the mapping technique resulted in wider error bars than those of conventional point measurement techniques. Future work will also include upgrading the imaging system for a tenfold increase in speed at full resolution.

The research was published in *Review of Scientific Instruments* (doi: 10.1063/1.4949520).

Scalable biomanufacturing technique may increase QD availability

ORNL

Using this 250-gal reactor, ORNL researchers produced three-fourths of a pound of zinc sulfide quantum dots, shown in the inset.

OAK RIDGE, Tenn. — A method for biomanufacturing large amounts of zinc sulfide nanoparticles inexpensively could lead to their wider availability and use in applications such as light-emitting displays, sensors and solar panels.

A research team from Oak Ridge National Laboratory (ORNL) used bacteria fed by sugar at a temperature of 150 °F in 25- and 250-gal reactors to produce about three-fourths of a pound of zinc sulfide quantum dots (QDs). This was achieved without using process optimization, indicating that even higher yields of QDs may be possible using this method. The ORNL biomanufacturing technique for producing QDs is based on a platform technology that can produce nanometer-size semiconducting materials as well as magnetic, photovoltaic, catalytic and phosphor materials.

Unlike many biological synthesis technologies, ORNL's biomanufactured QD synthesis occurred outside of the cells. As a result, the nanomaterials were produced as loose particles, making them easy to separate through washing and centrifuging.

Successful biomanufacturing of light-emitting or semiconducting nanoparticles requires the ability to control material synthesis at the nanometer scale with sufficiently high reliability, reproducibility and yield to be cost-effective. ORNL research team leader Ji-Won Moon said that goal had been achieved, noting that the ORNL approach reduces production costs by approximately 90 percent compared to other methods.

ORNL researchers envision their QDs being used initially in buffer layers of photovoltaic cells and other thin-film-based devices that can benefit from their electro-optical properties as light-emitting materials.

"Since biomanufacturing can control the QD diameter, it is possible to produce a wide range of specifically tuned semiconducting nanomaterials, making them attractive for a variety of applications that include electronics, displays, solar cells, computer memory, energy storage, printed electronics and bioimaging," said Moon.

The research was published in *Applied Microbiology and Biotechnology* (doi: 10.1007/s00253-016-7556-y).

Watch a video describing the QD production method on the web version of this story: **www.photonics.com/A60798**.

LED technology monitors construction-site safety

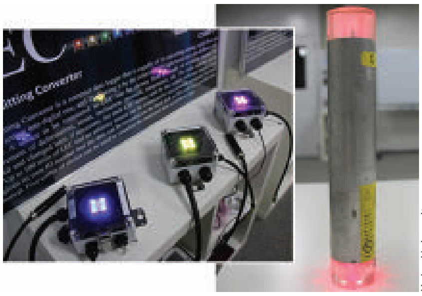
KOBE, Japan — A safety monitoring method called On-Site Visualization (OSV) has been implemented in metro system construction sites in Jakarta, Indonesia, as part of a Japan International Cooperation Agency (JICA) project.

OSV, developed by professor Shinichi Akutagawa of Kobe University, is a real-time data processing technology used to check safety levels at construction sites. A device with built-in LEDs is attached to walls and pillars at the building site and measures any irregularities or tilting. The LEDs light up like traffic lights to indicate the danger level with different colors: blue for "no irregularities," and yellow and red for "danger of collapse."

The clear method of representation was designed for implementation in countries with low literacy rates, where an increase in public works has been accompanied by a sharp rise in the number of accidents. Researchers monitored safety levels using OSV for a fixed period at three metro system building sites in the center of Jakarta — two stations in the city center and an elevated track in the south. The project received a positive evaluation from the head of construction at Jakarta Mass Rapid Transit.

In many developing countries, an increase in public works is accompanied by a sharp rise in the number of accidents, and there is a growing need for safety monitoring.

The JICA project, titled Economic and Social Development Support in Developing Countries through Partnerships with the Private Sector, had participants from multiple private organizations in the OSV Consortium (an industry-academic collaborative group that promotes use of OSV technology).

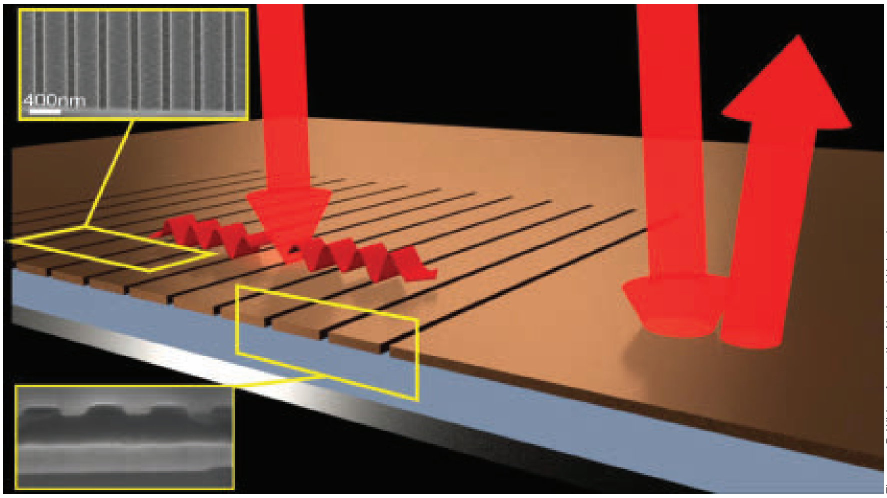


Kobe University

Two LED devices are attached to walls, and change color to warn of danger, measuring small irregularities in structures.

Ultrathin TLA materials could broaden IR applications

SYDNEY — Ultrathin gratings composed of common materials were shown to increase the absorption efficiency of light to almost 99 percent when thin grooves were etched into the film, directing the light sideways. The semiconductor materials are compatible with optoelectronic applications such as photodetectors and optical modulators, and could make IR technology less expensive and more accessible.



Thomas P. White, Australian National University

When light falls on a very thin, uniform layer, almost all of it is reflected **(right-hand arrows)**. By etching thin grooves in the film, the light is directed sideways and almost all of it is absorbed **(left-hand arrow)** even though the amount of material is very small. Insets show electron micrographs of the structuring. The absorbing layer is only 0.041-μm thick.

A team comprising researchers from the University of Sydney, Australia National University and University of Technology Sydney began their investigation by examining total light absorption (TLA) in homogeneous ultrathin films, finding that TLA was difficult to achieve in uniform ultrathin layers.

The team then turned their attention to producing ultrathin gratings of common materials. They demonstrated TLA of TE (transverse electromagnetic) polarized light using antimony sulphide (Sb_2S_3) semiconductor gratings, placed above a metal reflector. They reported that the asymmetric configuration allowed for TLA with only a single incident beam.

The researchers then fabricated a 41-nm-thick antimony sulphide grating structure with a measured absorptance of A = 99.3 percent at the visible wavelength of 591 nm. The results showed that the absorption within the grating was A = 98.7 percent, with only A = 0.6

percent within the silver mirror. In contrast, a planar reference sample absorbed only A = 7.7 percent at this wavelength.

The research team also investigated the range of material parameters that might be compatible with TLA in ultrathin gratings. Results showed that ultrathin gratings made of a wide range of weakly absorbing semiconductors could absorb nearly 100 percent of TE-polarized light.

"Conventional absorbers add bulk and cost to the IR detector as well as the need for continuous power to keep the temperature down," said professor Martijn de Sterke. "The ultrathin absorbers can reduce these drawbacks."

Researcher Björn Sturmberg said the findings did not rely on a particular material but could be applied to many naturally occurring weak absorbers.

"There are many applications that could greatly benefit from perfectly absorbing ultrathin films, ranging from defense and autonomous farming robots to medical tools and consumer electronics," Sturmberg said.

The near-perfect absorption of light in subwavelength thickness layers generally relies on exotic materials, metamaterials or thick metallic gratings. The structures developed by the Australian team are simpler to design and fabricate than existing thin-film light absorbers, which may require complex nanostructures or difficult-to-create combinations of metals and nonmetals, in addition to exotic or metamaterials. High-quality IR detectors cost approximately $100,000 and some require cooling to −200 °C. Significant cost, efficiency and sensitivity gains may be possible from making photodetectors using less material.

The research was published in *Optica*, a journal of The Optical Society of America (OSA) (doi: 10.1364/optica.3.000556).

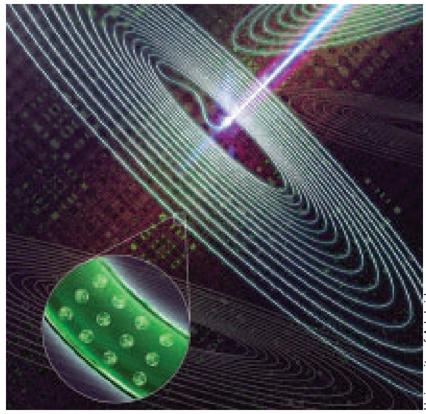
Luminescent nanoparticles advance smart glass technology

ADELAIDE, Australia — A method for embedding light-emitting nanoparticles into glass without losing any of their unique properties could be a major step toward smart glass applications, such as 3D volumetric displays, biomedical imaging systems and remote radiation sensors.

The "hybrid glass" combines the properties of novel lanthanide-containing upconversion nanoparticles with well-known aspects of glass, such as transparency and the ability to be processed into various shapes including fine optical fiber.

The research, conducted by the University of Adelaide in collaboration with Macquarie University and the University of Melbourne, was published online in the journal *Advanced Optical Materials* (doi: 10.1002/adom.201600296).

"… [N]euroscientists currently use dye injected into the brain and lasers to be able to guide a glass pipette to the site they are interested in," said Adelaide researcher Tim Zhao. "If fluorescent



University of Adelaide

Graphic representation of nanoparticles embedded in glass.

nanoparticles were embedded in the glass pipettes, the unique luminescence of the hybrid glass could act like a torch to guide the pipette directly to the individual neurons of interest."

The researchers reported a versatile direct-doping approach for integrating bright upconversion nanocrystals in tellurite glass with tailored nanoscale properties. Following a two-temperature glass-melting technique, the doping temperature window of 550 to 625 °C and a 5-min dwell time at 577 °C were determined as the key parameters, balancing the survival and dispersion of the nanocrystals in glass.

Although the method was developed with upconversion nanoparticles, the researchers believe their direct-doping approach could be used with other nanoparticles with interesting photonic, electronic and magnetic properties.

"If we infuse glass with a nanoparticle that is sensitive to radiation and then draw that hybrid glass into a fiber, we could have a remote sensor suitable for nuclear facilities," said Zhao.

To date, the method used to integrate upconversion nanoparticles into glass has relied on the in-situ growth of the nanoparticles within the glass. The researchers said better control over the nanoparticles and glass compositions is necessary to continue developing the technology.

Compound transforms IR into broadband white light

MARBURG, Germany — A compound that can transform near-infrared (NIR) light into broadband white light could offer a cheap, efficient means to produce visible light. The light is also exceedingly directional, a desirable quality for devices such as microscopes that require high spatial resolution, or for applications with high throughput, such as projection systems.

Researchers from the Philipp University of Marburg and Justus Liebig University Giessen designed their compound of tin and sulfur, with a diamondoid-like structure, then coated the scaffolding with organic ligands. When irradiated with NIR laser light, the structure of the compound altered the wavelength of the light through a nonlinear interaction process, producing light at wavelengths that are visible to the human eye.

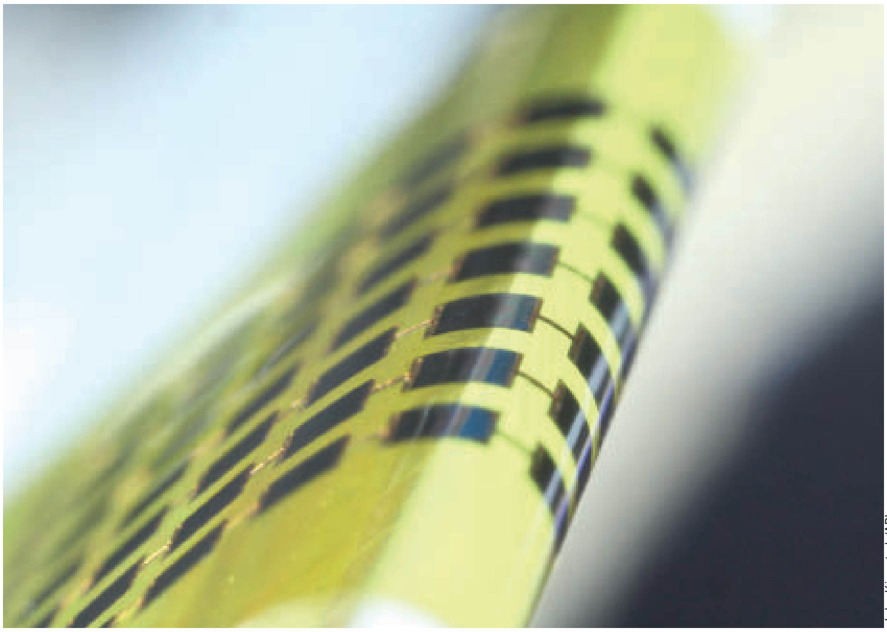
The researchers noted that the warm, white-colored light emitted was similar to a standard tungsten-halogen light source (2856 K), and can be adjusted based on levels of excitation via the laser.

The development could open up new routes for advanced directed illumination technologies, especially since the materials used in this system are inexpensive, readily available and scalable. The research was published in *Science* (doi: 10.1126/science.aaf6138).

1-µm-thick solar cell could advance wearable electronics

GWANGJU, South Korea — An ultrathin photovoltaic that is flexible enough to wrap around an object just 1-mm thick may offer the reliability and flexibility that wearable technologies require, at a performance level comparable to thicker photovoltaics.

Researchers at the Gwangju Institute of Science and Technology used transfer printing to make ultrathin, vertical type



Juho Kim et al./APL

Ultrathin solar cells are flexible enough to bend around small objects, such as the 1-mm-thick edge of a glass slide shown here.

gallium arsenide photovoltaic devices with a total thickness of 1 µm — about one quarter the size of similar devices with a lateral design.

To achieve the desired thinness, the researchers transfer-printed their device directly onto metal electrodes on flexible receiver substrates for a direct electrical interconnection, without the aid of an interlayer adhesive that would add to the material's thickness. The cells were then "cold welded" to the electrode on the substrate by applying pressure at 170 °C and melting a top layer of photoresist to act as a temporary adhesive. The photoresist was later peeled away, leaving a direct metal-to-metal bond. The metal bottom layer also served as a reflector to direct stray photons back to the solar cells to be recycled.

Systematic studies with four different types of solar microcells demonstrated that the vertical-type solar cells generated a level of electric power comparable to that of thicker cells. The experimental results also showed that the ultrathin vertical-type solar cells were durable under extreme bending and thus suitable for use in the manufacturing of wearable flexible electronics. In bending tests, the ultrathin cells demonstrated the ability to wrap around a radius as small as 1.4 mm.

"The thinner cells are less fragile under bending, but perform similarly or even slightly better," said researcher Jongho Lee.

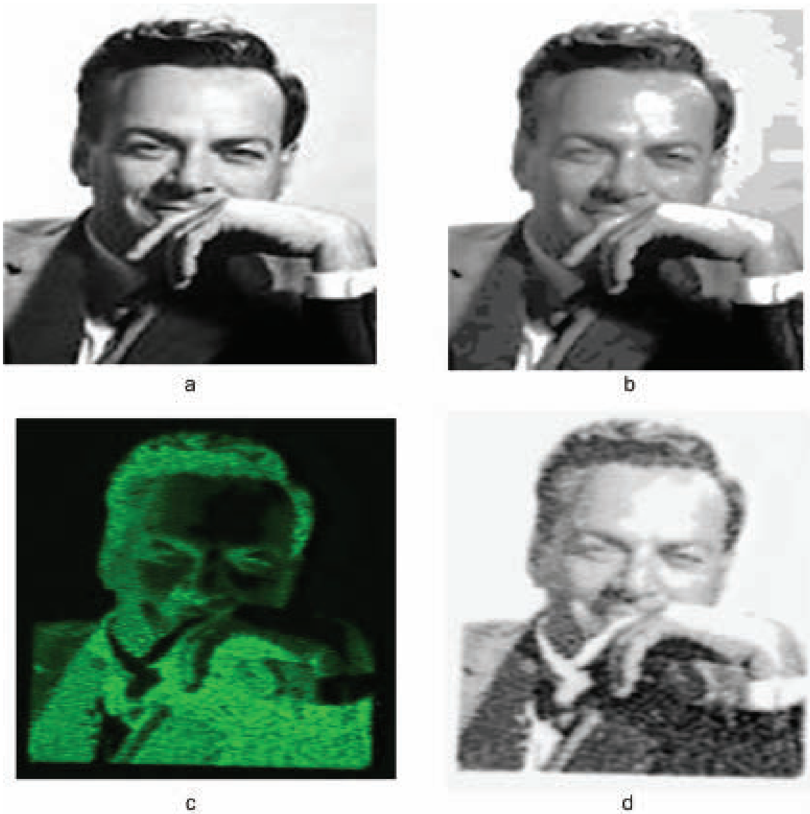
Ultrathin photovoltaic devices may benefit applications that require extreme mechanical flexibility with electrical performance capabilities similar to those of thicker devices. The thin cells can be integrated onto glasses, frames or fabric and might power the next wave of wearable electronics, said Lee.

The research was published in *Applied Physics Letters* (doi: 10.1063/1.4954039).

Ultrafast lasers enable high-density data storage

OTTAWA, Ontario — A laser-based data storage and retrieval technique could increase the storage capacity of conventional optical discs, such as DVD and Blu-ray, without the need for special preparatory steps. The scalable technique stores information bits in a multilayer structure using the 3D volume of the disc, and ultrafast lasers are used to keep the changes in the disc on a micron scale.

Conventional discs can currently be transformed into ultrahigh capacity stor-



Mary Evans Picture Library/The Canadian Press

A 5-bit (32 gray-level) image fabrication. **(a)** Multi-gray image of Richard Feynman, Nobel laureate in physics in 1965 (105 × 147 pixels). **(b)** Processed image after assigning 32 gray levels corresponding to write laser pulse energy range of 25 to 130 nJ. A femtosecond laser operating at 800 nm was used as write laser. **(c)** Confocal fluorescence microscope image of **(b)** obtained by a CW, 488-nm read laser at 100 μW of power. **(d)** Reconstructed negative image of **(c)**.

age media by encoding multilevel and multiplexed information within the 3D volume of the recording medium. However, in most cases the recording medium must be photosensitive, which requires doping with photochromic molecules or nanoparticles.

To exploit 3D optical data storage capabilities without the need for dopants, researchers at the University of Ottawa used a pulsed laser to record data in micron-sized modified regions of a disc. Upon excitation by the read laser, each modified region emitted fluorescence. The fluorescence moieties induced by the laser demonstrated different emission profiles upon excitation at different wavelengths. The researchers correlated the intensity of the fluorescence signal with the energy of the recording laser and used this to assign 32 gray levels, corresponding to five bits of data.

The research team demonstrated that up to 20 layers of embedded data were possible. By tailoring the read laser power and detector sensitivity, the number of layers in a conventional optical disc that could be imaged without loss of information could be extended up to 30 (up to 60, if data on both sides of the disc was read).

The flexibility provided by this technique enables data to be stored in commonly available plastics and makes data accessible at any excitation within the visible spectrum. The stored data can be embedded in the bulk material and is thermally stable up to the glass transition temperature of the recording medium.

Storage capacities of up to 0.2 TB, scalable up to 0.5 TB, were demonstrated. Higher storage capacities could potentially be achieved by overcoming the diffraction limit of light to record data on a submicron scale.

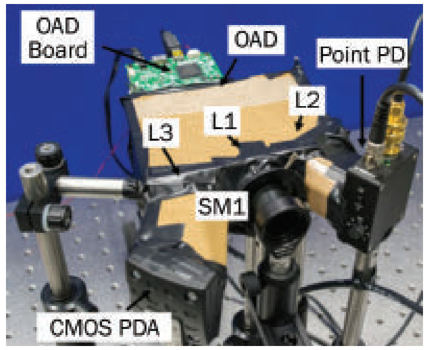
The research was published in *Scientific Reports* (doi: 10.1038/srep26163).

Coded Access Optical Sensor boosts CMOS/CCD performance

CORK, Ireland — Cork 1A camera technology dubbed Coded Access Optical Sensor (CAOS) now works in unison with CCD and CMOS camera sensors to extract previously unseen images.

The CCD sensor camera — a technology that earned its inventors a Nobel Prize in 2009 — and CMOS sensor camera, dominate imaging applications from medicine to industrial testing and machine vision to astronomy. Now researchers from University College Cork, led by professor Nabeel Riza, have demonstrated a CAOS-CMOS design that combines the CAOS imager platform with a CMOS multipixel optical sensor.

Unlike current CCD and CMOS cameras, the CAOS camera exploits the extreme dynamic range of electronic wireless technology by engaging time-frequency coding of agile pixels in the image space combined with time-frequency domain decoding via electronic processing to extract the pixel light intensity information.



Nabeel Riza/*Optics Express*, a publication of The Optical Society (OSA)

Image captured by CAOS camera of an extreme contrast and brightness target.

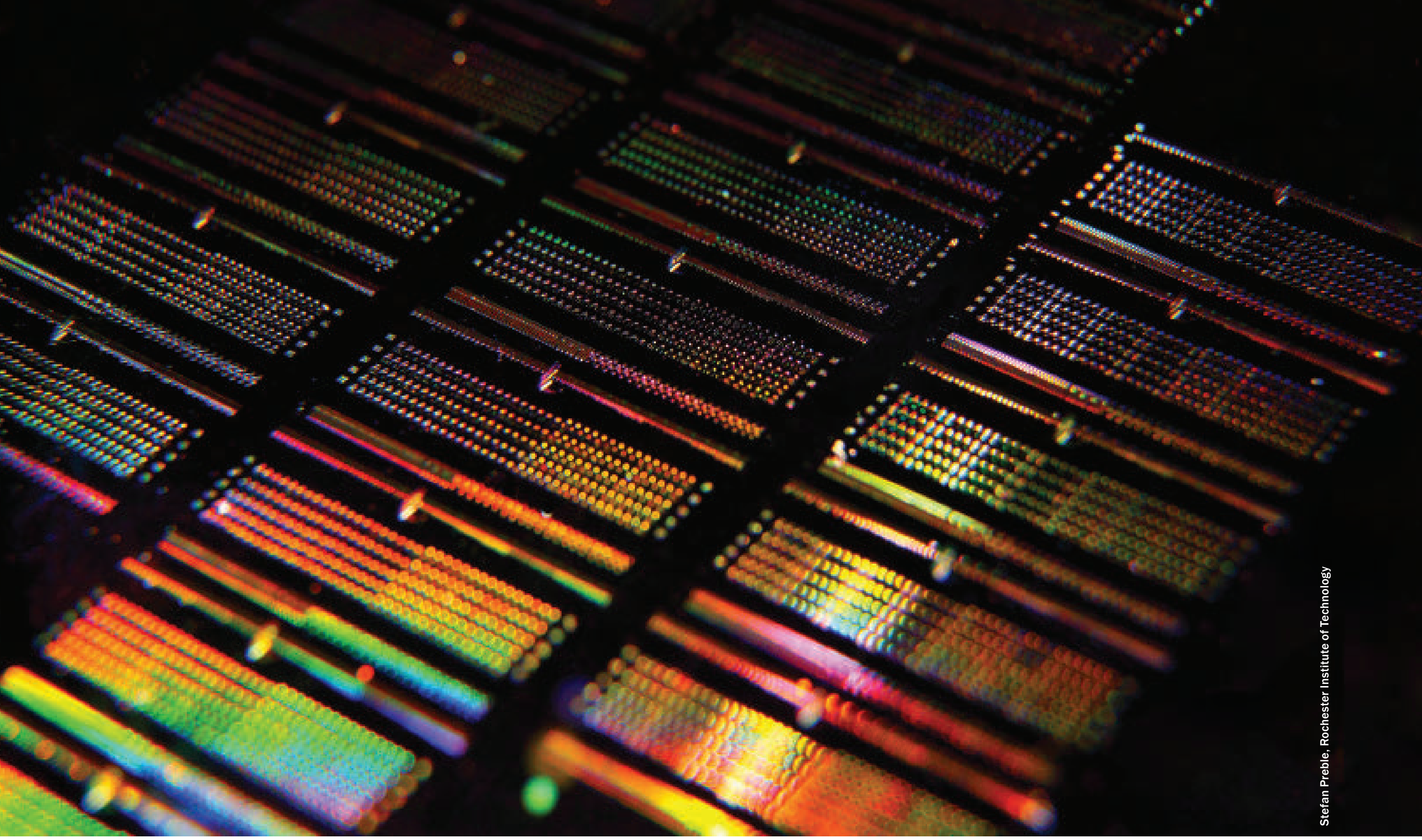
Riza and his team demonstrated a three-order (a factor of 1000) improvement in camera dynamic range over a commercial CMOS sensor camera when subjected to test targets that created extreme brightness, as well as extreme contrast (>82 dB) conditions.

In addition, compared to prior cameras, the CAOS camera features exceptionally low-noise interpixel crosstalk performance along with optical spectrum flexibility — such as from the UV to near-infrared range, and high-speed imaging capabilities.

The experimental CAOS-CMOS camera comprised a digital micromirror device, a silicon point-photo-detector with a variable gain amplifier, and a silicon CMOS sensor with a maximum-rated 51.3-dB dynamic range. White light imaging of three different brightness simultaneously viewed targets not viewable with the CMOS sensor alone, demonstrating an 82.06-dB dynamic range.

Applications for the camera could include industrial machine vision, welding, laser analysis, automotive, night vision, surveillance and multispectral military systems. The research was published in *Optics Express*, a publication of The Optical Society (OSA).

The web version of this story contains an additional image: **www.photonics.com/A60804**



This working integrated photonic wafer created by Rochester Institute of Technology researchers contains thousands of integrated photonic devices including waveguides, filters, couplers, modulators and more. These integrated photonic chips will lead to higher performance sensors, computers and communication networks.

For **Integrated Photonics**, a Tale of Two Materials

With its suitability for monolithic integration for optics and photonics, silicon has been widely hailed as the material of the future. But graphene — with its capacity for signal emission, transmission and detection — could be the next disruptive technology.

BY MICHAEL D. WHEELER
MANAGING EDITOR

Last July, the U.S. unveiled a national institute for integrated photonics backed by $600 million in federal, state and private funding. The Rochester, N.Y.-based American Institute for Manufacturing Integrated Photonics, better known as AIM Photonics, brings together academia, federal research institutions and companies in an effort to emulate the successes of the electronics industry over the past 40 years.

The reason for the fanfare and concerted effort lies in the exciting breakthroughs integrated photonics promises: the development of chips capable of controlling the relative phase of light for use in robotics or self-driving cars; biological and chemical sensors that can detect even the subtlest environmental change; optical computing; and data communications.

Indeed, integrated photonics — a term that encompasses the design and fabrication of electronic/photonic devices and their components on a chip — is on the precipice of exciting breakthroughs.

“These electronic-photonic chips will represent a new paradigm in circuit design and enable a wide range of future applications including: high bandwidth, low power interconnects within chips and between them; highly sensitive biological/chemical sensors that exploit the interference properties of light; and analog photonic chips for RF signal transmission and processing in cellular networks and radar," said Stefan Preble, Ph.D., director of Rochester Institute of Technology's (RIT) Integrated Photonics Group, who is leading the integrated photonics efforts of RIT's Future Photon Initiative.

Today's integrated photonic circuits are rudimentary compared to the complexity of today's electronic circuits. Yet they are likely to be far more complex — by orders of magnitudes — within five to 10 years, as the technology matures and electronic and photonic functionalities are integrated, Preble said.

He, like others, draws strong parallels with where photonics technologies are today and where microelectronics were 40 years ago.

"In the '70s, there were only thousands of transistors in computer chips, but because of improvements in integrated circuit manufacturing, it is now possible to have billions of transistors in the same footprint," Preble said. "It's well-known that the density of these circuits has traditionally followed Moore's law, where the number of transistors on a given wafer doubles every two years."

Potential of silicon 'enormous'

For that trajectory to occur, researchers must continue to push the boundaries when it comes to materials.

The first advances came in the late '90s with the development of planar waveguides that were created out of glass substrates using photolithography. Efforts to insert these waveguides into integrated circuits were soon abandoned as they proved to be too large for use on circuits, and problems arose integrating both lasers and detectors, due to incongruities with the materials.

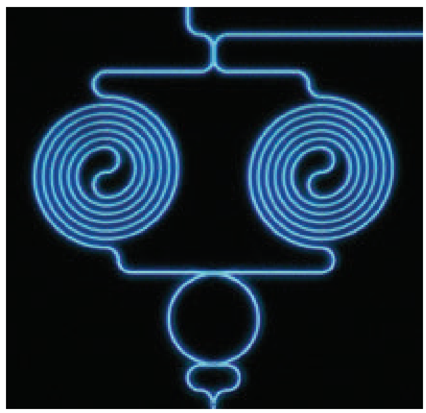
By the early 2000s, all eyes were on silicon, with its high refractive index and capabilities that included confining light and support for internal reflection. It's also transparent in the same wavelength regions used in fiber optics (1300 to 1600 nm).

But along with these characteristics came another: silicon's compatibility with traditional CMOS manufacturing. Done in volume, CMOS manufacturing can be very inexpensive and makes use of the same infrastructure in place for manufacturing microelectronics.

"Silicon waveguides have inherent cost advantages over other integrated photonic technologies," Preble said. "Furthermore, silicon waveguides have proven to be more compact and operate with lower loss than III-V based waveguide platforms."

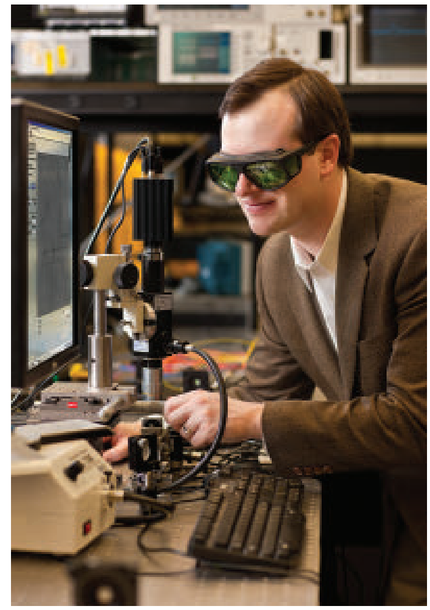
One challenge is the difficulty — and cost — associated with packaging. Silicon photonic chips must be connected to optical fibers, and these fibers are significantly larger than the waveguides. This results in a large mismatch in energy confinement between the optical fiber and nanophotonic waveguide, presenting a challenge in coupling light between the two.

Mode converters have been used to ease this transition, achieving coupling efficiency rates that exceed 70 percent.



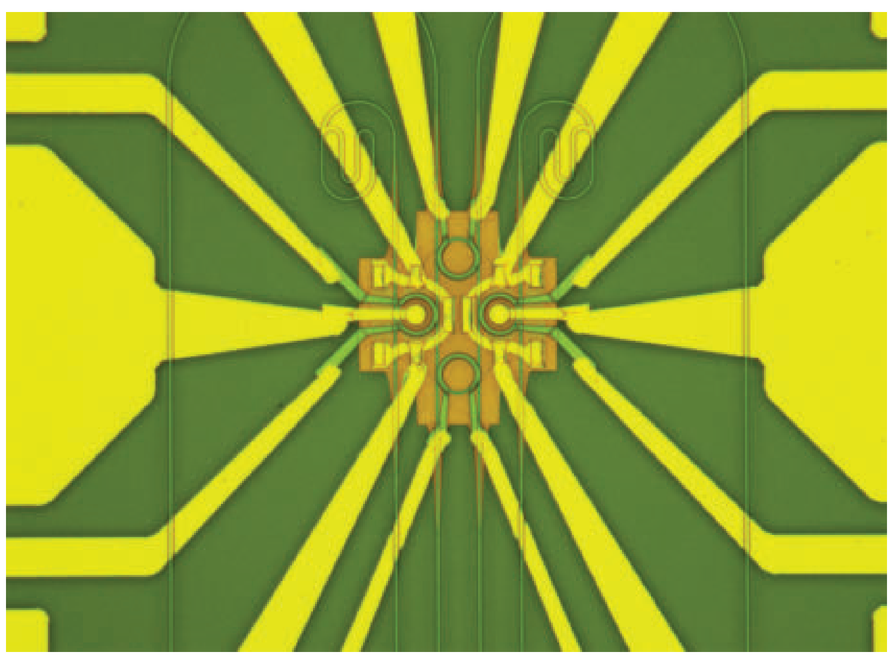
Stefan Preble, Rochester Institute of Technology

Integrated photonics will enable secure communication systems that exploit the quantum properties of light.



John Myers/Myers Creative Imaging

Stefan Preble, director of Rochester Institute of Technology's Integrated Photonics Group, at work in his lab.



Stefan Preble, Rochester Institute of Technology

An on-chip circuit converts electrical data into photons. This combination allows information to be transferred at much higher rates with lower power.

Kaiam Corp.

A high-volume production facility in Livingston, Scotland, is used to produce silica-on-silicon integrated optics and silicon MEMS wafers **(above and right)**.

But these high efficiencies are only realized when the optical fibers are "actively" and precisely aligned. A laser and detector must be used to monitor the amount of light getting in and out of the chip, and then the fiber is locked in place using epoxy.

"In order to solve the packaging issue, passive alignment techniques, similar to the pick-and-place tools commonly used for electronic chips, are required to overcome the time-sensitive active alignment being used today," Preble said.

IBM, based in Armonk, N.Y., has been at the forefront of efforts in passive alignment.

Engineers there have been working on novel optical input/output (I/O) solutions aimed at low-cost, wide optical bandwidth and a large optical port count. Their approach involves leveraging fully automated microelectronic packaging facilities for photonic packaging specifically, and utilizing microelectronics wafer production facilities for photonic wafer fabrication. This is in contrast to today's highly specialized, state-of-the art facilities with only partial automation.

Another drawback for silicon is the difficulty in integrating lasers. Since silicon cannot be used as a laser material, traditional III-Vs such as gallium arsenide (GaAs) must be integrated on the same silicon wafer. And this must be done cost-effectively.

The first significant breakthrough came in 2006, when a team of researchers that included Intel's Mario Paniccia and John Bowers of the University of California, Santa Barbara, discovered how to embed an electrically pumped AlGaInAs-silicon

Kaiam Corp.

evanescent laser architecture in which the laser cavity was formed from silicon[1].

More recently, new techniques have been developed for directly growing III-V lasers on silicon wafers. In 2014, another group led by John Bowers used a technique called beam epitaxy to grow quantum dot lasers on silicon.[2]

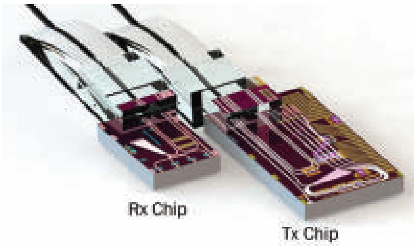
This March researchers from the University College London, University of Sheffield and Cardiff University unveiled a silicon-based laser that could be fully integrated on photonic and electronic circuits — without wafer bonding. The 1300-nm wavelength laser could operate at temperatures up to 120 °C for up to 100,000 hours.

"Realizing electrically pumped lasers based on [silicon] substrates is a fundamental step towards silicon photonics," said Cardiff University professor Peter Smowton.

Conventional fabrication methods

Replicating these critical advances from the lab to a real-world manufacturing environment remains a work in progress.

An exciting development came last December, when researchers from the University of California, Berkeley, the Massachusetts Institute of Technology (MIT) and the University of Colorado, Boulder, used conventional fabrication methods in a foundry that mass produces computer chips to build what they said was the first fully integrated photonic chip that incorporated all the photonic interconnects (I/O) needed to communicate with other chips.[3] The device consisted of two processor cores with more than 70 million transistors and 850 photonic components, and demonstrated a bandwidth density of 300 Gb/s per square millimeter, about 10 to 50 times greater



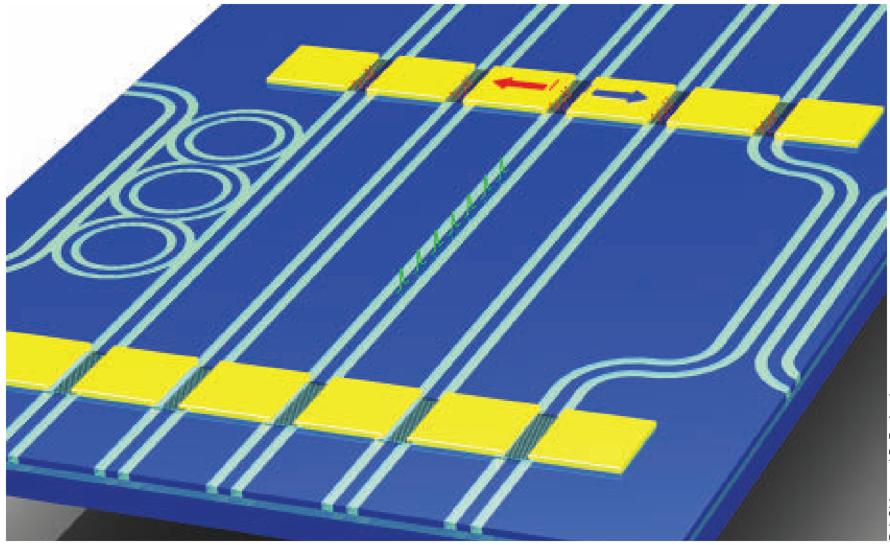
Mellanox Technologies

A silicon photonics 100Gb/s and 200Gb/s wave division multiplexing (WDM) chipset.

than packaged electrical-only microprocessors on the market.

Today, a growing number of firms, including Intel, IBM and Cisco, are actively developing and commercializing silicon photonic technology. Mellanox Technologies, with headquarters in Sunnyvale, Calif., and Yokneam, Israel, is another of these pioneers, fabricating its own integrated circuits and switches for servers used in enterprise data centers.

The company's silicon platforms are notable for efficiently supporting wavelength division multiplexing (WDM), which converts parallel channels into a single optical channel such as a waveguide or fiber strand. This optical integration reduces the fiber interconnect by a factor of eight, according to Arlon Martin, Mellanox's senior director of marketing.



R.J. Shiue and D. Englund

Graphene and other two-dimensional materials are being developed as active components on photonic integrated circuits. In this image, photonic modulators **(bottom row)** encode data in digital pulses carved from a continuous-wave input laser. These pulses are detected by chip-integrated photodetectors **(top row)**. Other optical components such as ring filters and beamsplitters can be integrated on the same circuit.

Mellanox's 200 Gb/s InfiniBand and

Ethernet transceivers conform to the compact quad small form-factor pluggable (QSFP) — the most widely used package in data center connectivity. The enabling technologies are 50 Gb/s modulators and detectors built on silicon photonics.

"For silicon photonics, low-speed and low-cost lasers can be used, because the difficult, high-speed modulation is done in silicon," Martin said.

Mellanox also achieved what it touts as an industry first: packaging lasers with direct coupling to the silicon chip — without a lens, isolator or filter. This eliminates the need for a transmitter optical subassembly (TOSA), which is an expensive step in that it requires optical alignment of multiple components. Alignment of the components within the TOSA must take place in a cleanroom environment, because even a tiny speck of dust would disrupt the laser.

Martin added: "In five to 10 years we will have Tb/s links using silicon photonics. We may see SiP integrated with switches, routers and servers/adapters for data center interconnects."

Increasing demand for bandwidth

The ever-expanding appetite for bandwidth in the data center and beyond has led Newark, Calif.-based Kaiam to push the bounds of silicon photonic integration too.

The startup demonstrated a 100 Gigabit/s course wavelength division multiplexing silicon photonics transceiver, the CWDM4, at OFC 2016 in Mrch. The module combines all the high-speed electronics components together with high-performance silicon modulators and detectors in a single 3D stack. The silicon chip carries out transmit and received functions via silicon modulators and silicon receivers.

"Kaiam's ability to easily and accurately assemble the silicon photonics chip in the module, as well as couple light on and off the chip efficiently, has made the technology feasible from a transceiver perspective, at this early stage, with room for more silicon advancements that [will] pave the way for a fully integrated photonics chip," said Ramsey Selim, senior design engineer for Kaiam.

The next step will be getting light from the silicon chip to the fiber directly, which is a technical challenge for the moment, he said.

Selim echoed the advantages of silicon as the material of choice, given the huge investments in the semiconductor infrastructure, while the small feature size of silicon chips — and subsequent smaller footprint — enables lower-cost, high-volume manufacturing.

"Permanently tuning the waveguide properties post fabrication is still a challenge," Selim said. "The technology is still limited by the lack of a silicon laser, although some companies are bonding III-V lasers directly onto the silicon chips."

Graphene: 2D material of the future

If silicon is the material of today — and the foreseeable future — then graphene represents the next frontier.

In its simplest terms, graphene is a thin layer of pure carbon atoms that are bonded together in a hexagonal honeycomb lattice. Not only is it the thinnest

Matter Dynamics Lab

Eva Campo and her research team in the lab at Bangor University in the U.K.

crystal structure known at one atom thick, but also the strongest compound discovered — several hundred times stronger than steel, as well as being the best conductor of heat at room temperature and also the best known conductor of electricity.

Graphene is capable of strong light-matter interactions, and high optical nonlinearity, allowing for all-optical signal processing. This avoids the need for the conversion of the optical signal to the electrical, bypassing the need to design high-speed interfaces between optical electronic parts.

"Graphene alone assembles a multiplicity of functions such as signal emission, transmission, modulation and detection," said Eva Campo, Ph.D., a professor at the School of Electronic Engineering at Bangor University in Wales. "In comparison with silicon and even III-Vs, graphene's properties are superior in terms of thermal conductivity, optical damage threshold and also third-order optical nonlinearities."

These properties make it ideal for optical communications — specifically photodetectors in the mid-infrared and long-wave range, nonlinear optics and mode-locked lasers, said Dirk Englund, an assistant professor of electrical engineering and computer science at MIT in Cambridge, Mass.

"In optical communications, you need a way of encoding signals on the transmitter side and detecting them on the receiver side. If this light is in the telecom band — about 1.5 µm in wavelength — then it can transmit through silicon with low attenuation," he said.

As a result, it's possible to guide telecom light in silicon waveguides in a photonic circuit.

To encode information onto the intensity of the light, a modulator is needed. That's where graphene, with its strong tunability, has shown promise.

"Since the telecom laser is below the bandgap of silicon [and] not absorbed, silicon itself doesn't make a good detector. Graphene can again help here since it allows very fast photodetection," Englund said.

Future promise

Still, there are considerable hurdles impeding commercialization. At the SPIE Photonics Europe Conference in Brussels in April, experts noted that graphene wasn't yet at a point suitable for front-end integration on integrated circuits, where Campo said graphene can really outperform current technologies. The issues cited at the SPIE forum included CMOS scalability and material performance — both several orders of magnitude below optimal levels.

Current efforts are focused on the reliable and cost-effective growth of graphene, with recent continued development of techniques such as chemical vapor deposition.

Growing graphene on very flat surfaces

is important to produce "high mobility" graphene. This technique involves growing graphene over large foils and then transferring them roll-to-roll, which, unfortunately, can sometimes cause large- or small-scale rippling, inflicting damage on the electronic performance of the graphene.

"This strain distribution has been identified as the major handicap in fabrication," Campo said, adding that her research group, in collaboration with Wright Patterson-AFRL, Synchrotron Research, Brookhaven and Lawrence Berkeley National Laboratories, is devising synchrotron hyperspectral spectroscopies aimed at improving fabrication, by collecting metrics across the waver form in and out of plane strain.

To improve graphene fabrication, a growing list of companies such as Lucent, IBM and Samsung are investing significant resources into exploring and developing scalable production techniques for graphene. Research teams from MIT, including Englund's from Cambridge University, as well as the Institute of Photonic Sciences (ICFO) in Barcelona and others are also engaged in the effort, along with the Graphene Flagship, a 1€ billion research program in Europe that combines 140 research partners in 23 countries.

Due to the uncertainty in manufacturing the new material, and the formidable hurdles presented in order to engineer and optimize graphene-based devices, a significant and sustained effort is required to bring them to commercialization.

"Graphene modulators are pretty competitive on paper, but there is still some ways to go to make their production scalable and easily integrated with modern integrated photonics; and to prove the resulting devices are sufficiently better to cause people to switch," Englund said. "The next 10 years will tell!"

Added Campo, "Once the technology is fully developed, graphene might supplant silicon, but the current vision is for a hybrid integrative approach."

"In order to meet the increasing demands for broadband data transmission, a hybrid fabrication approach taking advantage of the properties of both silicon and graphene seems a suitable solution," she said.

michael.wheeler@photonics.com

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Did this article pique your interest?
Watch for the January trends issue, for more comprehensive coverage of integrated photonics.

Simulation, Experiment Unite **Graphene** and Plasmonics

Simulation tools bring the complex physics of two-dimensional materials and plasmonics together in a way that could change the face of optoelectronic devices.

BY VALERIO MARRA
COMSOL INC.

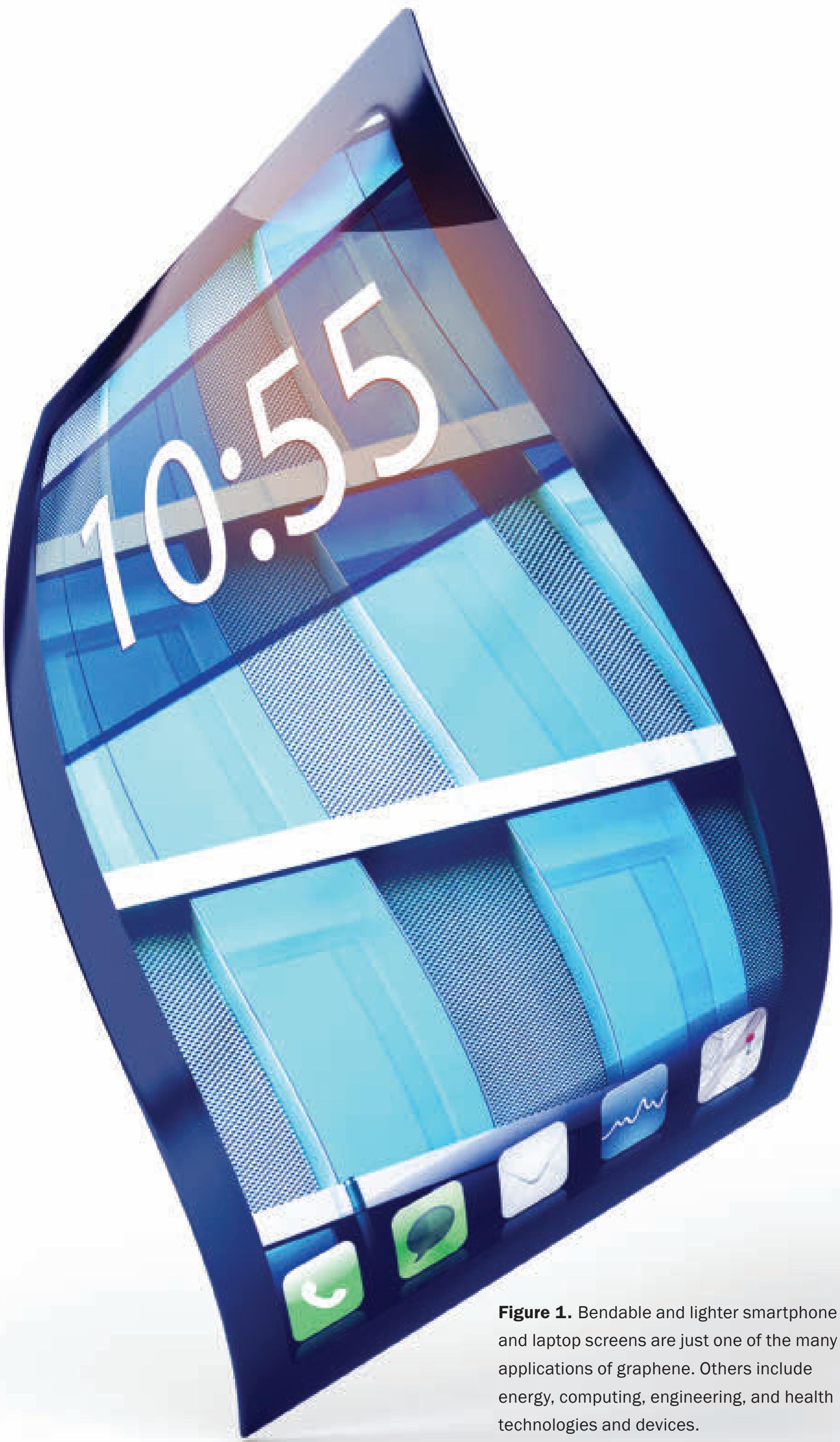

Figure 1. Bendable and lighter smartphone and laptop screens are just one of the many applications of graphene. Others include energy, computing, engineering, and health technologies and devices.

Ever since a single-atom-thick film of graphite was first successfully synthesized back in 2004, graphene has been on a decade-long ride through applications ranging from photovoltaics and next-generation batteries to electronics.

While its electrical and thermal conductivity made it attractive for electronics, its equally interesting optoelectronic capabilities were initially overlooked. But it soon became clear that graphene has incredible potential as a transparent conducting electrode and could be an alternative to the commonly used indium tin oxide (ITO). Graphene offers comparable or better optoelectronic performance in addition to its mechanical strength and flexibility. Other potential uses are diverse, and include applications such as transparent conductors used in touchscreens and photovoltaics (Figure 1), lab-on-a-chip devices for the sensing of viruses or proteins, improved night vision, mid-IR imaging applications and solar cells.

In addition to optoelectronics, graphene's star has shone particularly bright in photonics when it is used in combination with the field of plasmonics, the exploration of light on ever-smaller scales. Squeezing light into smaller dimensions is fundamentally challenging due to the

Images courtesy of **Purdue University**.

diffraction limit. The use of plasmonics helps address this challenge and enables light confinement even at the nanoscale. This is achieved by coupling incident light into oscillations of electrons known as plasmons — hence the name plasmonics. Today, plasmonics is an active branch of photonics that deals with the efficient excitation, control and use of plasmons.

Graphene-enabled plasmonics

Computational nanophotonics efforts at Birck Nanotechnology Center, Purdue University, led by Alexander V. Kildishev, associate professor of electrical and computer engineering, have been leading the way in combining graphene with plasmonics to bring it closer to practical optoelectronic applications.

The work of Kildishev and his colleagues deals with a fundamental problem in graphene research: the difficulty of fabricating high-quality, large-area graphene films. Until graphene production improves, Kildishev and his team are leveraging simulation tools to perform design and optimization of devices made from graphene.

Through both simulation and experimental testing, Kildishev and his colleagues have been able to demonstrate tunable graphene-assisted damping of plasmon resonances in nanoantenna arrays, which is important for designing tunable photonic devices in the mid-infrared range[1]. Since the mid-infrared is where fundamental vibrational resonances reside for a wide range of molecules, it is critical to have tunable plasmonic devices that work in that range for applications in sensing and imaging.

On the other hand, moving closer to even shorter infrared (IR) waves — the telecom range — is also of ultimate importance for telecommunications and optical processing. The group at Purdue has shown efficient dynamic control of Fano resonances in hybrid graphene-metal plasmonic structures at near-infrared wavelengths. Fano resonances are seen in the transmission of specifically coupled resonant optical systems. Researchers are currently leveraging the properties of Fano resonances for use in optical filtering, sensing and modulators (Figure 2).

Leveraging the predictive power of Comsol Multiphysics software models is part of the team's process for designing tunable elements for the next generation of plasmonic and hybrid nanophotonic on-chip devices, such as sensors and photodetectors. The photodetectors could ultimately find use in the sensing of infrared electromagnetic radiation for multicolor night vision and thermal imaging. Another application may be in biosensing, where the resonant lines of plasmonic elements are tuned to match

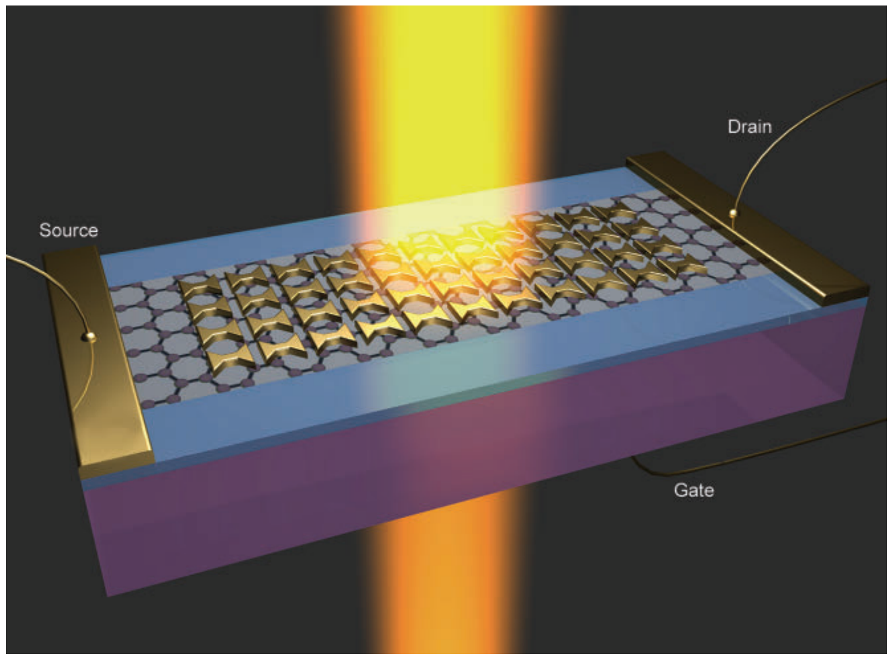

Figure 2. Design of Fano resonant plasmonic antennas on top of a single-layer graphene sheet optimized with modeling to achieve resonance at a 2-μm wavelength. The design tunability has been successfully validated in experiments using ion-gel top electrolyte gating[2].

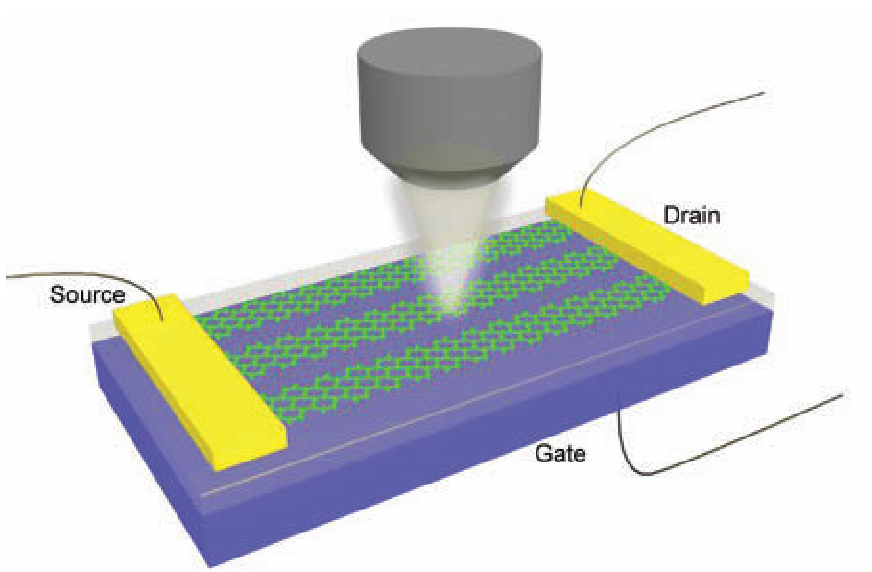

Figure 3. 3D artist's sketch of the experimental setup used for studying plasmon resonance in graphene nanoribbons (GNRs), simulated with Comsol Multiphysics software using the surface current approach. The lattice orientation of GNRs is for illustration only and dimensions are not to scale.

the resonances of the spectral optical responses of viruses or proteins.

In their work, the Purdue researchers combined the unique properties of graphene with plasmonic nanoantennas to modulate the antenna's optical properties. Having a tunable resonant element along an optical path is as critical to optoelectronics as having a transistor in an electric circuit.

"By using the nanopatterned graphene with an electrical gating (Figure 3), it's possible to modulate light flow in space with unparalleled spatial resolution," said Naresh Emani, a former Ph.D. student advised by Kildishev, now with DSI, Singapore. "The reduced dimensionality and semi-metallic behavior of graphene plasmonic elements gives us, along with its other properties, a very vital feature — electrical tunability. This critical functionality is not attainable with conventional metal plasmonics."

Plasmonic devices based on noble metals lack this level of control over electrical tunability. Noble metals possess a large number of electrons in the conduction band, and consequently the electrical conductivity of metals cannot be easily modulated. But since graphene is a tunable semimetal, it does not contain any electrons in the conduction band in its pristine state. Therefore, its electron concentration — and hence its electrical conductivity — can be tuned chemically, modulated electrically, or even modulated optically.

The role of simulation and modeling

Numerical modeling has allowed researchers to optimize their designs without complications and the significant cost of nanofabrication processes.

"Compared to experimental work, mathematical modeling is low-cost, has the opportunity to validate its output through a reduced number of prototypes, has predictive power, and, finally, allows you to optimize for a desired functionality," stated Kildishev.

In a field where the quality of the graphene material can vary, it is critical that there always be a tight connection between numerical results and experiments in order to better understand the impact of all variables involved.

In most cases, by fitting model parameters to experiments, Kildishev's team can retrieve the actual physics of a given process. Having a validated mathematical model in hand always provides better understanding and interpretation. Once they understand the phenomena in terms of a mathematical model, the comprehensive knowledge of the whole mechanism can be applied to other new ideas.

Of course, mathematical modeling has its own barriers. Many problems do not have analytical solutions and Kildishev's team must revert to alternative options.

This is where numerical techniques come in as tools for circumnavigating these hurdles, according to Ludmila Prokopeva, a high-performance computing specialist on Kildishev's team. Properly designed simulation tools provide stability, accuracy and speed. There is often a need for substantial high-performance computational machinery, especially for nanostructured devices that require full 3D simulations.

The multiphysical and multiscale essence of computational nanophotonics necessitates the use of powerful simulation tools. It is never one simulation tool that works in all situations.

Kildishev's team has a wide range of custom and commercial software, and they are always looking for ways to incorporate new and interesting physics. With Comsol software, the researchers can couple several physics interfaces sharing the same mesh or even having separate meshes. They also link the solvers to complex material functions, for example, implementing several complex dielectric models for graphene — written in MATLAB software. Some of these dielectric functions are impossible to handle for a straightforward explicit input in terms of plain arithmetic or look-up tables. They are also able to introduce nonlinear effects, couple these to a heat transfer analysis, and add quantum emitters.

Because of its atomic thickness, graphene behaves like a 2D material, but many researchers use a thin artificial thickness and have to resort to a 3D model in their simulations just because of the inability to treat 2D materials naturally in their software. The 3D approach brings unphysical shifts, uncertainty in optimization procedures and significant complications to the numerical calculations. The Purdue team was able to model 2D materials natively in terms of surface conductivity, such as surface current.

While waiting for manufacturing techniques to mature, the Purdue team used a theoretical model for graphene's optical conductivity and simulated the device response to numerically investigate the system properties (Figures 2 and 4).

The experimental studies focused on very diverse facets of novel graphene applications, including IR sensors, hybrid photovoltaic electrodes and other 2D materials. So Kildishev's team collaborated with their "next-door" experiment-oriented teams of professors Yong Chen, Alexandra Boltasseva, Vlad Shalaev, Ashraf Alam, David Janes and Gary Cheng at the Birck Nanotechnology Center at Purdue, and with the Ted Norris and Vinod Menon groups within the Materials Research Science and Engineering Center (MRSEC) at Purdue. The collaborations provided a base for validating new modeling approaches and feedback on the fabrication and optical characterization of real-life graphene-based nanostructures.

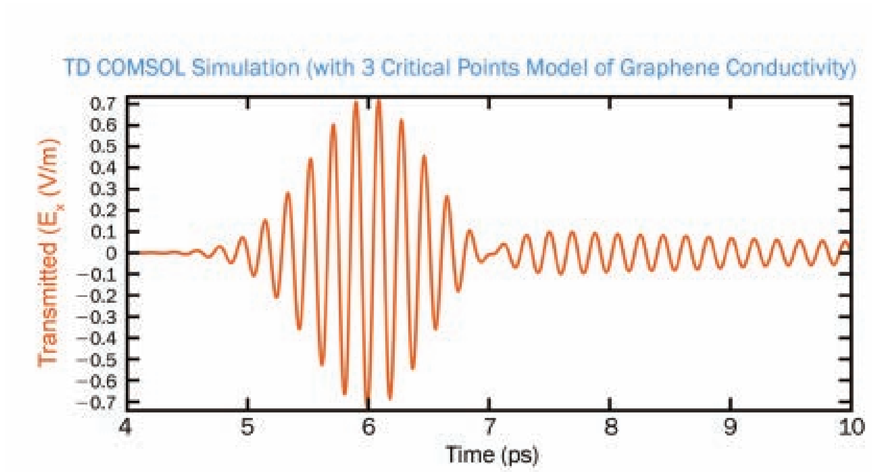

Figure 4. The time-dependent electric field of a Gaussian pulse transmitted through an array of graphene nanoribbons.

Alexander V. Kildishev, associate professor of electrical and computer engineering, Birck Nanotechnology Center, Purdue University.

Looking ahead to quantum optics and flexible touchscreens

The Purdue team is continuing its simulation work to understand and predict the behavior of graphene so that it may be put to use in devices such as photovoltaics, optical modulators and — one day — flexible touchscreens. They are looking to make graphene nanoribbons so that they can begin fabricating a preliminary light modulation device[3,4].

"Generation and modification of short optical pulses is an important aspect of imaging and sensing," explained Kildishev. "Currently, the devices capable of achieving this functionality at mid-IR wavelengths are rather bulky and are not tunable. We envision a prototype device that can dynamically change the frequency content of an incoming optical pulse or light beam. This will enable higher sensitivity detection for night vision and mid-IR imaging applications."

They also have longer-range aspirations to explore the plasmonic properties of graphene in the quantum optics regime. Kildishev and his colleagues believe the quantum optics regime will be the next frontier for the science of light and has been relatively unexplored in the mid-IR wavelengths.

"Semiconductor quantum wells show some interesting quantum properties but are restricted to low temperatures so far," said Kildishev. "If we successfully address some of the challenges in graphene research, it might end up outperforming semiconductor quantum wells. If we are able to do this, we could significantly reduce the size of many devices."

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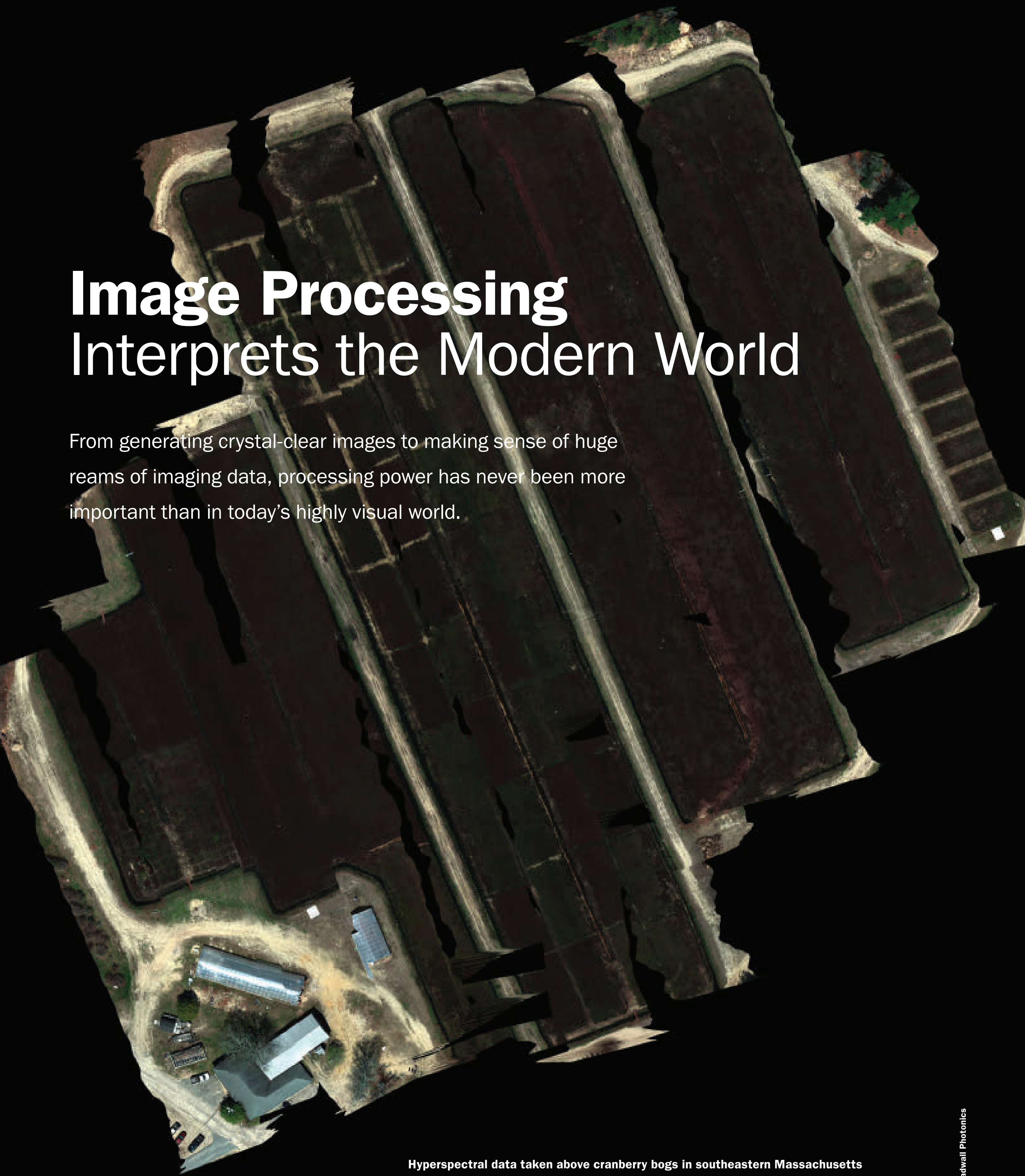
Image Processing Interprets the Modern World

From generating crystal-clear images to making sense of huge reams of imaging data, processing power has never been more important than in today's highly visual world.



Hyperspectral data taken above cranberry bogs in southeastern Massachusetts is orthorectified and overlaid on top of a Google Map image.

Headwall Photonics

BY MARIE FREEBODY
CONTRIBUTING EDITOR

From the moment we wake up and open our eyes, we are processing images. It is this image processing that enables us to successfully complete tasks from the mundane to those that are undertaken only by the gifted professionals trained to make split-second decisions — from the pro basketball player to the jet fighter pilot.

This image processing takes place in arguably the most complex and powerful computing device known to man — the human brain. But as well as a sophisticated processing center, the human brain is also versatile and creative and so has engineered technologies capable of performing all kinds of image processing tasks for us.

From the everyday snapping of camera phones, as well as image enhancement via playful apps, to advanced biometric sensing, factory machine vision and driverless automobiles, image processing systems take visual information and convert it into usable data. From this meaningful data, dedicated software will provide output in a convenient form — or even analyze it to make decisions.

"For centuries and certainly more, people have tried to visually represent things using drawings or paintings, later by taking photographs. Since the emergence of computers and particularly digital imaging, images now correspond to arrays of quantized values," said William Guicquero, a Ph.D. research engineer at Grenoble, France-based Leti, a technology research institute at CEA Tech and one of the world's largest organizations for applied research in microelectronics and nanotechnology.

"The amount of data that are needed to directly store such arrays is, most of the time, hardly affordable by computer systems in terms of storage capacity and/or processing capabilities," he said. "It constitutes one of the most important limitations. For example, an uncompressed, RGB demosaiced video sequence of two seconds from a 16-MP image sensor at 30 fps would generate approximatively 3 GB of data. This is where image processing comes into play by proposing to change the representations in which we have to deal with images."

Embedded and deported processing

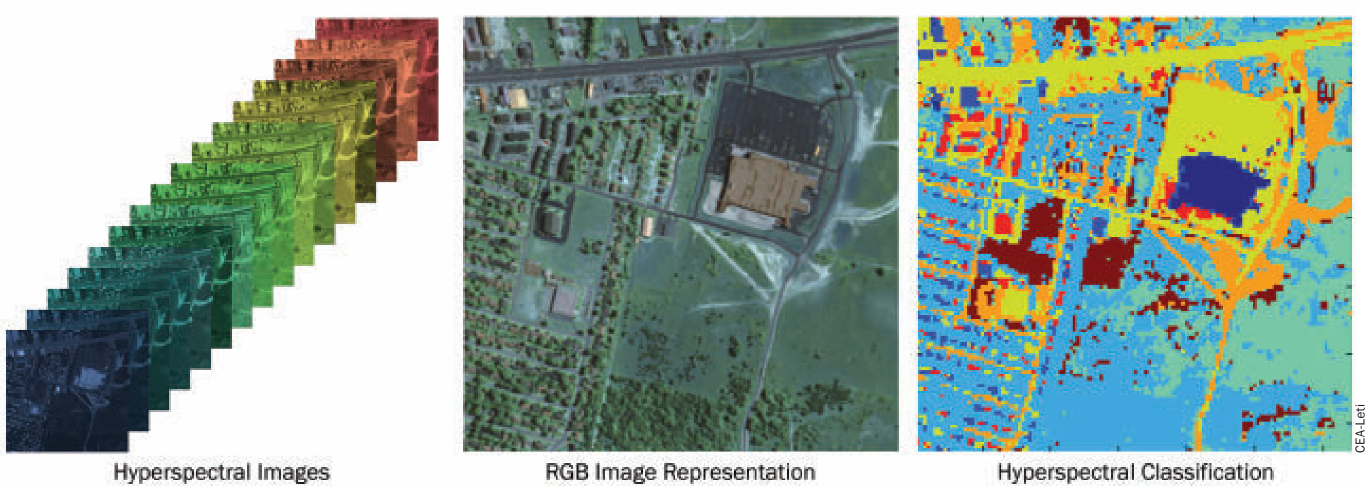
Image processing can be divided into two branches: embedded and deported. Embedded processing occurs close to the sensing system and does not involve the same constraints as deported computer vision, which has the advantage of more computational resources.

The current trend regarding acquisition systems is to propose novel sensing approaches that reduce constraints in terms of power consumption, frame rate, dynamic range, spectral sensitivity and so on.

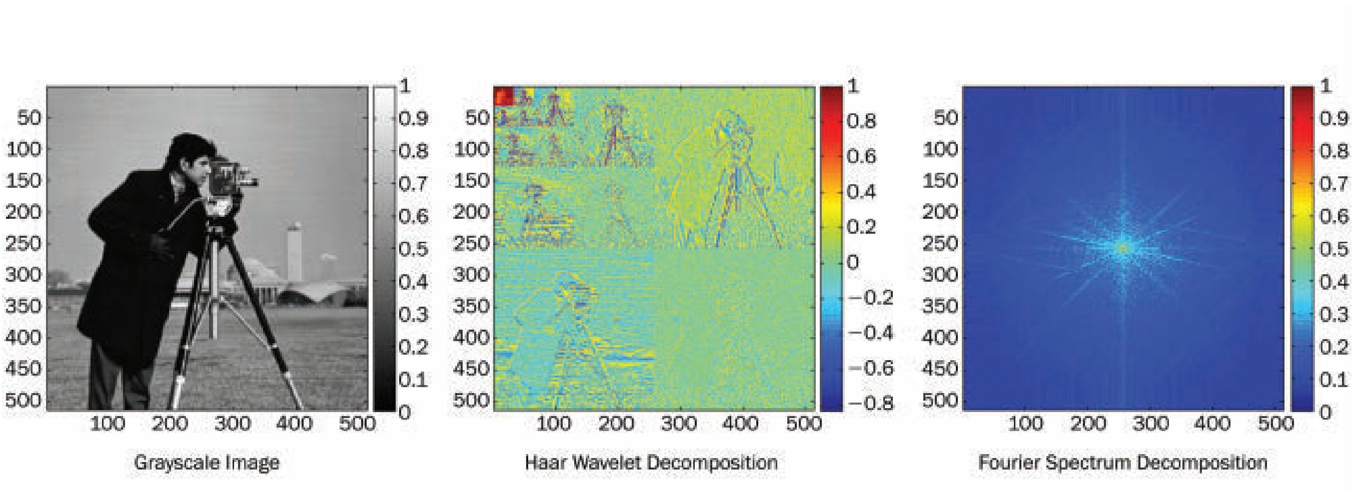
At the top of the list of alternative techniques that currently show the most promise are compressive sensing (CS) and event-based acquisitions. On the other hand, direct decisions taken by the acquisition system without either storing or transmitting the image is also investigated for some specific applications such as food/product/land monitoring, mainly in the context of autonomous systems.

When it comes to deported processing, computer vision intensively employs advanced machine learning tools to let the computer understand the underlying meaning of images and videos. Recently, results obtained using convolutional neural networks (CNN) for image investigation demonstrate that deep-learning can be highly relevant in specific contexts, such as face detection.

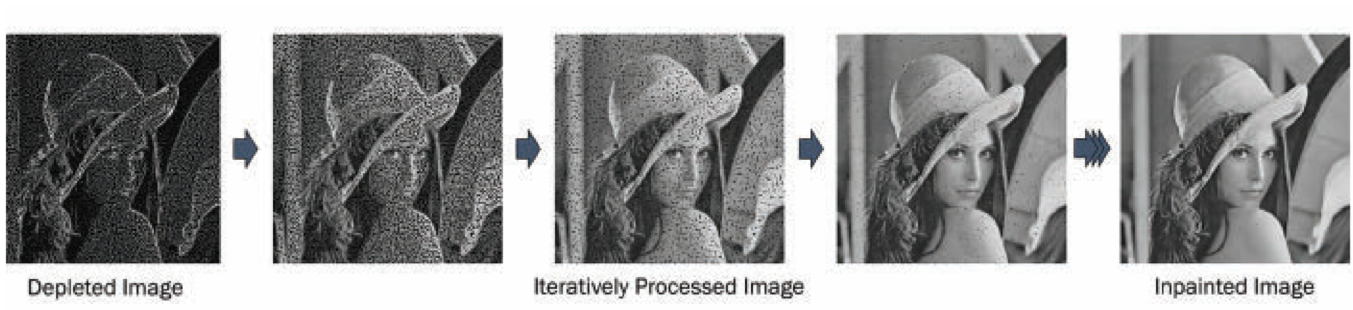
"Robustness of state-of-the-art algorithms will be improved in the near future by the use of such 'bio-inspired,' nonlinear techniques, in the hope that it would not considerably increase the overall computational complexity," Guicquero said. "However, it will surely have an impact on object detection and classification. Regression analysis and dimensional reduction tools are also going to play a more important role as well, for instance for object pose estimation."



Pixel patches classification of a hyperspectral image (URBAN test dataset), based on local spectral signatures.



Examples of two commonly used signal representation changes based on multiscale and spectrum decompositions.



Example of an inpainting process. This operation consists in finding the grayscale values of missing (or corrupted) pixels.

Processing power grows

"Image processing has always been about getting the job done with what was available," said Yvon Bouchard, director of OEM Applications at digital imaging and machine vision specialists Teledyne Dalsa, Montreal. "There has been always the battle of the ideal way and the practical approach to get the job done. This probably will never change since both the processing power and the amount of data to process keep on growing."

As the sheer volume of imaging information captured by today's vision systems continues to rise, image processing power steps in to convert image arrays into manageable units.

"Mathematical transforms based on Fourier analysis, for example, discrete cosine transform, or multiscale analysis — discrete wavelet transform— has been widely used for image compression purposes," Guicquero said. "Without those kind of mathematical tools there would hardly be portable devices with embedded high-resolution cameras or even internet video-streaming websites."

Indeed, some of the big improvements in optical systems are in the image processing software at the sensor level.

The image from an imperfect optical system can sometimes be corrected via image processing. Some examples are removing distortion from an image, or refocusing an image using a technique referred to as light-field imaging.

"The real benefit of image processing has been to allow computer algorithms to replace human eyes in the interpretation of images where decisions need to be made. The advantages here are the same as in all areas where computers have impacted society: speed, efficiency/automation, accuracy and consistency," said Akash Arora, product manager at software and services specialist Zemax of Kirkland, Wash.

Improvements in image processing have enabled major advances in a wide range of technical areas, including biometric sensing, remote sensing, factory machine vision, driver assistance/driverless automobiles, facial recognition, virtual reality/augmented reality and many others.

"The optics used in these applications aren't necessarily revolutionary," Arora said. "Processing the image with a software algorithm that can make consistent, accurate decisions thousands of times a second is the true revolution."

That's not to say optical components aren't contributing to progress in the field. Advances in sensors now make it possible to image more than visible information.

"For example, [with] the thermal energy and the distance to objects (3D), combined with fusion technology, we can now examine senses with new information about what is going on and intervene in a way which was impossible in the past," said Bouchard. "The availability of low-cost sensing devices is now opening up markets which never existed before — the various applications for remote sensing using drone technology is just one example of this."

Headwall Photonics based in Fitchburg, Mass., experts in hyperspectral imaging, is only too familiar with the expanding market enabled by drone technology. Its sensors and software can be fitted and flown over fields to provide key vegetative indices that are needed for precision agriculture and environmental mapping.

"Users are essentially looking for answers to 'How effective is my fertilization and irrigation?,' 'Is there plant stress I need to be aware of?' and 'Are there any early warning signs of diseases that may affect an upcoming harvest?'" said Christopher Van Veen of marketing communications at Headwall Photonics.

"The various vegetative indices we are keying in on represent the answers, and our 'deliverable' to customers is much more that than simply a hyperspectral sensor and the software that drives it. The 'big data' coming from these sensors contains actionable information that the remote-sensing community clearly demands."

Rethinking signal investigation

A major sector benefiting from enhanced processing is medical imaging. In the case of magnetic resonance imaging (MRI), for example, it is not only compressed sensing that has revolutionized its use, but also a rethinking of traditional signal investigation and interpretation — known as "inverse problems."

"Traditional techniques are mostly based on signal analysis, whereas new techniques capitalize on synthesis using structural assumption of the signal," Guicquero said. "Most of the image processing problems can be now stated as inverse problems supposing an acquisition model of hidden variables. Thanks to recent algorithmic advances, those inverse problems can now be solved at the expense of an acceptable increase of algorithm complexity."

The resolution of inverse problems has reduced MRI scan times while improving image motion blurring by taking only a part of the data that is commonly acquired by conventional MRI systems and processing it.

This decrease in examination times helps physicians scan torsos, especially in pediatrics, removing the need to anesthetize children to reduce movements of lungs and abdomen.

Another sector that stands to benefit is consumer electronics, and in particular, augmented reality devices. Such systems seem to benefit the most from advanced image processing thanks to an optimized combination of sensing devices, computer vision programs, computer graphics rendering and display devices, all involving image processing.

"The image processing community seems to be deeply motivated to be a driving force in the technology race," Guicquero said. "The introduction of reproducible research allows the scientific community to progress even faster by communicating more efficiently with code sharing. Open source libraries — for example, OpenCV — that are collectively maintained by the community help students, engineers and researchers to reduce the required time for coding new ideas."

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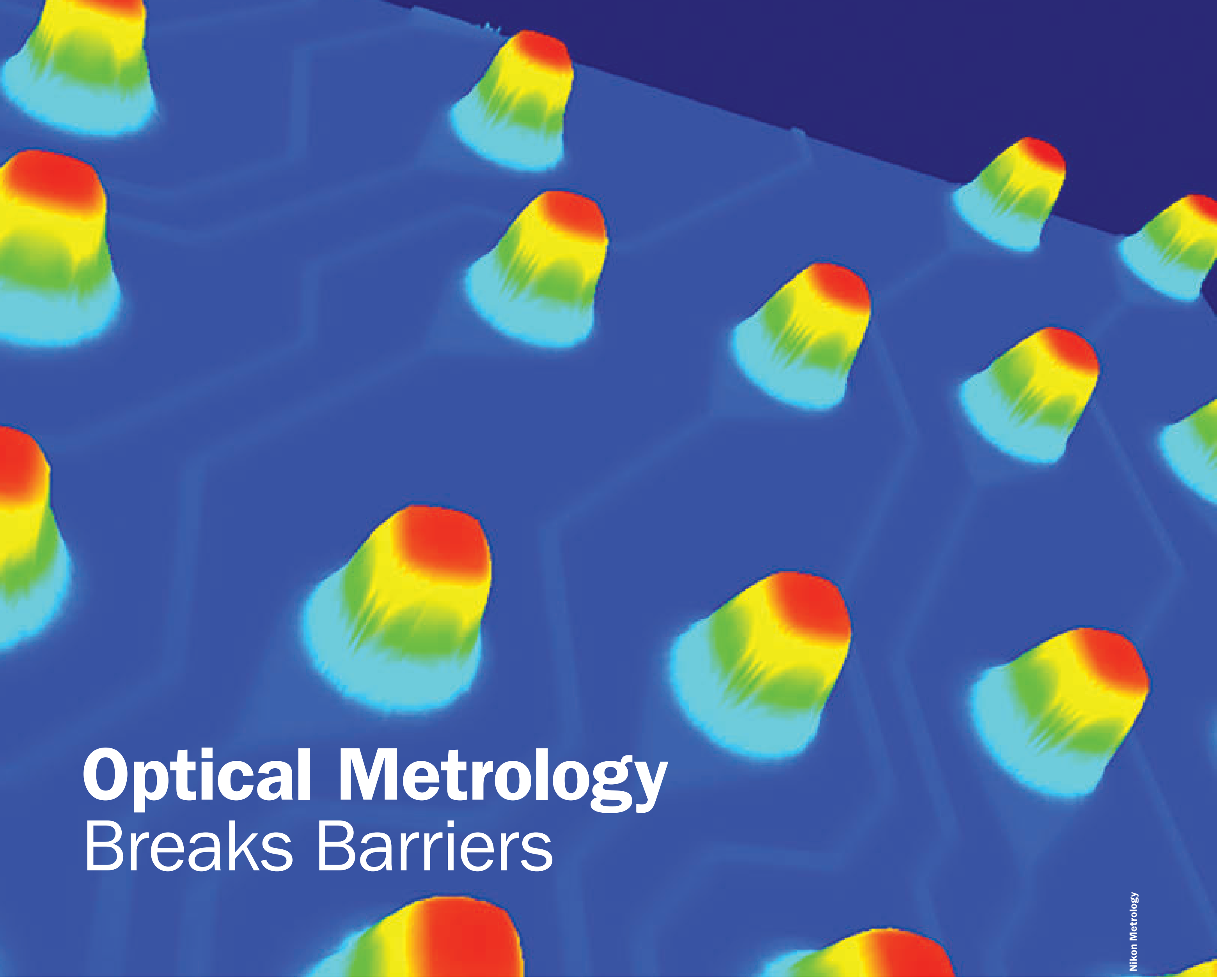


Nikon Metrology

Optical Metrology Breaks Barriers

Superresolution techniques break the diffraction limit;
laser speckle analysis allows for better metrology of the tiniest features.

BY HANK HOGAN
CONTRIBUTING EDITOR

At one time, the diffraction limit, half the wavelength of light, acted as a cutoff to optical measurement. That's no longer the case. Superresolution techniques now allow optical metrology well below that point in the XY direction, while interferometry and other approaches produce precise optical measurement in the Z, or vertical, direction.

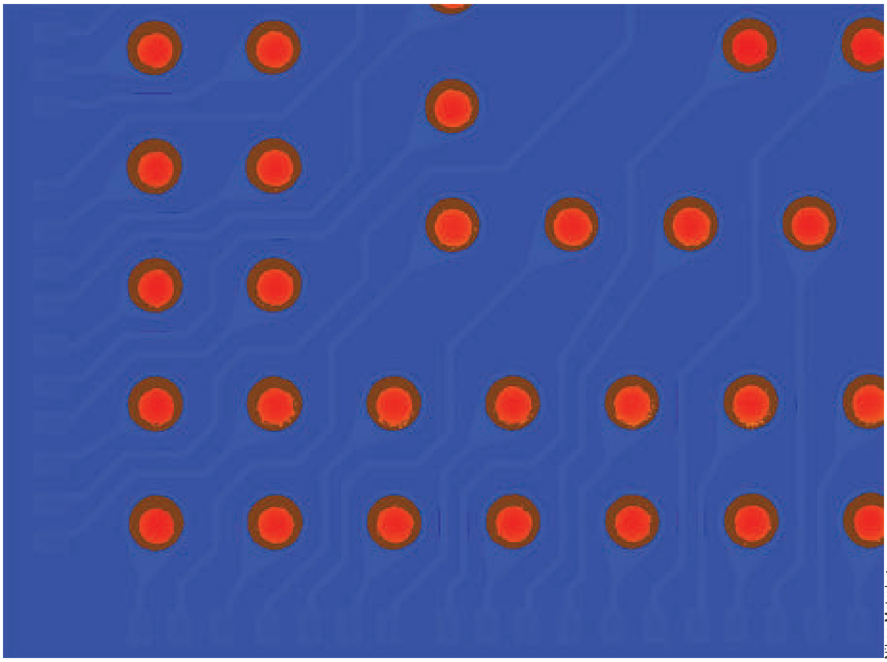
Other innovations involve laser speckle analysis and the combination of different technologies, enabling better metrology on ever smaller features. On the horizon are techniques that could enable widefield superresolution.

Optical measurement is typically employed for two reasons, according to Oscar Rodriguez, manager of application specialists for industry and material science in Europe for Leica Microsystems GmbH. The Wetzlar, Germany-based company makes subdiffraction limit resolution systems based upon selective deactivation of fluorophores in biological samples.

"You need to use optical technologies because of the [feature] size. We're entering into the microscopic world. Or you're using optical technologies because they're noncontact and fast," Rodriguez said.

With standard resolution techniques, optical measurements of a few hundreds of nanometers are achievable in X and Y. In Z, technologies based on interferometric, confocal and focus variation techniques enable much more precise metrology.

Interferometry exploits the interference between light beams, which start as one, are split and then brought back together after traveling down different paths.



Nikon Metrology

Confocal imaging **(above)** enables the creation of a three-dimensional view **(at left)** for optical metrology of bond bumps on semiconductor chips.

Interferometric systems can detect pathway differences in nanometers.

Other three-dimensional metrology techniques are confocal or focus variation based. Both depend on the blurring of features outside a focal point, with this being particularly acute for a confocal system. Sweeping the focal point through space enables measurements to be made.

The different techniques offer distinct advantages and end users are interested in having flexibility. “The trend that we’re seeing is to combine different measuring technologies,” Rodriguez said.

Another trend is to combine a laser with a broadband source, like an LED. By doing so, systems can do coherent- and noncoherent-source metrology and merge that with high-speed imaging.

Interferometry forms the basis for many of the metrology products from Middlefield, Conn.-based Zygo Corp., according to Peter de Groot, executive director of research and development. He noted that building optics depends upon making measurements in the microns or nanometers.

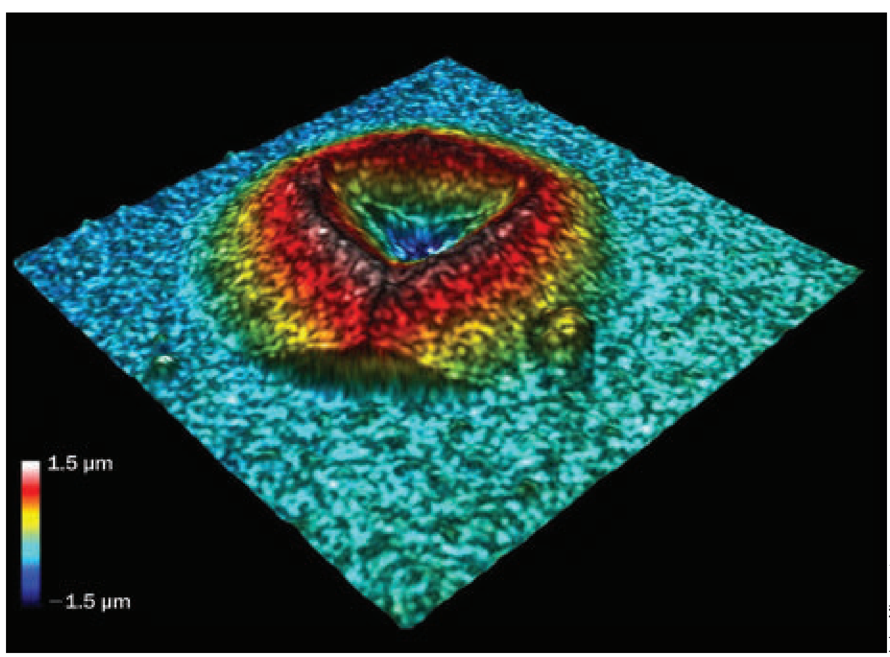
High-volume examples of this can be found in today’s phones, which have cameras constructed with low-cost, high-precision optics. Those cameras, in turn, can be used to make optical measurements. In an SPIE 2014 paper, J.H. Burge and others from the University of Arizona showed that an app on a camera-equipped phone could produce results comparable to a standard interferometer. Another example of phone-based metrology is an affordable, internet-connected imaging system in portable microscopes for field work in the developing world, de Groot said.

The need for measurements in the micron range is now showing up in nonoptics areas, such as car fuel injectors. Emission and fuel efficiency requirements have resulted in tolerances of a half micron or less, far smaller than the tolerances of thousandths of an inch, or 50-plus microns, of years past.

“That’s a trend which has caused that entire industry to switch over from mechanical tools to high-performance optical noncontact tools that give them aerial surface measurements on the scale of a few nanometers,” de Groot said.

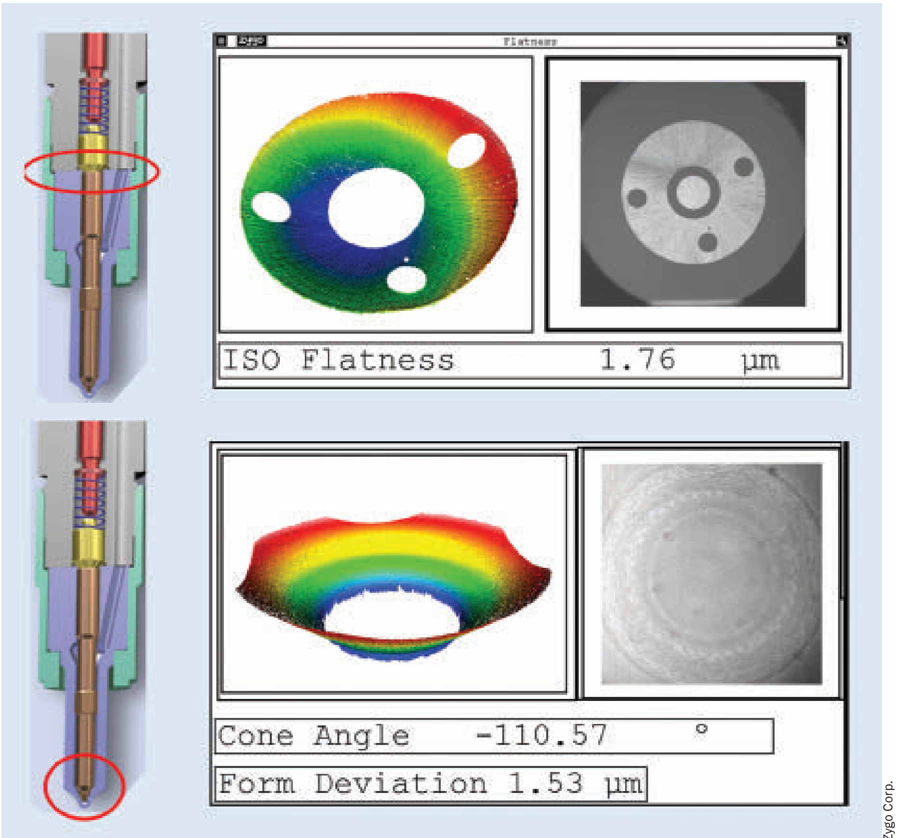
Software compensates for optics’ shortcomings

For optical metrology systems, the increasing use of software means that lenses do not have to be as high quality as in the past because software can oversample the incoming signal, do noise filtering or do a better job weeding out weak signals. Software and optical techniques also minimize the coherent noise

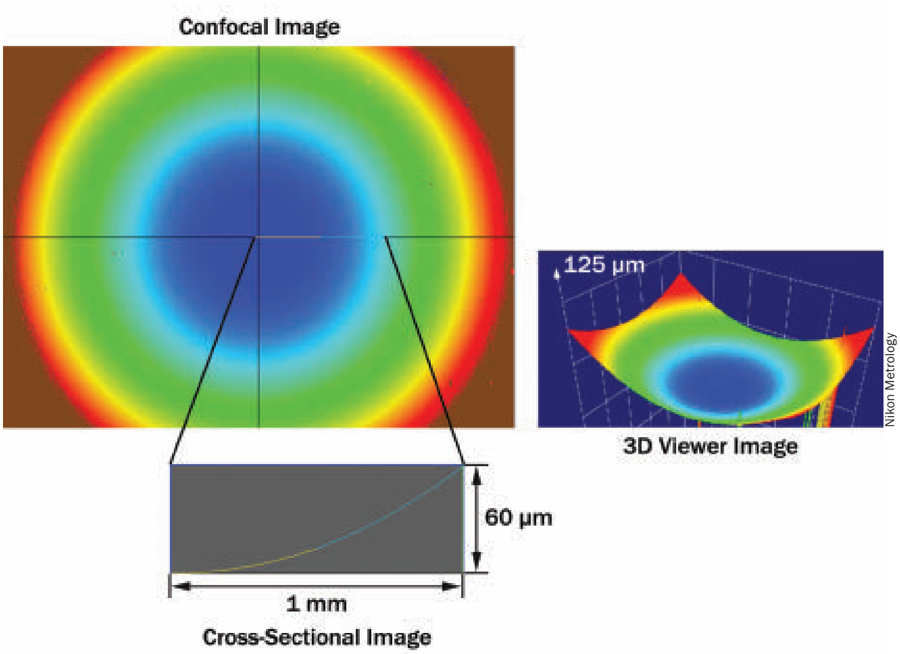


Leica Microsystems

Confocal-based optical metrology enables characterization of a thin aluminum nitride film on silicon.



Many industrial components, like fuel injectors, now require measurement tolerances well below a micron, making them candidates for optical metrology.



Optical metrology helps make the optics that enable optical measurement possible, as shown here with a confocal system image of a lens surface.

created by a laser beam scattering off dust and particles in the light path, thereby improving measurements.

According to Bhanu Singh, confocal product manager for Nikon Metrology of Brighton, Mich., the demand today is for automated multisensor systems. These might combine different optical techniques, like confocal and bright-field images, to create the capability for wide area X, Y and Z measurements. Such a combination can offer significant advantages in industrial or other high throughput settings.

"You have a single setup. It reduces your setup time. You don't need multiple fixtures across different systems. You don't need different tools," Singh said.

A high degree of automation also provides data that can be tied to a specific part at a particular point in manufacturing. Measurement traceability is a requirement in medical device and aerospace manufacturing.

In an example of combining techniques, Nikon Metrology presented at a recent semiconductor industry event a solution to the problem of inspecting bond bumps on chips and probe tips on test boards. The confocal system sends the output of a high-intensity mercury xenon lamp through a pinhole in a spinning Nipkow disk. That is complemented by two additional sensors: one for bright-field optics and another using a laser. This yields two-dimensional bright-field and three-dimensional confocal images over a 650- × 550-mm area with a 10-nm resolution in the Z.

The system's measurement capability is good enough to handle the 5- to 10-micron demands of today's circuit board manufacturers, according to Singh. He added that measurement needs should move into the 1- to 5-micron range in three years or so.

More data = more challenges

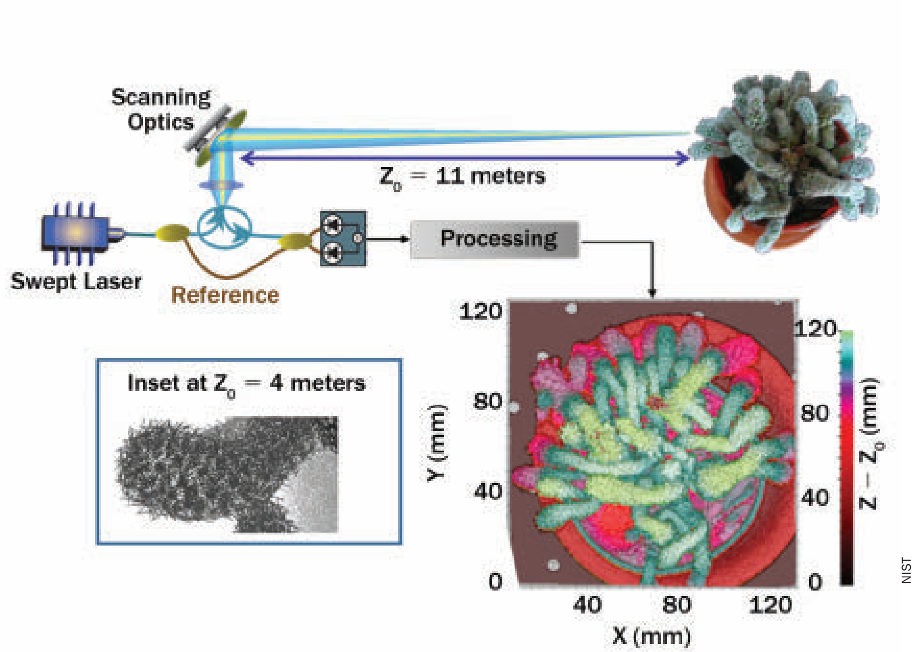
A consequence of greater resolution, the use of multiple wavelengths, and increasing automation is that more data is generated. That presents challenges in moving, storing and analyzing it.

Singh hasn't seen a demand for wide-field superresolution. He attributed this to the lack of a compelling reason to implement such a capability. There's also the cost of such solutions, which currently have only been demonstrated in laboratory settings.

As for the future, even with the increasing use of software to make up for component deficiencies, metrology benefits from hardware advances and innovations. Thus, laser beam quality improvements help. So, too, can steps taken to reduce noise arising from the interaction of the laser and the object being measured. Such interaction produces speckle, created by diffuse scattering from the reflecting surface.

The resulting phase noise is a fundamental precision limitation in coherent laser ranging and so presents a problem to some optical metrology techniques, according to research from the National Institute of Standards and Technology (NIST) in Boulder, Colo. Esther Baumann, a NIST scientist, was lead author of a 2014 *Optics Letters* paper about this work.

She said that there are approaches to mitigate speckle noise, such as bright



A cactus imaged at almost 11 meters using a laser ranging system capable of 10-μm resolution shows the possibility of precise optical metrology at a distance.

speckle tracking that is then used in laser feedback or to adapt the scanning pattern. Another solution is to filter out dark speckle in software. A third is a laser center frequency change when a dark speckle occurs.

In their paper, the NIST team demonstrated yet another approach: a laser with a high optical sweep bandwidth. Scanning the laser center frequency across a terahertz range, the researchers achieved range precisions below 10 µm, opening up the possibility of precise optical metrology at a distance.

However, the proof of principle system wasn't in a configuration suitable for a commercial application. "Our setup was rather big and not very rugged," Baumann said.

She added that shrinking the size of the demonstration system is a job best left to industry. So, too, is determining the best approach to reducing speckle noise.

A final likely future optical metrology development involves wide-field superresolution. There's significant research going on aimed at demonstrating and then deploying systems that image and perform measurements in X and Y far below the diffraction limit of light. The present lack of commercial products that do this is not surprising, said Nicholas X. Fang, a professor of mechanical engineering at the Massachusetts Institute of Technology. Superresolution is one of Fang's research interests.

From theory to lab

Fang noted that it may take 20 years or more for a technique to move from theory to lab demonstration to commercial practice. Based upon the theoretical discovery of superresolution in the mid-1990s, it may be five or 10 more years before a commercial product appears.

Some superresolution techniques improve measurement at the expense of scan time. For example, those that selectively turn on and off fluorophores require multiple passes. Other techniques, such as interferometry, only provide better-than-diffraction-limit metrology in one direction.

Possible techniques that avoid such issues use metamaterials. These are made of regular repeating structures that are much smaller than the wavelength of interest.

According to Fang, the semiconductor industry may both need superresolution and have the means to achieve it. The need is that the critical dimensions of advanced chip structures are closing in on 10 nm. Currently, imaging and measurement of these features is nonoptical. However, an ideal solution would be one that covers large areas economically, much like optical microscopes did for earlier chip generations.

As for the solution, the same structures — metal lines and connecting holes or vias — that need inspection and metrology can form the basis for a metamaterial. Semiconductor manufacturers routinely create regular repeating patterns in chips out of elements that are much smaller than the wavelength of light.

Discussing possible components for a superresolution metamaterial, Fang said, "Those interconnects and vias become the natural candidates."

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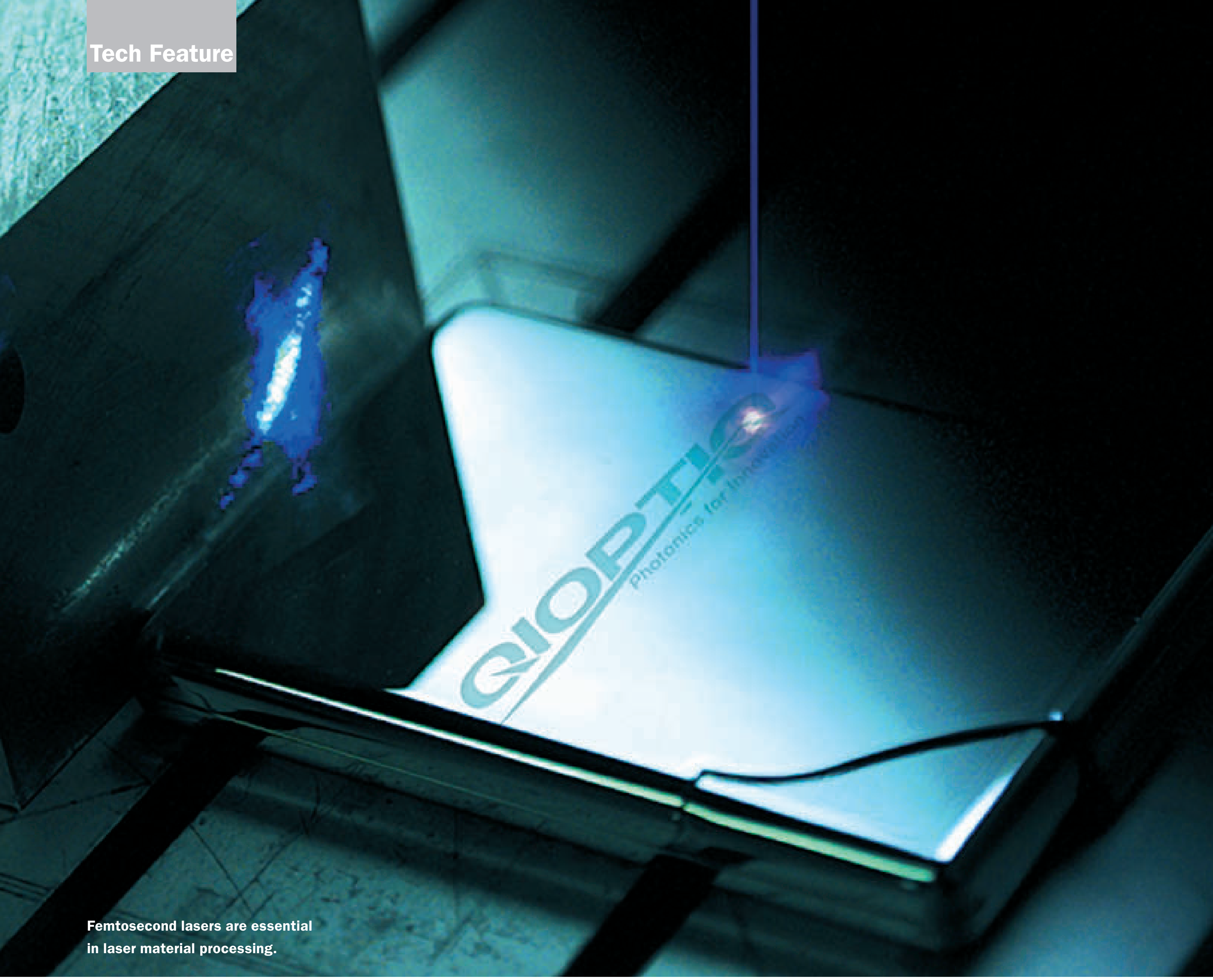


Femtosecond lasers are essential in laser material processing.

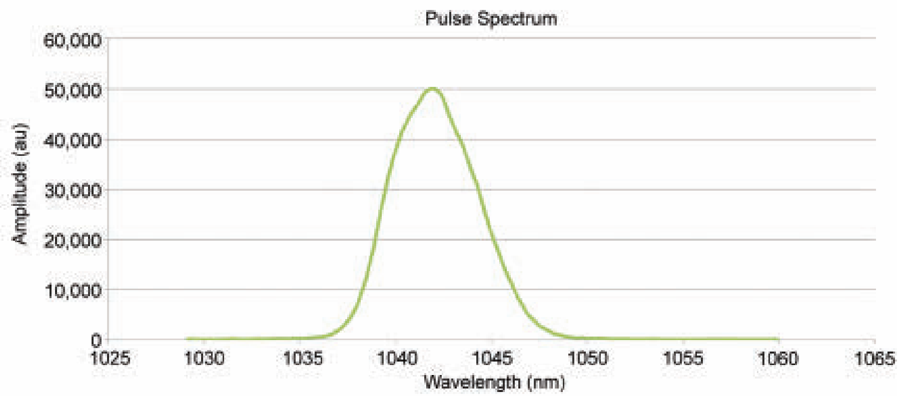
Innovations Make **Ultrafast Lasers** Even Faster

Recent developments in Pockels cells and Faraday isolators are paving the way to increased power and higher repetition rates.

BY MARKUS FEGELEIN
QIOPTIQ PHOTONICS GMBH & CO. KG
AN EXCELITAS TECHNOLOGIES COMPANY

Ultrafast lasers or ultrashort pulse lasers emit pulses in the range of a few femtoseconds up to a few picoseconds. These lasers are essential tools for a variety of applications like laser material processing including cutting, marking, drilling, additive manufacturing and spectroscopic research.

In laser material processing, ultrashort pulses are popular because they only evaporate the material at the laser beam focus position without overheating the surrounding material. Other material processing applications use the high intensity of amplified ultrashort pulses to excite



Spectra Physics, High Q Laser GmbH, Rankweil, Austria

Figure 1. Spectral width of a 400-fs pulse emitted from a Yb:YVO Laser. FWHM: full width half medium.

Qioptiq, an Excelitas Technologies company

Figure 2. Qioptiq's DBBPC HR Pockels Cell, with two Beta Barium Borate (BBO) crystals for switching frequencies up to 1.3 MHz.

two-photon absorption processes, such as laser cutting of glass, sapphire or cornea — transparent materials that do not absorb the fundamental wavelength but the second harmonic wavelength.

Spectroscopic applications make use of the same two characteristics but in a different way. In analog photography, a light flash or a very short shutter time reduces film exposure to freeze fast-moving objects. Similarly, ultrashort laser pulses can be considered ultrafast stroboscopes to observe chemical reactions in the femtosecond time frames where they occur.

The broad wavelength spectrum of ultrashort pulses is a key consideration when designing ultrafast lasers. Short pulses are composed of many wavelengths, the more colors contributing to the pulse, the shorter the pulse can be. Therefore every component that is used in an ultrafast laser's beam path must be suitable for operation with a broad spectral range. So not only are mirror and window coatings needed to cover a broad spectral range, but the laser media must also emit and amplify over a broad spectral range (Figure 1).

Dopant determines spectral range

The active laser media is the key element of every laser. For solid-state lasers, this most often consists of a glass or crystalline host to which a dopant is added. This dopant roughly determines the center wavelength of a laser while the combination of dopant and host sets the spectral range of the emission, the laser gain itself and ultimately the length of the laser pulse.

Of all common dopants, titanium, hosted in a sapphire crystal, has the broadest amplification spectrum, and therefore is perfectly suited for the generation of pulses in the range of a few tens of femtoseconds.

For industrial applications, ytterbium (Yb) is commonly used since its pump absorption spectrum is very broad and it efficiently converts pump energy into laser light. When hosted in YAG crystals, the gain is so high that the laser rod can be reduced to a thin disc since the light only needs to travel small distances in Yb:YAG to reach notable amplification[1]. On the other hand, the spectral gain of Yb in YAG is so small that these disk lasers can only emit picosecond pulses. When hosted in vanadate (YVO_4) crystals, the emission spectrum gets much broader, making Yb:YVO_4 the material of choice for femtosecond lasers in the 1030-nm region. Also, the gain of Yb:YVO_4 is considerably smaller compared with Yb:YAG — hence long laser crystals are needed to reach enough amplification.

As a host, crystalline material is preferred because of its typically higher thermal conductivity and damage threshold compared to glass. Glass manufacturing, however, is much easier and therefore less expensive and available in large dimensions[2]. Besides the selection of an appropriate laser media mode locking, control of dispersion effects and amplification are important to build a powerful ultrafast laser.

Mode locking

Consider a Ti:sapphire crystal in a laser cavity that is pumped by a continuous wave (CW) laser. If the cavity is correctly aligned, the laser will start oscillating in the free running regime, which means it will oscillate simultaneously and continuously at all resonance frequencies of the cavity within the emission spectrum of the Ti:sapphire crystal. To move the laser from the CW regime to the pulsed regime, all the modes of different frequencies need to be locked on a fixed phase relation between each other (mode locking).

Mode locking can be done in two ways. In active mode locking, the resonator losses are modulated synchronously to the round-trip time of the resonator cavity, for example, by an acousto- or electro-optic modulator. In passive mode locking, resonator losses are modulated by a saturable absorber or a Kerr lens.

For a saturable absorber, the absorption losses decrease with increasing light intensity. Therefore, when the laser starts oscillating continuously, intensity spikes, which are found in the laser noise, have fewer losses than lower or average intensities. After many round-trips, a single pulse remains[3]. The pulse will oscillate in the cavity and as it passes the output coupling mirror, a small portion of the pulse will be emitted. Given a typical resonator length of 1.5 m, the round-trip length is 3 m. Thus the pulse, traveling at the speed of light, will pass the output coupler 100 million times a second, yielding a 100-MHz pulse repetition rate.

Dispersion

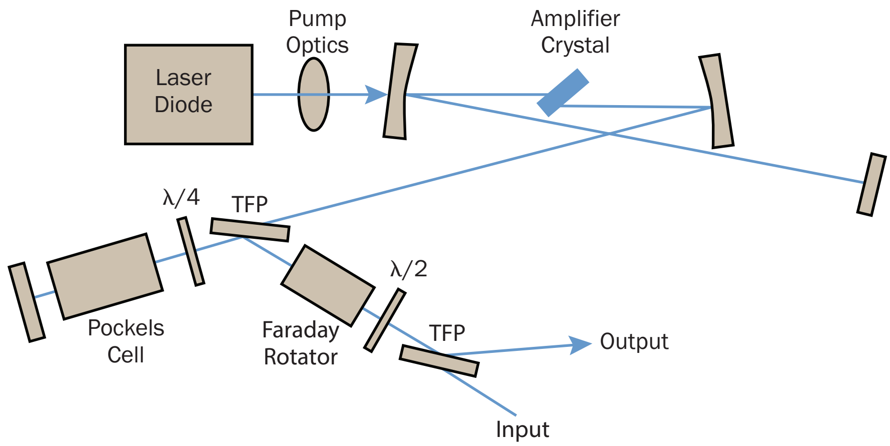
Ultrashort pulses take round-trips in the cavity, passing all optical elements within the cavity at least once (for a ring resonator) or twice (for a linear cavity) per round-trip. Since the pulse consists of many colors, it will experience group delay dispersion as typically red light travels faster than blue light through optical media. This will broaden and chirp the pulse, which needs to be compensated by either a pair of prisms or diffraction gratings, or by so-called chirped mirrors for which the penetration depth of red light is deeper than for blue light.

Amplification

Due to the high repetition rate of 80 to 100 MHz, peak intensities of ultrashort pulses emitted by an oscillator are rather small, even if the oscillator yields modest average power. Since many applications, especially in material processing, need much higher peak intensities, it is essential to amplify the ultrashort pulses. This amplification is realized by a master oscillator power amplifier (MOPA) system in which ultrashort pulses of a master oscillator are coupled into an amplifier. Laser media with broad spectral gain often exhibit low gain, so the pulse needs to travel a very long distance through the media to gain considerable amplification.

The most widespread amplifier type for femtosecond pulses is the regenerative amplifier. In this type of amplifier, a Pockels cell picks one pulse out of the 100-MHz pulse train emitted by the seed oscillator into the amplifying resonator where it takes many round-trips through an amplifier crystal. Both end mirrors of the regenerative amplifier are highly reflective to keep the losses per round-trip as low as possible. With each round-trip and each passage through the amplifier crystal, the pulse gains more energy. For Yb:YVO or Nd:Glass the pulse takes approximately 100 round-trips until it is coupled or dumped out again.

Ultrashort pulses can reach very high peak powers relatively quickly. To avoid damage to optical elements, pulses are stretched before they are coupled into the amplifier or stretched while they are inside the cavity by using the group delay dispersion described in the previous section. In the first case, a combination of gratings stretches the pulse. In the second, optical elements inside the amplifier cavity stretch the pulse, mostly the transparent elements like the Pockels cell or the amplifier crystal. The stretched pulses have the same energy as the ultrashort pulses but much lower peak intensity since they have a longer duration. The amplification of stretched pulses is often referred to as chirped pulse amplification. After the amplified stretched pulses are dumped from the amplifier cavity, they need to be compressed again, which is done most often with a pair of gratings[4].



R. Paschotta (2008). *Encyclopedia of Laser Physics and Technology*, p. 632. Berlin: Wiley-VCH Verlag

Figure 3. Setup of a regenerative amplifier. A Pockels cell combined with a quarter-wave plate and a thin-film polarizer (TFP) act as an optical switch. The Faraday rotator is used for separating input and output pulses.

To avoid amplified pulses from running back into the seed laser and causing damage or instabilities, a Faraday isolator decouples the seed oscillator from the amplifier.

The key to fast switching

Particularly in laser material processing applications, ultrafast systems not only need high pulse peak powers but also they can benefit from high repetition rates that reduce the process time per work piece. The Pockels cell picks the pulses from a pulse train emitted by the seed laser and determines the repetition rate. Given a typical cavity length of 1.5 m and 100 round-trips, the pulse stays in the cavity for approximately one microsecond; theoretically, approximately 1 million pulses per second can be amplified. Historically, the piezo effect prevented these high switching rates. The Pockels cell consists of an electro-optic crystal that, by applying high voltage, rotates the polarization of one single pulse out of the 100-MHz pulse train. This single pulse is then coupled into the amplifier via a polarizer.

When high voltage is applied to the Pockels cell, the electro-optic crystal gets deformed and stressed due to the piezo effect. This stress will cause additional birefringence via the elasto-optic effect,

Qioptiq, an Excelitas Technologies company

Figure 4. Qioptiq's low-outgassing Faraday isolator helps to increase the live time of encapsulated, high power and UV short pulse laser systems.

which will disturb the originally desired electro-optic effect. Since the pulses emitted by the seed laser are only separated by approximately 10 ns, a very fast, precise switching Pockels cell is required, which means the piezo ringing should be as small as possible. So, electro-optic materials would be chosen in this case where piezo effect is pronounced very weakly, like beta barium borate (BBO) or rubidium titanyle phosphate (RTP).

The switching voltage of BBO is much higher than for RTP; however, it has an easy-to-compensate group delay dispersion and a superb absorption coefficient, making it the perfect choice for high-power laser systems. Up to approximately 300 kHz BBO can be used relatively easily as a very precise switching electro-optic crystal. At higher frequencies, though, even small piezo ringing effects will cause trouble with the ringing of the crystal lattice dissipating as heat. For example, at 750 kHz the crystal can get heated up to 130 °C. This heat will cause thermal expansion and twisting of the Pockels cell housing, which results in misalignment of the crystal or damaged Pockels cell. Water cooling may drain the heat, but since water and high voltage do not mix well, the design of a water-cooled cell is too complicated to be economical.

New BBO Pockels cells have recently been developed with improved thermal management and very stiff and temperature-stable housing (Figure 2). Together with BBO crystals that have the smallest possible absorption, this Pockels cell represents a new benchmark in electro-optics for fast switching in the MHz range and the resulting high-average laser powers.

The Faraday isolator

As mentioned before, the Faraday isolator is a key element in a MOPA system since it decouples the amplifier from the oscillator. In many regenerative amplifier configurations, a Faraday isolator is also used to couple the pulse into the amplifier and dump the pulse back out again (Figure 3).

Since laser powers have increased dramatically and UV conversion of the amplified short pulses has become more popular, laser manufacturers are placing greater importance on the low-outgassing properties of components within their systems. Typically, Faraday isolators are manufactured with many adhesives, which are among the materials with the worst outgassing behavior. Recently, adhesives have been avoided wherever possible and if they cannot be avoided, they have been replaced with vacuum-compatible adhesives, which resulted in a complete new series of low-outgassing Faraday isolators (Figure 4).

For years, femtosecond pulses have been the shortest events that could be produced artificially by humans and hence, the laser systems have been operated at the edge of technical and physical feasibility. Today, technical issues are steadily being resolved and prices are reducing per mW output power, opening up exciting new frontiers in femtosecond technology for a wide variety of new applications.

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Meet the author

Markus Fegelein earned his Diplom degree in physics from the Swiss Federal Institute of Technology in Zurich (ETHZ). During his 10-year tenure at Linos and later on Qioptiq, Fegelein has served as product manager for Faraday isolators, Pockels cells and electro-optic modulators; email: markus.fegelein@qioptiq.de.

2016 Reader Issue

Beacons of the Photonics Industry

Photonics Media honors those in the industry who have made significant contributions in the areas of research, education and entrepreneurship.

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Annual Reader Poll

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Beacons of the Photonics Industry

'Far and away the best prize that life offers is the chance to work hard at work worth doing.'

— Theodore Roosevelt

As part of the annual Reader issue, *Photonics Spectra* is unveiling a new recognition program called The Beacons. Selected from nominations put forth by you, our readers, the distinction is reserved for those in the industry who have made significant contributions in the areas of entrepreneurship, research and education.

In the pages that follow, we profile all of this year's honorees. Among them you'll find a high school science teacher from Rochester, N.Y., who, in four short years has created a thriving precision optics fabrication program. You'll also learn how an accomplished scientist is leading a NASA-funded program to help a cadre of young interns acquire the skills needed to succeed in the remote sensing field.

Among our Beacons for the researcher grouping, we split the designation into the categories of "Leadership" and "Unsung Hero." For the former, we feature a post-doctoral researcher whose work in the "Golden Window" involves near-IR wavelengths for non-invasive imaging of brain and breast tissue.

In a nod to those with an entrepreneurial vision, we highlight the work of the co-founder of one of Germany's pre-eminent machine vision companies, whose contributions to object recognition software can be seen in thousands of manufacturing facilities worldwide.

Congratulations to all of this year's honorees!

Michael D. Wheeler
michael.wheeler@photonics.com

Research/Leadership

Richard Boudreault
Aerospace Technologies Inc.

Researcher Richard Boudreault's contribution to photonics "spans more than 35 years in laser imaging, photonic materials, image recognition, earth and space telescopes, intersatellite optical links, and vision systems for the robotic manipulator of the space station," according to his friend and colleague Robert Boily of Inforex Inc., who nominated Boudreault for this designation. Boudreault describes his career in simpler terms: He uses physics and engineering to solve problems, "turning wrongs into rights."

Boudreault led international teams to the successful development of two laser imaging systems: one designed for biological research in vivo on small laboratory animals, and the other for nonionizing detection of breast cancer, offering an alternative to x-ray imaging. Boily notes the latter was the world's first

Richard Boudreault

time domain laser-fluorescence system for medical imaging.

Boudreault also developed several optical technologies for space applications flown on spacecraft from the European Space Agency and NASA. As CEO of Orbite Aluminae, he led corporate R&D on advanced materials, namely high-purity aluminium oxide (HPA) and rare earths. HPA is an important material for the manufacture of LEDs, sapphire crystal glass, fiber optics, flat displays, smart phone screens and other optical elements. Orbite Aluminae technology produces high-quality HPA using a green manufacturing process. Sustainable environmental systems — including the optical measurement and management of methane gas emitted from permafrost — are among his ongoing paths of inquiry.

In addition to his research and business leadership, Boudreault has also taught internationally at the university level. He has authored 15 patents, with another 69 pending. In his career, he has founded six private and four public ventures as a principal, as well as three national-level centers of excellence. Boudreault expresses a rare combination of entrepreneurship and technical prowess, and he described the M.B.A. program he attended to *Photonics Spectra* as "translation school." He earned this degree after having already launched various projects and enterprises. He found it gave him the framework and, most importantly, the language skills to effectively interact with financial stakeholders. He said such skills enabled him to better communicate the market potential — and broad social benefits — of the technologies at hand.

Boudreault holds a Bachelor of Science degree in physics from the University of Montreal. He also studied international environment at the University of Quebec, earned his M.B.A. with a focus in innovation management and finance from the University of Sherbrooke, and earned his M.Eng. at the Cornell School of Mechanical & Aerospace Engineering.

Stephen Griffin
InnovaQuartz LLC

Stephen Griffin, founder and chief technology officer of InnovaQuartz, acknowledges that advocating for science and logic are part of his 21st century job description. The inventor and entrepreneur was nominated as a Beacon by his business partner Brian Barr, who said that in the field of fiber-optic laser energy delivery for surgery, Griffin's multidisciplinary training and unique insight allow him to formulate solutions to fiber optic surgical device problems well before the balance of the field can articulate a cause.

With over two dozen patents issued or pending, products based on Griffin's works dominate fiber-optic medical devices for lasers in interventional urology, and his current research aims to disrupt the broader field of endoscopic laser medicine. Among his inventions are polychromatic surgical lasers capable of actively tuning the output spectrum in response to spectroscopic feedback from tissues in targeting the disease state, while sparing adjacent healthy tissues. His multifunctional lateral and circumferential delivery optical fiber devices can maintain high transmission efficiency during prolonged and high temperature soft tissue contact, while simultaneously gathering tissue data.

The commercial and clinical success — and thus, broad reach — of Griffin's work is due in part to his ownership and responsible management of intellectual property. Griffin told *Photonics Spectra* that he "took ownership of the process early on, even before I had a clear idea for a patent," reading patents and case law in the field, and performing his own prior art searches; this preparation work itself yielded patent ideas.

"An inventor who commercializes his devices must involve himself more deeply in the patent process because patents are the principal available barrier to competition," Griffin said. "Keeping the giants at bay — or better yet, capturing their investment — requires strong intellectual property."

Griffin has also continuously participated in education of his customer base, especially in the surgical laser field. He's watched the peer-reviewed communication pathway devolve into blogs and social media, and remains a staunch

Stephen Griffin

supporter of peer communities that support "intellectual battles," while at the same time, citing the opportunity social media presents to quickly and broadly educate target end-users, ensuring great ideas make it out of the R&D lab and into the clinic.

Griffin earned his associate's degree in electronics from the USAF School of Advanced Aerospace Sciences and a bachelor's degree in microbiology from Arizona State University, where he also performed graduate work in analytical chemistry.

Lingyan Shi
Columbia University

Post-doctoral researcher Lingyan Shi was nominated for the Beacon honor by Robert Alfano, a professor at the City College of New York, who cited her work in the "Golden Window," a near-infrared region being explored for noninvasive imaging of brain and breast tissue. Her research interests include cardiovascular biomechanics, microscopic transport modeling, the blood-brain barrier (BBB) and drug delivery. Her primary research focuses are in vivo quantification of BBB permeability and its regulation by chemical and physical stimuli on a rodent brain microvessel model using multiphoton near-infrared femtosecond laser microscopy.

Shi is an active member of SPIE, serving as chair of two Photonics West conferences, as well as a topical committee member. She has authored or co-authored more than 25 papers, and also reviews textbooks and journals. An active member of the Society for Neuroscience, the American Society of Mechanical Engineers, OSA and IEEE, among other organizations, Shi has taught high school

'Younger students have a lot of passion for science and technology and they want to understand concepts better through hands-on experiments. They often ask questions to make me think deeper.'

— Lingyan Shi

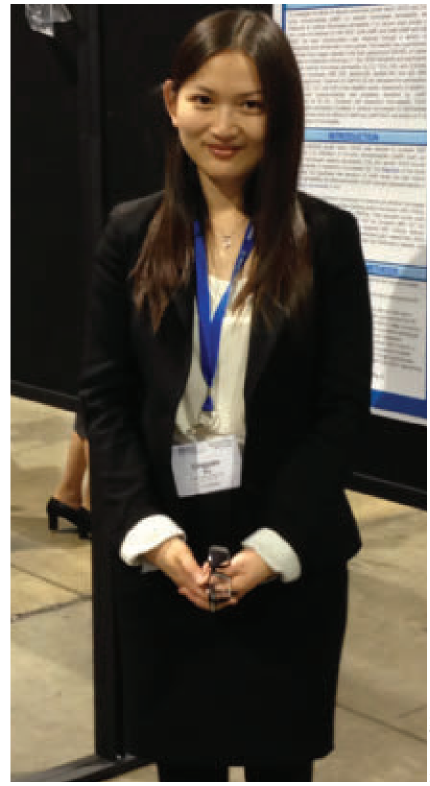
and undergraduate students about state-of-the-art photonics technologies.

These days, Shi told *Photonics Spectra* she's using stimulated Raman scattering microscopy to study the metabolism of cancer and neurologic diseases. She also hopes to discover or develop molecules that emit in the Golden Window, in addition to developing the laser in that wavelength range, and a photodetector in shortwave-infrared regions such as InSb and InGaAs detectors.

Biomedically minded from an early age, Shi found inspiration to enter the field of photonics as an undergraduate at Tianjin University in China. Her program offered access to medical devices for study and, as she said, playing around in the lab. Many of the diagnostic tools used light, leading to Shi's realization of light's importance in medicine.

"Lingyan Shi's research will stimulate the use of supercontinuum sources in visible, NIR and SWIR, extending into MIR, along with advances in photodetector arrays in these spectra regions, [and] will usher in a wide scope of photonic applications," Alfano said.

Shi holds a bachelor's degree in biomedical engineering from Tianjin University, an M.S. in biomedical engineering from the New Jersey Institute of Technology, and a Ph.D. in biomedical/medical engineering from The City College of New York.



Lingyan Shi

Educators

Bill Brocklesby
University of Southampton, Optoelectronics Research Centre

As light-based applications increase in complexity, so does the need for highly skilled workers with photonics and optics backgrounds. Creating a workforce that can develop, improve and implement photonics technologies requires teachers who are not only knowledgeable but also passionate about their field, whose enthusiasm is contagious, and who are equally proficient in the subject and in how to share their knowledge with students.

University of Southampton

Bill Brocklesby, an associate professor at the Optoelectronics Research Centre of the University of Southampton, U.K, is an educator whose passion has motivated students, and whose knowledge has given them a strong start in the photonics industry and the confidence to pursue their career goals. He was nominated as a Beacon by former student Stuart Nunn, who spent two years studying photonics while an undergraduate at the University of Southampton.

"During [my] time [at Southampton] I had the pleasure of having Dr. Bill Brocklesby as one of my lecturers. His passionate teaching delivery and knowledge of the field and related applications of the field was an inspiration for me to pursue the field of photonics in industry," Nunn said, adding that Brocklesby's guidance has served as "part of the foundation that has since helped me to consult the photonics component choices within these industries."

This is a testament to Brocklesby's strength as an educator, and his passion for photonics.

'His passionate teaching delivery and knowledge of the field … was an inspiration for me …'

— Stuart Nunn, technical sales engineer

Paul Conrow
East High School

When East High School science teacher Paul Conrow first met with the executive director of the Rochester Regional Photonics Cluster several years ago, his vision was to develop an ophthalmic lab at East High to provide glasses for students who could not afford eyewear. Once he learned more about Rochester's optics industry and potential career paths for city high school students, he developed both the opthalmic lab and an optical fabrication lab. Conrow has since become the driving force behind the school's optics program.

Conrow started the precision optics fabrication program four years ago as a single, general elective class offered to juniors and seniors. Fifteen students were part of the first-year course, and by its third year, the program had expanded to include multiple sections and approximately 50 students. He then began offering classes to sophomores, too.

Now in its fourth year, the optics program at East High continues to grow. A third section has been added to the Fabrication 1 level, and a Fabrication 2 level section has been introduced. During the last school year, classes also included freshmen students.

Conrow continues to expand the optics program. Recently, he approached a local coating company about adding coatings to the subject matter covered in one of the program's fabrication classes. As a result, a machine for coating was purchased and will be installed in the optics lab at the school in the coming academic year. Conrow works closely with local business leaders, as well, to understand the needs and goals of the industry, ensuring the program supports workforce development for the ever-growing optics industry.

Conrow, who was nominated for the Beacon designation by Alan Parsons of AccuCoat Inc., said his hope is that students will continue their pursuit of higher education in optics, and that through training and hands-on experience they will be armed with the skills they need to enter the optics fabrication workforce upon graduation.

'With Paul's enthusiasm and devotion, the precision optics program has evolved from a single elective into a full program offering … Several students that graduated this year have already been hired by local optics companies to put their new skills to work.'

— Alan Parsons, AccuCoat Inc.

Michele Kuester
DigitalGlobe

An expert in space-, airborne- and field-based Earth remote sensing, Michele Kuester leads a team of interns in a hands-on program offered through the NASA-backed Colorado Space Grant Consortium (COSGC). Her young “space cadets” learn how to be calibration scientists, using an ASD Inc. FieldSpec 4 to measure the spectral reflectance of calibration targets, and other instruments to measure atmospherics. She helps prepare her interns for a challenging career in space science by teaching them how to develop protocols for equipment use, write code for data assessment, research weather history to better understand outliers, and set up equipment.

As the lead scientist responsible for the absolute radiometric calibration of DigitalGlobe VNIR and SWIR multispectral sensors, Kuester is able to provide her group of interns with unique insight into the surface and atmospheric measurements of calibration made at the time of a sensor overpass. Interns learn how a radiative transfer model is used to predict the top-of-atmosphere radiance that the sensor should be reporting for the calibration target(s).

“Thanks to Dr. Kuester’s leadership and expertise, many of Colorado’s college and university students now have hands-on field experience, as well as the experience of working as part of an aerospace science team,” said nominator Betsy Kenaston, who works as a webinar planner and moderator for ASD Inc. “Dr. Kuester’s energetic guidance and willingness to share her extensive knowledge has brought them closer to achieving a career in aerospace.”

Kuester holds a Ph.D. in atmospheric and oceanic sciences from the University of Colorado Boulder, and has more than 15 years of experience in the Earth remote sensing field. In addition to Earth remote sensing and absolute radiometric calibration, her areas of expertise include ecological remote sensing, radiative transfer and atmospheric dynamics. Her work at Westminster, Colo.-based DigitalGlobe involves the calibration and validation of the radiometric response of Earth-observing sensors.


Kady Blecha

Entrepreneurs

Alan J. Leszinske
TecMed Inc.

Alan J. Leszinske has supported optical entrepreneurs as much as he has been one. He is CEO and chairman of TecMed Inc., a Cheyenne, Wyo., medical technology intellectual property (IP) company with a blood glucose management solutions portfolio. The company, which he founded in 1995, has a unique business model that grew out of his diverse experience in research, finance and management.

Leszinske's work has yielded four patents, with others pending in the U.S. and 38 other countries worldwide. He has also developed advanced electro-optical switches for imaging and sensing/detection for government, military and aerospace applications. From 1994 to 2007, Leszinske served as president of the Complex Light Valve Corp., an Albuquerque, N.M., R&D company that focused on electro-optical applications and the development of intellectual property. In addition, he served as the principal of Contract Funding & Acquisition Inc. — an Albuquerque private capital organization that provided equity capital to 14 startup companies and other support in the form of project management and oversight — from 1992 to 2007.

More recently, a privately held company has received a license for Leszinske's optics-based measurement technology, and with that is developing an automated blood glucose measurement instrument and device designs for use in surgical and critical care environments. TecMed is marketing advanced designs for these applications to commercialization partners for manufacture and distribution.

"Quietly and with an aversion to the limelight, Alan has worked to create, develop and refine optical technology that will usher in new standards in patient care and diabetic home monitoring. His vision and insight have led to game-changing technological breakthroughs and unheralded advancements in electro-optical components and applications,"


TecMed Inc.

said Steven Schroeder, a contractor and colleague at TecMed, who nominated Leszinske for this honor.

Leszinske was also nominated for the Beacon designation by colleague and advisor Dr. Vincent Figueredo of the Thomas Jefferson School of Medicine, and Andy Braman, a colleague at TecMed.

Leszinske received his bachelor's degree in liberal arts general studies with a focus on experimental methods and statistical/probability analysis from Grand Valley State University in Allendale, Mich.

Carsten Steger
MVTec Software GmbH

For more than two decades, Carsten Steger has played an important role in bridging the gap between machines and vision. A co-founder of MVTec Software GmbH in Munich, where he is also the company's research director, his work on image understanding and object recognition has helped advance machine vision technology, particularly in the international automation industry.


MVTec Software GmbH

Steger was a driving force behind the development of MVTec's HALCON product, which is standard software for machine vision with an integrated development environment. In 1996, Steger founded MVTec with three of his research colleagues at the Technische Universität München (TUM) Department of Computer Science. Since then, he has been awarded five patents for systems and methods for various types of object recognition and automatic parameter determination.

"Mr. Steger has been dedicated to push scientific research at MVTec forward and therefore has been playing a key role in strengthening the advancement of machine vision technology in international industry automation," said Steger's nominator, Jörg Stelzer, a communications consultant for Schwartz Public Relations.

Steger received his doctorate in 1998 from TUM, where he has served as an adjunct professor since 2001. He has co-authored more than 80 scientific publications, including several books, such as *Machine Vision Algorithms and Applications* (Wiley-VCH Verlag GmbH, 2008). According to information from Google Scholar, Carsten's works have been cited over 3,600 times. Since 2013, he has served on the German Association for Pattern Recognition's technical committee. He is a past recipient of the American Society for Photogrammetry, Remote Sensing's Talbert Abrams Grand Award, and the 5th International Conference on Quality Control by Artificial Vision's Best Paper Award.

Research/Unsung Heroes

'The hero is one who kindles a great light in the world, who sets up blazing torches in the dark streets of life for men to see by.'

— Felix Adler (1851-1933), a professor of social and political ethics at Columbia University

Russell Lidberg

St. Cloud State University (SCSU)

Assistant professor Russell Lidberg works in photonics and optics research, with labs focusing in several areas: interferometric sensors, laser/materials interactions, nonlinear optics, and optical materials for sustainable energy. His photonics lab, in particular, investigates novel methods of studying solid state materials. His work has made a positive impact on his students, including Rita Schwieters, a student in his lab at SCSU in Minnesota who nominated him for this Beacon recognition.

"Thanks to [Lidberg], I feel confident in my ability to perform advanced photonics research, and I know my colleagues in his lab feel the same," she said, noting that he is revered as a supportive, highly skilled instructor who takes on students who have minimal optics backgrounds but an interest in this field of study.

As a faculty member for the Electronic, Optical and Magnetic Materials and Devices research group, Lidberg works within the College of Science and Engineering (COSE) as director of the Imaging Center and Clean Room in the Integrated Science and Engineering Laboratory Facility, a student-centered science facility at COSE. According to informa-

'Thanks to [Lidberg], I feel confident in my ability to perform advanced photonics research, and I know my colleagues in his lab feel the same.'

— Rita Schwieters, SCSU

tion from SCSU, he has also served as a liaison between the school and regional industry, and is one of the core developers of specialty programs in materials science and nanomaterials.

"A large part of [Lidberg's] teaching approach is to incorporate industrial skills that will help us become successful in industry or graduate school," Schwieters said. "He helps us build confidence in our ability to do photonics research."

He has backed students' research and work, as well, including for SCSU's Student Research Colloquium Proceedings in 2009. There, he sponsored several student presenters in topics such as Fluorescence Lifetime Study of Tetracene Single Crystal.

Outside of the academic realm, Lidberg co-authored a paper published in 2015 in *Applied Physics Letters* — Temperature dependent c-axis hole mobilities in rubrene single crystals determined by time-of-flight. The paper focused on his team's study of "hole mobilities (μ) in rubrene single crystals (space group Cmca) along the crystallographic c-axis … as a function of temperature and applied electric field by the time-of-fight method."

Murthy Chavali
Vignan University

In addition to being dean of international relations and director of the Center for International Affairs at Vignan University in Andhra Pradesh, India, Murthy Chavali is a veteran professor and researcher, with more than 20 years in the classroom and the lab. According to a former colleague and collaborator who nominated him for this honor, Chavali has made a positive impact on the industry as a whole, as well as on numerous students, many of whom have gone on to post doctoral and Ph.D. programs; some are even now leading their own labs.

He has had papers published in at least 160 industry journals, in addition to nearly 200 research reports. He has been a familiar face at various conferences worldwide, having made 187 presentations, as well as 55 poster presentations. Chavali has also been cited in at least 10 book chapters, holds four patents and has served as a guest lecturer at institutions more than 200 times.

Outside of his academic and R&D accomplishments and influence, Chavali was named a Top 40 Under 40 on the Power List in 2014 — presented by *The Analytical Scientist*, a U.K. publication focused on analytical science, chemistry and technology in agricultural, environmental, food, forensic and pharmaceutical applications — as a top influential analytical scientist, for his contributions to photonics R&D.

In addition to his work, Chavali is involved with several professional societies, as noted by Vignan University — the Laser Association of India; the International Frequency Sensor Association in Ontario, Canada; the American Institute of Aeronautics and Astronautics in the U.S.; the Society for Automotive Engineers in Japan; the European Association for Cancer Research, based in Nottingham, U.K.; the International Society for Optical Engineering in the U.S.; and the Asia Pacific Nanotechnology Forum in Australia.

Among Chavali's research interests are optical waveguide technology, IR sensors, LIF, chip-based chemical and biochemical sensors, analytical chemistry, nanomaterials and nanotechnology. According to his nominating collaborator, Chavali's current research focuses on areas of photonics, nanotechnology applications for gas and liquid sensor applications, as well as synthesis and fabrication of various organic and inorganic nanostructured materials, and nanosensor array technology.

2016 Reader Poll

Photonics Spectra asked its readers to weigh in on questions relating to work in the photonics industry. Here's what they said.

What advice would you give to your younger self, when you first became interested in photonics?

Work abroad when you are still young. Start a company if you have a good business idea.

Read everything! Keep current with each new development.

Learn more.

Write articles and papers as soon as possible, and as many as possible, as fast as possible.

[Know that] photonics is the technology that is going to cover 75 percent of the market in the coming years.

Which photonics technology is likely to go by the wayside in the future? Which technology is here to stay?

Imaging [is here to stay], as a tool for quick analysis in all its forms.

Photonics is too big an umbrella term. Those that fit will stay; those that do not fit will not die, but will wander off.

It's very difficult to describe what type of photonics will fade away as "old tech." On a global scale, tech is often acquired by measure of economic means. This format ... is global, hence, some entities will have the newest technology while other entities will have the oldest technology. The future of photonics has a bit more clarity with regard to "new, shiny reflective technology" — that's here to stay.

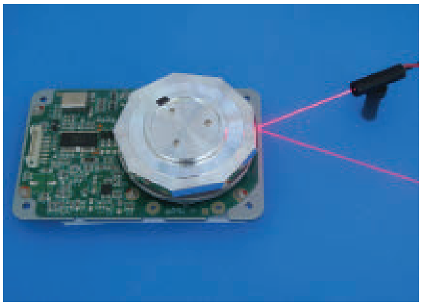
Plasmonics [is here to stay]. Incandescent lamps will pass away. LED technology is [here] to stay.

Fiber optics [is here to stay].

Did you have a mentor who helped shape your career? Why was he/she so important?

No [mentor]. I actually stumbled from electronics into electro-optics and lasers, thence into photonics about four decades ago.

[My mentor] encouraged me to leave a research organization and to join the industry.



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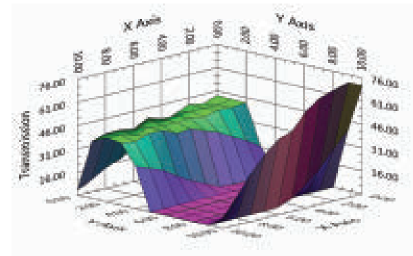

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1 Laser Module

Precision Laser Scanning LLC has announced the Start-of-Scan (SOS) laser for polygon scan heads. Used for materials processing, the scan heads employ high-power and ultrafast lasers. SOS detectors require a low-power continuous wave beam. The module has a tight 0.7-mm spot, so there is no need for manual focusing or external focusing optics. The beam is visible red and eye-safe, which makes for easy scan head alignment. The module is 8 mm in diameter and 30 mm long, enabling integration into a compact polygon scan head.

info@precisionlaserscanning.com

2 Prism Mounts

Edmund Optics offers Techspec Risley Prism Mounts, designed for 25-mm wedge prism pairs in a precision manual beam steering configuration. The devices are optimized for angles ranging from 0 to 26°, can be used with one or two prisms, and feature a clear aperture of 23 mm and a coarse rotation of 360°. The mounts allow independent rotational control for each prism. Constructed of sturdy anodized aluminum, they are ideal for steering applications that require one or two wedge prisms.

www.edmundoptics.com

3 Hyperspectral Mapping

Craic Technologies Inc. now offers 5D hyperspectral mapping (5DM) capabilities for its UV-VIS-NIR and Raman microspectrometers. 5DM provides microspectrometer users with the ability to map the spectral responses across surfaces of their samples by point scanning. With microscopic spatial resolution between each point, maps may be created representing all three dimensions, the two axes of the spectra and time, and developed from transmission, absorbance, reflectance, fluorescence, luminescence and polarization data.

sales@microspectra.com

4 Beam Profiling Camera

Gentec Electro-Optics Inc. has released a 4.2-MP beam profiling camera for very large beams, featuring an extra-large aperture of 20.5 × 20.5 mm. The aperture uses an optical fiber taper fixed on the optical sensor, which concentrates the beam onto an 11.3 × 11.3-mm sensor to produce a multiplication factor of 1.8. The camera measures beams as small as 120 µm.

info@gentec-eo.com

5 Source Driver

Innovations in Optics Inc.'s 5000B-500 solid-state source driver/controller independently drives, controls and modulates up to 20 different solid-state sources, including combinations of LEDs and LDs and IR VCSEL arrays. The device features both USB and Ethernet interfaces to control the intensity, pulse width and duty cycle of each solid-state source, and is designed for technical and industrial applications such as LED lighting for machine vision, CCTV security and surveillance, and license plate recognition for traffic enforcement or parking garage management.

sales@innovationsinoptics.com

6 Liquid Lens

Varioptic, a business unit of Parrot Drones SAS, offers the Arctic 25H series of variable-focus liquid lenses. It offers resistance to mechanical shocks and vibrations, and operates from −30 to 85 °C. Typical performance at 25 °C offers a wavefront error (optical quality) of 45-nm rms, and 97 percent transmission rates at 587 nm (the Arctic 25HO model) and 850 nm (the Arctic 25H1 model). The lenses also support continuous autofocus for video up to 30 fps. Two antireflective coatings are available.

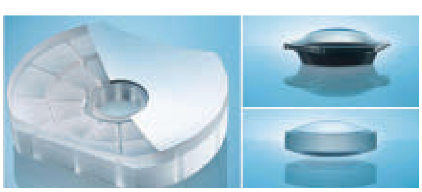
sales.varioptic@parrot.com

Centrifuge Windows

Meller Optics Inc. has released a line of sapphire centrifuge windows for demanding applications where chemical-, scratch- and high-pressure-resistance are required. The windows feature a scribed arrow on their edges to project the optic access and simplify alignment. Compatible with Beckman centrifuges and other instruments, they measure 19.03 mm in diameter. Designed for OEMs and field-replacements, the windows are available wedged and plano with chamfers 0.35/0 mm × 45° in two places and have a 30-5 scratch-dig surface finish.
steve@melleroptics.com

Sensor Module

Everlight Electronics Co. Ltd. offers APM-16D17-05-DF8 and APM-16D17-06-DF8 three-in-one sensor modules for use in environment brightness detection and smart switching in smartphones, tablet PCs, residential smart lighting and digital signage applications. The modules use a specially coated photodiode with an optical response similar to human eyes. They have a common I^2C interface, allowing them to be driven with a supply voltage of 1.7 V. They are optimized to sense the ambient brightness and adjust the backlight of a screen to the most clear and comfortable settings.
salesmarketing@everlightamerica.com



Custom Aspheres

SwissOptic AG, a subsidiary of Berliner Glas KGaA, offers small-batch production of customized aspherical lenses and freeform surfaces. Concave or convex aspheres are available with diameters from 12 to 300 mm and in various materials, such as optical glass, quartz glass, Zerodur, crystalline materials and metals. Specialties include development and production of lightweight structured aspherical mirrors, which offer weight reduction up to 90 percent, which can be key for airborne optical systems.
swissoptic@swissoptic.com

Laser Sensor

Ophir Photonics Group has announced the BC20-V1 laser sensor for the power measurement of scanned or intermittent beams. The photodiode sensor measures any wavelength over the spectral range of 400 to 1100 nm, and is able to measure the power of laser barcode scanners, laser printer scanners and the peak power of pulsed-mode lasers. It measures power from 0.1 to 20 mW. The BC20-V1 works with most Ophir meters and has a swivel mount for ease of operation.
sales@us.ophiropt.com

Driver Transmitter

The A50-150C VCSEL driver transmitter from **VI Systems GmbH** is optimized for very low power consumption and versatile deployment in short reach optical interconnects for data center and high-performance computing applications. The driver integrated circuit is capable of data transmission of up to 54 Gb/s in non-return-to-zero modulation format.
www.v-i-systems.com

Panoramic Helicopter Display

Elbit Systems Ltd. has announced the BrightNite multispectral panoramic solution for helicopters. The system delivers essential data directly to the eyes of a pilot, enabling intuitive flight in pitch dark and other degraded conditions. It is composed of nongimbaled, uncooled FLIR and highly sensitive CMOS sensors that present an ultrawide field of regard intuitive image to a display system. The

system processes real-time panorama video, enhanced by a 3D conformal mission symbology concept and transmits high-resolution video to the helmet-mounted display.
sales@elbitsystems.com

NIR Sensor

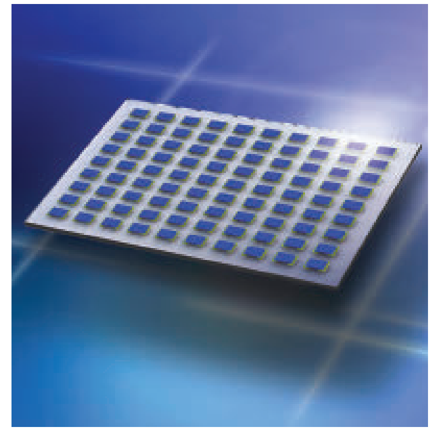
Invisage Technologies Inc. has announced the Spark4K NIR camera sensor for Internet of Things devices. The 1.1-µm pixel, 13-MP sensor in a 1/3-in module features 4K video at 30 fps, ideal for augmented reality, autonomous and authentication systems that require high-resolution, high-dynamic-range NIR (near-infrared) imaging with global shutter capability.
jennifer.lillie@invisage.com

High-Speed Camera

Vision Research Inc. has released the Phantom VEO series of high-speed cameras in a small, rugged, 5-in. cube. Comprising eight individual models across four performance levels and two body styles, the devices incorporate high-performance, 12-bit, 35-mm CMOS sensors with a choice of lens mount. The cameras are designed for a range of applications including scientific analysis, material testing and defense research.
info@vision-research.com

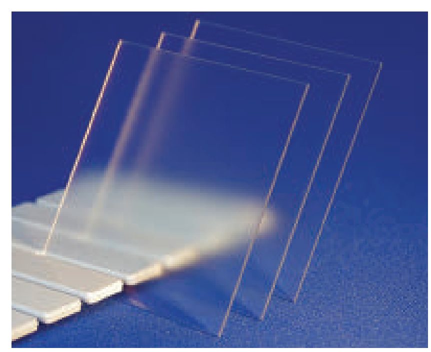
Laser Measurement App

The LabMax-Pro laser measurement app from **Coherent Inc.** enables operation of the company's laser power and energy sensors using a tablet computer running the Android operating system and having a display screen of 9 in. diagonal or greater. Capabilities include instantaneous power reading, pulse shape analysis, beam position, data logging and statistics, as well as the ability to save data files and share them between mobile devices.
sean.bergman@coherent.com



IR Sensor Coating

Grauling Research Inc. offers the IR-ISE photoconductive IR sensor coating to enhance the performance and efficiency of IR sensors. The thin-film coating was developed for use with lead sulfide (PbS) and lead selenide (PbSe) sensors and can reduce the surface reflection of incident radiation by utilizing environmentally rugged, single- or multilayered thin-film coatings. The coating also seals and protects the device, eliminating the need for glass encapsulation, which reduces the size and weight of the photodetector.
eisenhauerdl@graulingresearch.com



Monolithic Diffusers

Luminit LLC offers monolithic glass light shaping diffusers with angles from 1° to 15°, offering OEMs a cost-effective path to improve the beam quality of light engines. Available in various shapes, the material composition of the diffusers is entirely borofloat glass, avoiding organic material that can degrade or outgas over time. The diffusers can endure temperatures up to 400 °C and provide light transmission between 91 to 93 percent or 95 to 98 percent with the optional antireflection coating.
sales@luminitco.com

USB3 Camera Module

The 5-MP 24B5.0XUSB3 monochrome USB3 camera module from **Videology Imaging Solutions Inc.** is the first in a series of cameras that will oper-

ate with the company's own image processing firmware. The module uses a 1/2.5-in. image sensor, offering low-light, near-IR performance and frame rates up to 14 fps at full resolution. Higher frame rates at reduced resolutions are possible through binning. The device provides a parallel BT.1120 that can be run simultaneously with the USB.
info@videology.nl

Optical Mounts

Siskiyou Corp. has announced the OGX series of optical mounts, available for both 1- and 2-in.-diameter optics such as mirrors, beamsplitters, filters and lenses. The use of fine pitch adjusters provides adjustment resolution as fine as 5.3 arc seconds over a total motion range of 7°. The mounts are primarily intended for space-constrained applications in high-performance optical systems that require extremely precise adjustment and exceptional long-term stability. Applications include airborne and spaceborne laser systems, laboratory use, astronomy instrumentation, and miniaturized life science instruments and tools.
sales@siskyou.com

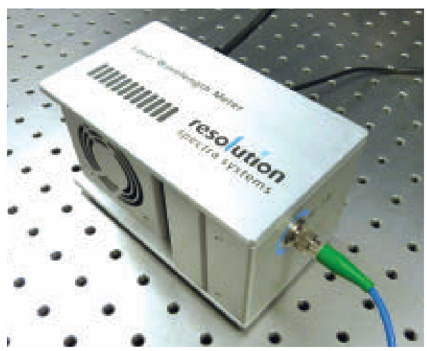
Interferometer

Äpre Instruments offers the S100 HR laser Fizeau interferometer for optical manufacturing. The system offers the affordability of a continuous zoom interferometer with the performance of a modern imaging system. It is designed for accurate metrology of highly sloped surfaces and fine resolution of midspatial frequencies. The system features diffraction-limited, 4-MP imaging, better than $\lambda/20$ accuracy, even at 8 fringes/mm slopes. Using the company's REVEAL software, the S100 HR can provide custom reports in as few as 6 s.
rsmythe@apre-inst.com

NIR Longpass Filter

Midwest Optical Systems Inc. has announced the LP900 Near-IR longpass filter. The filters sharply block light below 900 nm while allowing longer wavelengths to pass, and are designed for viewing

reflected 915-nm laser diode light. The filters can also be used in IR digital photography as detector windows, as well as in various scientific and forensic applications.
http://midopt.com/contact-us



Wavelength Meter

Resolution Spectra Systems' LW-10 laser wavelength meter is designed for CW and pulsed lasers. The compact, high-resolution device offers robust calibration with 20-MHz resolution, 200-MHz accuracy and multiple software interface capabilities. Optional calibration as a laser spectrum analyzer is available with spectral resolution up to 3 GHz. Applications include use in the visible and near-infrared range for tunable laser monitoring, laser stability control, frequency locking, atom cooling and spectroscopy.
info@resolutionspectra.com

LED Drivers

Thomas Research Products has released the LED12W-D series of 12-W, dimmable LED drivers. The constant-current drivers are designed for use with standard 0- to 10-V dimmers. They feature a <10 to 100 percent dimming range and universal 100- to 277-V input, and are Type HL for use in hazardous locations. The IP66-rated Black Magic thermal advantage plastic housing is intended for damp location use.
info@trpssl.com

Broadbeam Beamsplitter

Newport Corp. has introduced a terahertz-visible broadband beamsplitter that is 2 in. in diameter

and made of high-quality N-BK7 glass with transmission specifications for the visible wavelength range. An indium tin oxide front surface coating reflects terahertz wavelengths from 1 to 120 THz while transmitting the visible. The back side is coated with a broadband antireflection coating optimized for visible wavelengths, 400 to 700 nm. Applications include spectroscopy, remote sensing, explosives detection, astronomy and telecommunications.

annawang@newport.com

MEMS Sensor

Bosch Sensortec GmbH's BMX160 is a compact, nine-axis microelectromechanical (MEMS) sensor for smartphones, smart watches, fitness trackers, smart jewelry and augmented reality devices. The sensor is housed in a $2.5 \times 3 \times 0.95\text{-mm}^3$ package, combining accelerometer, gyroscope and geomagnetic sensor technologies. The sensor has a built-in power management unit and ultralow power background application, enabling the application processor to remain in sleep mode for a long period of time. With low power consumption of <1.5 mA, the sensor is designed for applications with extreme form-factor restraints.

www.bosch-sensortec.com

Unmanned Ground Vehicle

Milrem AS and **Leica Geosystems AG** have released the Pegasus Multiscope, an unmanned ground vehicle for off-road use in surveying, security and monitoring applications. Using the cameras calibrated to the 3D point cloud, change detection with Leica MapFactory for AutoCAD can be seen within 2 to 3 cm. Thermal imaging is also available. The multiscope can follow a preprogrammed route and detect disturbances, and can traverse dangerous or difficult areas such as unstable riverbanks when surveying for dam construction.

www.leica-geosystems.us

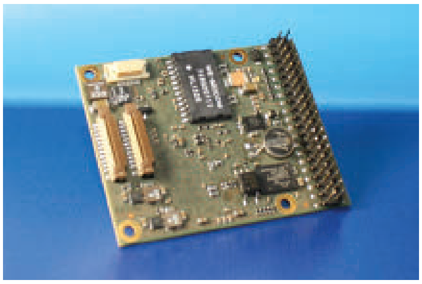
DOE Tuner

Holo/Or Ltd.'s diffractive optical element (DOE) tuner enables small adjustments to the output characteristics of a DOE. Placing the tuner between the DOE and focusing lens allows for image size control in most elements. In multispot beam splitters, finer control is allowed over the separation angle. The tuner can also be placed before the DOE in order to fine-tune the input beam size. In beam splitter elements, this placement can also control the output spot size. For top hat beam shapers, nominal beam size can be achieved.

sales@holoor.co.il

Circuit Board

Vision Components GmbH offers the Q-Board circuit board for conversion of existing internet protocol (IP) cameras into intelligent transportation systems. The Q-Board supports streaming through an integrated FFmpeg library. It can also be connected to any conventional IP camera, supporting almost all standard IP streaming protocols, video codecs and container formats. The 40×50-mm



device is based on the ARM Dual Core ZYNQ processor with 2 × 866 MHz, and features the Carrida software engine.
miriam.schreiber@vision-components.com

Chemical Identifier

Rigaku Analytical Devices has announced enhancements to its Progeny ResQ handheld chemical identification tool. The 4C Technology feature indicates the overall threat level posed by the presence of multiple individual chemicals. A new threat alert and on-board camera allows users to monitor, respond and document an incident utilizing a single handheld chemical identification device. With a 1064-nm excitation laser, Progeny ResQ can overcome issues of sample-induced fluorescence interference that affect Raman systems using shorter excitation wavelengths.
info@rigakuanalytical.com

Chip LED

Rohm Co. Ltd. has added seven colors to its PICOLED series of low-profile, ultracompact chip LEDs optimized for wearable technology, portable devices and drones, allowing for greater color expression and more design freedom. The SML-P1 series of thin, compact chip LEDs utilizes a comprehensive, integrated production system and eliminates problematic wavelength variations, and 15 colors are available. Combining a lower gold wire loop with a thinner light-emitting element enables a form factor of 0.2 mm.
www.rohm.com/web/global/contactus

Express Custom Optics

Präzisions Glas & Optik GmbH now offers 48-hour Express Service for the manufacturing of custom optics. Optical windows or substrates, front surface mirrors, antireflective coated glass, beam splitters and optical filters, among other products, can take advantage of the service. Each is manufactured and shipped within two working days.
sk@pgo-online.com

Positioner

Physik Instrumente LP offers the PIHera XY positioners with travel to 1800 µm and <1-nm resolution. The flexure-guided piezo positioning stages have vibration-less motion, virtually unlimited resolution and fast response. With the exclusion of rolling elements, there is no bearing rumble to affect the uniformity or straightness of motion. The stages are equipped with absolute-measuring

direct-metrology capacitance sensors and provide a positioning accuracy of 0.02 percent.
info@pi-usa.us

Panel Platforms

Wave2Wave Solution Corp. has integrated MXC connectors into its EVO and EXO panel platforms, extending optical backplane technology into structured cabling with expanded and collimated laser beams. The EVO panel series offers the highest level of scalability and density, supporting a variety of applications and fiber connectivity in telecom and data centers. The EXO panel series is a modularized platform that supports a variety of connectivity types and applications on the same 1U chassis, allowing for flexibility.
info@wave-2-wave.com

TERS Probes

Horiba Scientific offers Silver OMNI TERS Probes to maximize nanoRaman tip-enhanced Raman spectroscopy (TERS). The probes enable all modes of operation such as top, side and bottom optical access. Used in conjunction with Horiba's nanoRaman systems, the probes produce Raman signal enhancement at 633/638 nm on a reliable test sample. Combining the nanoRaman system with the TERS probes provides the highest enhancement TERS solution, down to 10-nm resolution and lower.
joanne.lowy@horiba.com

AUGUST

OSA Latin America Optics & Photonics Conference (Aug. 22-25) Medellin, Colombia. Contact +1 202-223-8130, info@osa.org; www.osa.org/meetings.

IEEE International Conference on Group IV Photonics (Aug. 24-26) Shanghai. Contact +1 732-562-3895, m.figueroa@ieee.org; www.gfp-ieee.org.

● **SPIE Optics + Photonics (Aug. 28-Sept. 1)** San Diego. Contact +1 360-676-3290, customerservice@spie.org; www.spie.org/optics-photonics.xml.

SEPTEMBER

● **China International Optoelectronic Exposition (CIOE) (Sept. 6-9)** Shenzhen, China. Contact +86 755-86290891, cioe@cioe.cn; www.cioe.cn/en.

SEMICON Taiwan (Sept. 7-9) Taipei, Taiwan. Contact Jasmin Liu, +886 3-560-1777 Ext. 307/309, semicontaiwan@semi.org; www.semicontaiwan.org.

Executive Infrared Imaging Forum (Sept. 8) Shenzhen, China. Contact Clotilde Fabre, Yole Developpement, +33 472-83-0180, fabre@yole.fr; www.yole.fr.

● **ENOVA Paris (Sept. 14-15)** Paris. Technology exhibition focusing on electronics, embedded measurement, vision, optics and Internet of Things. Contact Nadège Venet, + 33 0-144-318-257, nadege.venet@gl-events.com; www.enova-event.com.

European MEMS Summit (Sept. 15-16) Stuttgart, Germany. Contact SEMI, +1 408-943-6900, semihq@semi.org; www.semi.org.

● **ECOC (Sept. 18-22)** Düsseldorf, Germany. 42nd European Conference and Exhibition on Optical Communication. Contact Event Administrator Luisa Margione, +44 0-1732-752125, luisa.margione@nexusmediaevents.com; www.ecoc2016.de.

Strategic Materials Conference (Sept. 20-21) Mountain View, Calif. Contact SEMI, +1 408-943-6900, semihq@semi.org; www.semi.org.

OCTOBER

Inpho Venture Summit, Photonics and Beyond (Oct. 6-7) Bordeaux, France. Formerly Invest in Photonics. Contact Audrey Durand, +33 (0)5-56-79-44-86, audrey@inpho-ventures.com; www.inpho-ventures.com.

Micro Photonics (Oct. 11-13) Berlin. Contact Messe Berlin GmbH, +49 30-3038-2159, micro-photonics@messe-berlin.de; www.micro-photonics.de.

● **Photonex and Hyperspectral Imaging and Applications (HSI) (Oct. 12-13)** Coventry, England. Photonex and HSI colocated. Contact Xmark Media Ltd., +44 (0)1372-750555, info@xmarkmedia.com; www.photonex.org; www.hsi2016.com.

Photonics Asia (Oct. 12-14) Beijing. Contact +1 360-676-3290, customerservice@spie.org; www.spie.org/x6445.xml.

● **Frontiers in Optics: The 100th OSA Annual Meeting and Exhibit/Laser Science XXXII (Oct. 16-20)** Rochester, N.Y. Contact +1 202-416-1907, custserv@osa.org; www.frontiersinoptics.com.

SEMICON Europa (Oct. 25-27) Grenoble, France. Contact Eva Weller, SEMI Europe, +49 30-3030-8077-0, eweller@semi.org; www.semiconeuropa.org.

OSA Advanced Solid State Lasers Conference and Exhibition (Oct. 30-Nov. 4) Boston. Contact +1 202-416-1907, custserv@osa.org; www.osa.org/assl.

Avionics and Vehicle Fiber Optics and Photonics Conference (Oct. 31-Nov. 3) Colocated with the IEEE International Topical Meeting on Microwave Photonics. Contact Megan Figueroa, +1 732-562-3896, m.figueroa@ieee.org; www.photonicssociety.org.

NOVEMBER

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

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

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

DECEMBER

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

PAPERS

Photoptics 2017 (Feb. 27-March 1, 2017) Porto, Portugal
Deadline: Regular papers, Sept. 22; position papers, Nov. 3
The 5th edition of Photoptics will feature three tracks on optics, photonics and lasers, covering both theoretical and practical aspects. Researchers, engineers and practitioners interested in any of these fields are invited to present work on new methods or technologies, advanced prototypes, systems, tools and techniques, as well as general survey papers indicating future directions. Contact Photoptics Secretariat, +351 265-520-185; photoptics.secretariat@insticc.org; www.photoptics.org.

International Laser Safety Conference (ILCA) (March 20-23, 2017) Atlanta
Deadline: Abstracts, Oct. 6
ILSC is a comprehensive four-day conference covering all aspects of laser safety practice and hazard control. Scientific sessions will address developments in regulatory, mandatory and voluntary safety standards for laser products and for laser use. A two-day Technical and two-day Medical Practical Applications Seminar (PAS) complement the scientific sessions by exploring everyday scenarios that the laser safety officer or medical laser safety officer may encounter. Contact Laser Institute of America, +1 407-380-1553; ilsc@lia.org; www.lia.org/ilsc.

SPIE Defense + Commercial Sensing (April 9-13, 2017) Anaheim, Calif.
Deadline: Abstracts, Sept. 26
Defense + Commercial Sensing comprises technical conferences, courses and exhibitions on sensing, imaging, and photonics technologies for defense, security, industry and the environment. Focused topical tracks are agricultural applications, fiber optic sensors, pharmaceutical applications and unmanned autonomous systems. Contact SPIE, +1 360-676-3290; customerservice@spie.org; http://spie.org/conferences-and-exhibitions/defense--commercial-sensing.

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The most restful wavelength

A mouse study has revealed the role of a light-sensitive pigment in sleep regulation, and could deepen our understanding of how color balance — and light-emitting devices in general — affect human sleep cycles.

Researchers from Oxford University's Sleep and Circadian Neuroscience Institute exposed mice to bright light during the night, aiming to disambiguate two physically incompatible responses that had been previously observed — the inducement of sleep and a simultaneous increase in corticosterone, a stress hormone produced by the adrenal gland that causes arousal, or wakefulness. The team sought to understand how the two effects were related, as well as how they're linked to the blue light-sensitive pigment melanopsin, known to play a key role in human circadian rhythms.

The team exposed mice to three different wavelengths of light — violet, blue and green — at night. Based on the existing data about the role of melanopsin in sleep, they expected blue light would induce sleep fastest, as its 470-nm wavelength was closest to the peak sensitivity of the pigment, around 480 nm.

However, it was green light that produced the most rapid sleep onset, between 1 and 3 minutes. Blue and violet light delayed sleep — onset took 16 to 19 minutes for blue and 5 to 10 minutes for violet. The researchers confirmed the effect by testing mice using green and blue light at a time when they would usually be less active.

To investigate the role of melanopsin, the team performed the same test on mice lacking the pigment. For these mice, the colors had opposite effects: Blue caused rapid sleep onset, while green and violet significantly delayed sleep, showing that melanopsin is necessary for the substantial wavelength-dependent effects of light on sleep.

"This study shows that there are different pathways from the eye to the brain — one directly regulating sleep and the other increasing arousal," said researcher Dr. Stuart Peirson. "Melanopsin has a more complex role than previously thought, affecting both pathways. This is the first time that it has been shown to regulate adrenal stress responses."

Peirson noted that an obvious caveat of the study is that mice are a nocturnal species. As such, green light may be expected to increase wakefulness rather than induce sleep in humans. He also predicted that blue light would further enhance the wake-promoting effects of light by elevating adrenal stress hormones.

Sounds like "lights out" is the way to go for a stress-free night's sleep.

Julia Germaine
julia.germaine@photonics.com

CMS

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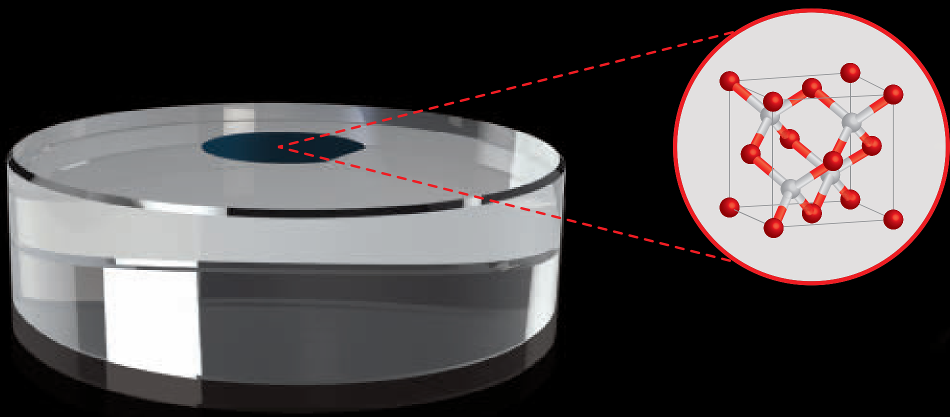

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radius of curvature: ≥ 10 cm

diameter: up to 20 cm

NIR absorption losses

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2015

< 4 ppm
2013

< 20 ppm
2011

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