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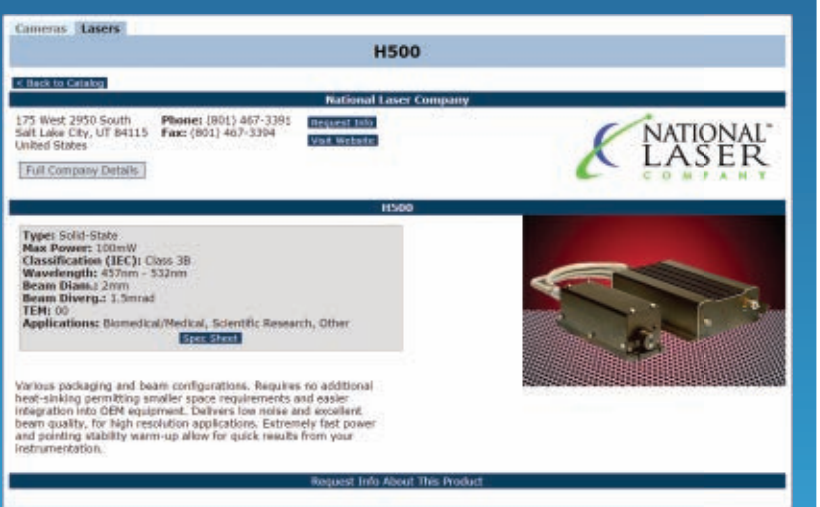

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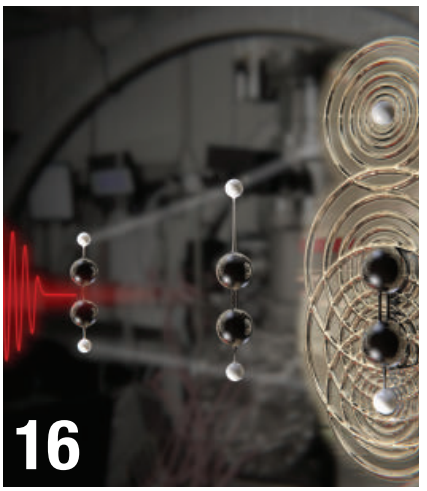
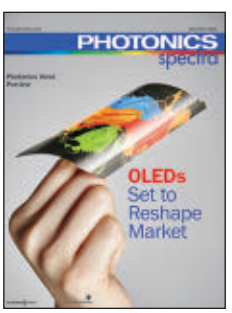


Departments & Columns

THE COVER
A flexible active matrix OLED display. Courtesy of Samsung Display. Cover design by Senior Art Director Lisa N. Comstock.



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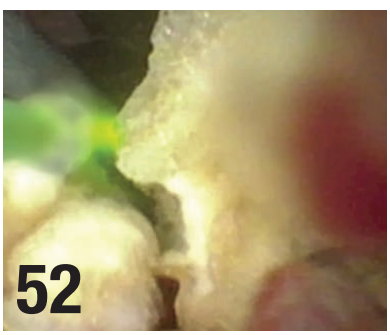
PHOTONICS: The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing.



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editorial COMMENT

A season for disruption

An Apple watch, a Samsung smartphone, an LG television, a virtual-reality headset. All are likely to make the short list of the most sought-after consumer electronics this holiday season.

Soon these and other luxury consumer goods are likely to include organic light-emitting diode (OLED) displays, prized for their crystal clear visual characteristics and compatibility with flexible and transparent materials. Industry watchers are so enamored with OLEDs that many say it's not a matter of "if" OLEDs are likely to displace conventional LEDs, but rather "when." See "OLEDs Step In Where Design Matters," on page 26.

Market disruption is a theme in "Medical Lasers Cut and Heal" on page 32. The medical market was one of the first to embrace lasers, with the first surgeries conducted in the years following Theodore H. Maiman's introduction of the ruby laser in 1960. But most uses were restricted to ablation, cutting or tissue removal. That's now changing with emerging applications including bioresponse and drug delivery, made possible by ever-more sophisticated systems that incorporate multiple wavelengths, and feature innovations in power.

The ongoing improvements in lasers across industry has spurred the development of new laser-specific optical coatings. But to achieve the optimal performance, a deeper understanding of the substrates available, their attributes and the various deposition techniques can save costs and headaches. See "No One-Size-Fits-All Approach to Selecting Optical Coatings," by Edmund Optics' Stefaan Vandendriessche on page 36.

From assessing optical coatings we move to assessing light sources — particularly LEDs and optical vortex beams, each with unique phase distribution properties that are difficult to measure using conventional interferometry. Optocraft GmbH's Johannes Pfund, Ralf Dorn and Christian Brock examine the use of Shack-Hartmann wavefront sensors in "Wavefront Sensing Under Unique Lighting Conditions," on page 42.

Also in this issue, Manijeh Razeghi and her colleagues at the Center for Quantum Devices at Northwestern University detail recent advances in terahertz optical frequency comb operations that, along with mode selecting and phase-matching mechanisms, have made single-mode THz emission at high powers possible. See "Breakthroughs Bring THz Spectroscopy, Sensing Closer to Mainstream," page 48.

And finally, for many in the industry, the year truly begins with Photonics West in San Francisco. For an insider's look at what's in store at this year's show, don't miss Senior Editor Justine Murphy's show preview on page 52.

Enjoy the issue!

Michael D. Wheeler

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Donghai Wu
Donghai Wu is a postdoctoral researcher at the Center for Quantum Devices (CQD) at Northwestern University. Page 48.

Welcome to

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The online companion to *Photonics Spectra*

What's Online:

Webinars Coming in January 2017

Low-Light Detection: SiPM vs. PMT

Wednesday, January 11, 1 p.m. EST

Presented by Hamamatsu Corp.

Slawomir S. Piatek will discuss the silicon photomultiplier (SiPM) versus the photomultiplier tube (PMT). He will review the principles of operation of each device, offer a side-by-side comparison of their optoelectronic characteristics, and conclude with application examples that illustrate various conditions under which one device would be preferable to the other. Piatek is a senior university lecturer of physics at the New Jersey Institute of Technology. He earned a Ph.D. in physics at Rutgers, the State University of New Jersey.

To register, visit: http://www.photonics.com/W103.

LAM Technology, Opportunities and Challenges

Thursday, January 12, 1 p.m. EST

Wayne Penn, applied physics consultant for Alabama Specialty Products Inc., will provide an introduction to laser additive manufacturing (LAM) in this webinar for engineers, managers and system integrators. Penn will cover 3D printing, the challenges of additive manufacturing (AM) and the role of laser welding and cladding technology in AM. He will present examples of industrial applications showing the use of additive manufacturing and conclude with a look at future initiatives in the area of LAM.

To register, visit: http://www.photonics.com/W102.

OLED Microdisplays

Thursday, January 19, 10 a.m. EST

Uwe Vogel, head of the Microdisplays and Sensors Division and deputy director at Fraunhofer FEP, Dresden, Germany, will speak on OLED microdisplay technology.

For more information about this webinar and to register, visit: www.photonics.com/webinars.

Large-Scale, Deep-Tissue Neuronal Imaging

Wednesday, January 25, 1 p.m., EST

Lingjie Kong will speak on advances in large-scale, deep-tissue imaging of biological dynamics, focusing on applications in neuroscience. Kong received his Ph.D. in optical engineering from Tsinghua University and did his postdoctoral training at Harvard University and at Howard Hughes Medical Institute's Janelia Research Campus. He is currently at Purdue and is planning to join the faculty at Tsinghua University.

To register visit: http://www.photonics.com/W104.

Coming in February:

February 10: Characterizing Photonics Devices With Transmission Electron Microscopy, **Eric Stach**, Ph.D., head of Electron Microscopy at Brookhaven National Laboratory.

February 16: High-Speed Imaging At and Beyond the Diffraction Limit, **Hari Shroff**, Ph.D., head of the Section on High Resolution Optical Imaging at the National Institute of Biomedical Imaging and Bioengineering.

For more information and to register for a webinar visit: photonics.com/webinars.

PicoQuant celebrates 20-year anniversary

Optoelectronics development company PicoQuant Inc. is celebrating its 20-year anniversary.

"We at PicoQuant focused from the beginning on offering innovative and high-quality products for international customers working as researchers in various scientific fields," said Rainer Erdmann, managing director and a founder of PicoQuant.

Inviting close partners, customers from science and industry, service providers and suppliers, as well as employees and their families, the company held an event to celebrate the milestone. Highlights included a performance from the company band and a video greeting from Nobel laureate W. E. Moerner. In his message, the scientist thanked PicoQuant for the longstanding collaboration and congratulated the company on its anniversary.

PicoQuant

PicoQuant is a research and development company that produces pulsed diode lasers and LEDs, photon-counting instrumentation, fluorescence lifetime spectrometers, and time-resolved confocal microscopes.

Dymax named top Connecticut tech company

The Connecticut Technology Council has named UV-curable adhesive equipment developer Dymax Corp. as one of the fastest-growing technology companies in the state with a spot on the Marcum Tech Top 40 list.

For the fifth year in a row, Dymax was recognized as a technology leader in the advanced manufacturing category. The council cites Dymax's annual revenue growth of at least $3 million, as well as growth in each of the preceding four years.

President Steve LaCroce accepted the award at a ceremony at the Oakdale Theatre in Wallingford, alongside 39 other companies.

Dymax develops innovative oligomer, adhesive, coating, dispensing and light-curing systems for applications in a wide range of markets.

Laser Light to collaborate with Equinix for optical satellite

Optical satellite service provider Laser Light Communications has selected Equinix Inc. as its interconnection provider for a network that will combine spaced-based optics and terrestrial fiber optic network infrastructure to create Space Cable, an optical satellite service.

The resulting All Optical Hybrid Global Network (HALO) will offer 100-Gbps connectivity to carriers, enterprises and government customers via Equinix facilities. Laser Light will establish its first point of presence at Equinix's DC11 International Business Exchange data center in Washington, D.C. The company will use that facility as an initial stepping stone toward installation, testing and demonstration of its capabilities, which will include not only laser communications, but software-defined WAN capabilities as well.

Laser Light will leverage eight to 12 satellites in medium Earth orbit to create a network that will offer an initial service capacity of 7.2 Tbps. The satellites will pass signals among themselves and to the ground via free-space optics. The space interconnections will include 48 links of 200 Gbps apiece, as well as 72 steerable up/down links to Earth at 100 Gbps. The company will complement the satellite network with its extended ground network of terrestrial fiber. Laser Light says it will leverage software-defined networking technology to fully leverage the network's spatial diversity for alternative routing to achieve the lowest latency, as well as select route options to circumvent any changing atmospheric conditions the satellite transmissions may encounter.

"We are excited to work with Laser Light as the interconnection provider for this cutting-edge satellite technology that greatly increases access to many parts of the world that are underserved by current fiber and wireless networks," said Ihab Tarazi, chief technology officer of Equinix. "By adding Space Cable as an equivalent offering together with terrestrial and submarine cables, Equinix customers looking for low latency solutions to reach new or emerging markets will have access to a full suite of data transport options."

• Photometrics camera named R&D 100 finalist • RIT awarded grant for ICP-RIE etch system • Ciena to supply Telecom Egypt •

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Amada Miyachi donates laser to veteran program

Machining equipment manufacturer Amada Miyachi America Corp. has donated a laser marking workstation to Workshops for Warriors, a nonprofit organization that provides vocational training to returning, wounded and disabled veterans of the U.S. Armed Services.

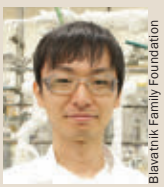
Workshops for Warriors will incorporate the new laser marking workstation into its existing curriculum. Students will use it to learn how to mark metals, ceramics and many plastics.

Amada Miyachi America manufactures equipment and systems for resistance welding, laser welding, laser marking, laser cutting, hermetic sealing, and hot bar reflow soldering and bonding.

$41.1B

—value of the global optical transceiver market by 2022, according to a report by RnR Market Research

PEOPLE IN THE NEWS


Blavatnik Family Foundation

Tomoyasu Mani, former Goldhaber fellow at the U.S. Department of Energy's Brookhaven National Laboratory and current assistant professor in the University of Connecticut's Department of Chemistry, has received the 2016 Blavatnik Regional Award for Young Scientists in the chemistry category. The awards, established in 2007 by the Blavatnik Family Foundation in partnership with the New York Academy of Sciences, celebrate the innovative achievements of postdoctoral scientists 42 years of age or younger who work in New York, New Jersey or Connecticut. Mani is being recognized for his "advances in the understanding of electron transport occurring in organic photovoltaics used in solar energy capture and conversion."

Defense and instrumentation technology developer Elbit Systems of America has named **Tiffany Nesbit** vice president of engineering, and **Douglas Sandklev** vice president of technology and innovation. Nesbit and Sandklev will be charged with continuing advancements in innovation of field-proven technologies and solutions to help meet U.S. warfighters' mission needs. Nesbit has more than 25 years of aerospace experience in research and development leadership roles, with her most recent position at Honeywell. Previous posts include director of engineering, interfacing with COMAC on developing the C919 aircraft; director of Aerospace Software Center of Excellence; and engineering lead for the Flight Controls Joint Venture Formation Team. With more than 20 years of experience, Sandklev will work closely with customers, including the U.S. government, prime contractors' research and development organizations, industry partners and its supplier base, to develop integrated technology strategies.


SPI Lasers UK Ltd.

SPI Lasers UK Ltd. has expanded its presence in China, appointing **Zack Huang** as sales director. Huang has worked in both the U.S. and China. Among his responsibilities will be to showcase the recently launched high-power CW PRISM and QUBE lasers. SPI Lasers designs and manufactures fiber lasers, and sells its products globally. Its major business operations, including R&D and manufacturing, are located in the U.K., with additional sales and customer support locations in Asia and North America.


Optical Innovations Co.

Optical consulting firm Optical Innovations Co. has appointed **James Horwitz** as its chief engineer. Horwitz, a physics graduate of New York University, brings more than 20 years of experience in the design, analysis and testing of optoelectronic systems to his new position. In his new role, he will be responsible for leading projects involving lens design, optomechanical design, and the building of custom lenses and optical instruments. Prior to joining Optical Innovations, Horwitz worked on the design of optical instruments for use in space at Raytheon Co., and on the design and testing of optics for a commercially available spectrophotometer at Mettler Toledo.


Basler AG

Digital camera manufacturer Basler AG has appointed **Sean Flynn** as regional sales manager for the southeastern U.S. Flynn will manage customer accounts in Alabama, Arkansas, Florida, Georgia, Illinois, Indiana, Kansas, Kentucky, Louisiana, Mississippi, Missouri, Oklahoma, South Carolina, Tennessee and Texas. Flynn brings 19 years of sales experience, with the majority of those in the vision industry. Prior to his most recent role as manager of a 15-state territory for an industrial camera manufacturer, Flynn worked as a territory sales manager for a leading distributor.

Optical system developer Fisba AG has appointed **Wallace Latimer** and **Jim Dooley** as new sales directors to increase Fisba's presence in the U.S. market. Latimer joins as sales director for customized optical systems, which encompasses vision systems, assemblies for low light cameras, illumination systems and optical systems for lasers. He brings more than 20 years of experience in sales and strategic management. Dooley will serve as sales director for advanced optical components. With years of career experience in precision and fiber optics, Dooley's background ranges from strategic account development to territory expansion.

Infinera joins AIM, launches partner program

Infinera Corp., a provider of intelligent transport networks, has become the latest member of the American Institute for Manufacturing Integrated Photonics (AIM Photonics), an industry-driven public-private partnership to enhance the development and manufacturing of photonic integrated circuits.

Infinera will provide access to its Indium Phosphide (InP) photonics technology and establish an InP-based foundry wafer access for AIM.

"As we welcome Infinera as the newest partner of AIM Photonics, today's partnership exemplifies another necessary and exciting step forward in the progression of this important state initiative," said John Maggiore, chairman of the New York State Photonics Board of Officers. "In New York, state funding is moving ahead on schedule as is the competitive process to identify a TAP [Testing, Assembly and Packaging] facility."

"Photonic integration has revolutionized the optical networking industry and Infinera has led the way starting with delivering the industry's first large-scale photonic integrated circuit, which started to ship in networking systems in 2005," said Fred Kish, Infinera's senior vice president of development and engineering. "We are happy to be working with AIM and SUNY Polytechnic Institute as a Tier 1 industry member. Through our focus on innovation, Infinera continues to advance integrated photonics to enable service providers and data center operators to deploy networks consuming less power and space while offering the capacity required to transport data over long distances. We are honored to join AIM in developing and designing the high-performance tools the nation requires to remain competitive."

Along with joining AIM, Infinera has launched a new partner program designed to enhance optical networking technology for customers facing growing bandwidth demands. The Infinera Partner Program allows clients the opportunity to build and grow their business through an application-optimized portfolio designed for long-haul, subsea, data center interconnect, and metro applications.

"Infinera's Partner Program is unique in that we provide trusted channel advisors around the world to help our channel partners win," said Bob Jandro, senior vice president of worldwide sales. "This enables us to ensure that we deliver exactly what end users need, while helping our channel partners build and grow profitably."

The expanded portfolio gives Infinera partners access to optical networking solutions — the XTM Series, DTN-X Family and Cloud Xpress Family — addressing the needs of network operators, data center operators, enterprise and government customers.

Infinera Corp. is a global provider of optical networking solutions for networks including long-haul, metro and the cloud. The company's aim is to enable an infinite pool of intelligent bandwidth that the next communications infrastructure can be built upon.

Final export control regulations seen as improvement

Final export control regulations released by the federal government regarding key photonic areas are an improvement over last year's proposal, according to leaders of SPIE, the international society for optics and photonics.

"These final rules are a positive step forward for the U.S. export control system," said SPIE CEO Eugene Arthurs. "The changes will help enhance international commerce in optics and photonics, and will assist research universities trying to provide educational opportunities for both U.S.- and foreign-born students."

In May 2015, the administration released the first proposed changes to the Category XII rules. SPIE, along with many others in the optics and photonics industry, voiced concerns with the proposal's direction.

In the largest response to proposed new rules in any one category, 120 companies, associations and universities submitted statements to the Department of State detailing why that proposal was a step back in efforts to positively reform the system.

"The overhead burden for export control compliance is a challenge to these businesses and to university research laboratories where covered products are used or developed," Arthurs said. "Well-written regulations that are limited to our highest priorities for control are key to reducing that burden."

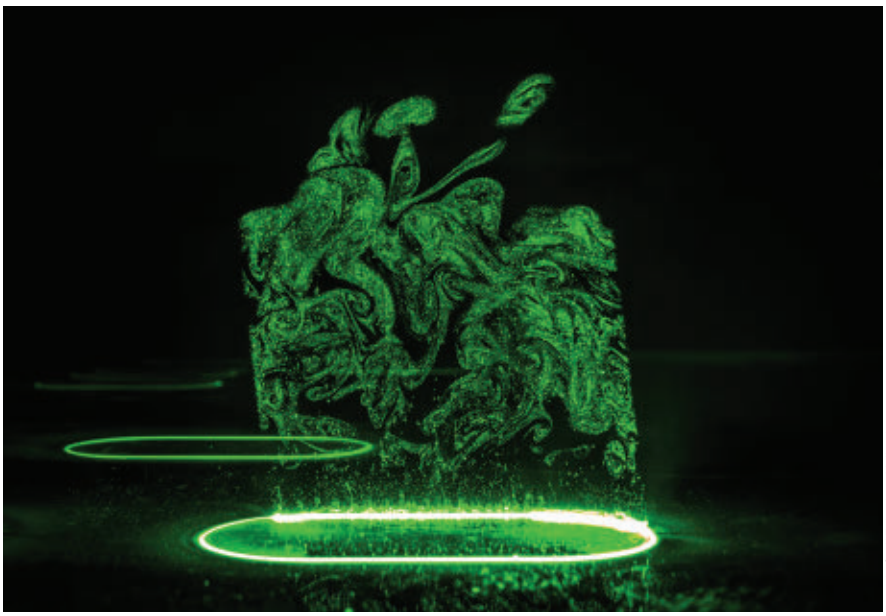
The initiative was launched in 2009 to allow for better protection while recognizing the economic realities that are important to industry. This approach is meant to strengthen national security, while improving the competitiveness of U.S. businesses.

"SPIE is very pleased with the direction taken in these final rules for Category XII of the U.S. Munitions List and Category VI of the Commerce Control List," Arthurs said. "We will continue to be involved as a society to build on this success on behalf of the companies and universities we represent."

$2.84B

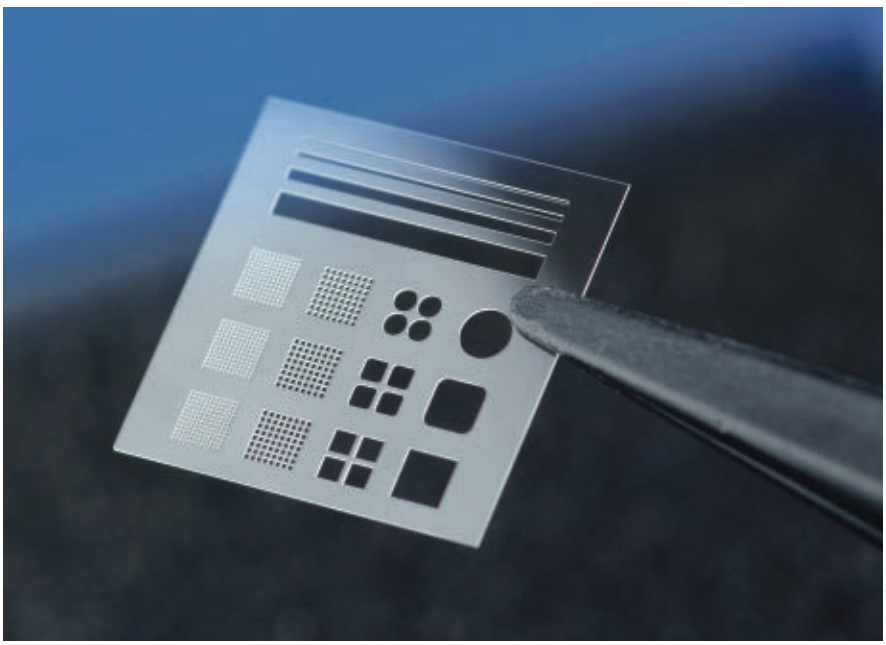
— value of the global aerial imaging market by 2022, as projected by Allied Market Research

Etching microstructures with lasers



Fraunhofer ILT, Aachen/Volker Lannert

Structuring process for glass using direct laser ablation with ultrafast laser pulses.



Fraunhofer ILT, Aachen

With the SLE technique, holes with particularly smooth edges can be bored through thin glass.

AACHEN, Germany — Consumer interest in analytics applications has prompted scientists in Germany to investigate how to use lasers to etch microstructures into thin glass. Through research, they found that irradiating glass in a particular way with an ultrafast laser has the effect of making the glass up to a thousand times more sensitive to subsequent wet chemical etching.

What this means to the scientific community is that it is possible to guide a laser beam — focused to a diameter of a few µm — through a glass block and etch a fine tube through the volume of the glass. Applications include creating tiny holes, etching complete microfluidic systems into glass, and making cuts with extremely high surface quality.

The BMBF-funded Femto Digital Photonic Production joint research project began in 2014. Representatives from the Fraunhofer Institute for Laser Technology have been working alongside six companies — Amphos, Edgewave, Trumpf, 4Jet, LightFab and Pulsar Photonics — to study new phenomena that arise when processing transparent materials with ultrafast laser pulses.

The researchers call the new procedure "selective laser etching," which has been tested on several different types of glass materials, including quartz glass, sapphire, BOROFLOAT 33 and Corning Willow. Etch selectivities of 1000:1 between laser-structured and unstructured areas were reached in BOROFLOAT 33, and roughly 100:1 in Willow glass.

The next phase of the project delves into the actual understanding of the process and lasts until 2019. The researchers' goal is to develop multiple beam systems for large surface use, as well as smaller systems for micro-processing, with other potential applications in biomedicine and electronics.

Novel pathway to light suppresses Kasha's Rule

BURLINGTON, Vt.— A discovery about how some molecules produce light, in apparent contradiction of Kasha's Rule, could have several applications, from industrial to biomedical.

To explore the origin of aggregation-induced emission, researchers from the University of Vermont and Dartmouth College assessed the emission properties of a series of BF_2-hydrazone-based dyes as a function of solvent viscosity. They found these molecules to be highly efficient fluorescent molecular rotors.

Further examination of the emission mechanism of the molecules revealed that the emission was not from the S1 state, as would be expected from Kasha's Rule, but from a higher energy state. Fluorescence

could be enhanced by restricting the molecular rotor's rotation and suppressing the internal conversion to the dark S1 state. When placed in a thin liquid, the rotating molecules gave off a weak, reddish luminescent glow. However, when the molecules were put into thicker solvents (in this case, mixtures of glycerol and ethylene glycol), the fluorescent light from the molecular rotors, instead of becoming weaker, glowed brightly in a vivid green color nearer the blue end of the spectrum.

The paddle-shaped part of the rotor must be able to rotate freely in order to activate the chemical pathway that allows it to give off heat energy, but in a thick solution this rotation is suppressed. The thicker the solution, the less the molecular paddles rotate; the less rotation, the more light can be emitted.

The phenomenon led the researchers to propose that suppression of Kasha's Rule was the photophysical mechanism responsible for emission in both the viscous solution and the solid state. The team has called their discovery Suppression of Kasha's Rule, or SOKR.

"One way to understand SOKR is to think about a water slide with two outlets where one outlet is located far above the pool and the other is located at the level of the pool," said professor Matthew Liptak. "In low viscosity solutions like water, the paddles rush all the way to the bottom outlet and enter the pool without a splash. In high-viscosity solutions like maple syrup, the paddles are slowed down, allowing some to spill out the top outlet, creating a waterfall or, in the case of light-emitting molecular rotors, bright green light."

The novel pathway to creating light may have practical use.

"The compound we found is very bright, and due to its viscosity sensitivity, may have a multitude of applications," said researcher Morgan Cousins. "We see uses for these kinds of molecules from industrial materials to new kinds of LEDs to biomedical imaging."

The SOKR molecules are not safe for use in a human, but the team is currently hunting for similar "bio-compatible" compounds, Liptak says, that could be incorporated into a medical dye or other test where they would glow brightly in more viscous parts of a cell and less in more watery parts. The molecules could be applied as a sensitive diagnostic tool because they precisely change the amount of light they emit based on the thickness of the solution in which they are placed.

The research was published in *Nature Chemistry* (doi:10.1038/nchem.2612).

The web version of this story features an animation showing the status of rotor molecules in a thick solution, emitting light before they are done vibrating: www.photonics.com/A61193.

Superresolution microscope builds 3D images by mapping negative space

AUSTIN, Texas — Thermal noise imaging, a novel method for making 3D images of biological structures at high resolution and under natural conditions, may offer insight into how cells communicate with one another, helping to further the development of artificial organs such as skin or heart tissue.

Nanometer-scale imaging of soft structures at room temperature poses a challenge because fast thermal fluctuations can lead to significant motion blur if the position of the structure is measured with insufficient bandwidth. Precise localization is also affected by optical heterogeneities.

For more well-defined imaging of soft structures, researchers at the University of Texas at Austin developed quantitative thermal noise imaging, a 3D scanning probe technique for imaging soft, optically heterogeneous and porous matter with submicroscopic spatial resolution in aqueous solution.

The researchers offered an analogy to illustrate how thermal noise imaging works: If you were to throw a glowing rubber ball into a dark room and use a camera to collect a series of high-speed

Jenna Luecke

Scientists at the University of Texas at Austin have developed a new microscopy technique for looking at nanoscale structures in biological samples that is analogous to using a glowing rubber ball to image a chair in a dark room.

images of the ball as it bounces around, you would see that as the ball moves around the room, it isn't able to move through solid objects such as tables and chairs. By combining millions of images taken so fast that they don't blur, you would be able to build a picture of where there are objects (wherever the ball cannot go) and where there are no objects (where the ball can go).

In thermal noise imaging, the equivalent of the rubber ball is a nanosphere that moves around in a sample by natural Brownian motion.

"This chaotic wiggling is a nuisance for most microscopy techniques because it makes everything blurry," says physicist Ernst-Ludwig Florin. "We've turned it to our advantage. We don't need to build a complicated mechanism to move our probe around. We sit back and let nature do it for us."

The researchers imaged individual microtubules and collagen fibrils in a network, demonstrating thermal noise imaging can yield quantitative nanoscale images of soft-matter structures; that the structures can be localized with a precision of about 10 nm; and that their local dynamics can be quantified with 50-kHz bandwidth and subnanometer amplitudes.

The probe particles used by the researchers are larger than fluorescent probes and are not specifically attached to a target. Because thermal noise imaging is not limited by labeling density or photobleaching, higher resolution can be achieved by recording more probe positions while confining the probe's diffusion to the same trapping volume.

The original concept for the thermal noise imaging technique was published and patented in 2001, but technical

challenges prevented it from being developed into a fully functioning process until now.

The tool has allowed the researchers to measure for the first time the mechanical properties of collagen fibrils in a network.

"If you want to build artificial skin, you have to understand how the natural components work," says Florin. "You could then better design a collagen network that acts as a scaffolding that encourages cells to grow in the right way."

The research was published in *Nature Communications* (doi: 10.1038/ncomms12729).

Creating 3D hands to increase security

EAST LANSING, Mich. — Researchers from Michigan State University have created a lifelike 3D hand model, complete with all fingerprints, to test the accuracy of fingerprint scanners. These scanners are commonly found at banks, police departments, airport immigration counters and even amusement parks.

The researchers, led by MSU professor Anil Jain, created the hand models using a high-resolution 3D printer, reproducing the ridges and valleys in real fingers.

"Like any optical device, fingerprint and hand scanners need to be calibrated, but currently there is no standard method for calibrating them," said Jain. "This is the first time a whole hand 3D target has been created to calibrate fingerprint scanners."

While creating the 3D hand and testing the accuracy of scanners, he realized that potentially someone could do the same thing and steal a person's identity, and perhaps "break into a vault." This revelation caused him and his team to do more research and they are currently looking into spoof-resistant commercial fingerprint scanners.

G.L. Kohuth

MSU researchers demonstrate how a 3D-printed model hand is used to test a fingerprint scanner for accuracy.

"We have highlighted a security loophole and the limitations of existing fingerprint scanning technology. Now it's up to the scanner manufacturers to design a scanner that is spoof-resistant," said Jain. "The burden is on them to tell whether the finger being placed on the scanner is real human skin or a printed material."

The study aims to design and develop standard models and procedures for consistent and reliable evaluation of fingerprint readers, and is funded by the National Institute of Standards and Technology.

"We are very pleased with this research and how it is showing the uncertainties in the process and what it can mean for the accuracy of the readers," said Nicholas Paulter, group leader for the Security Technologies Group at NIST and a co-author of the study. "The FBI, CIA, military and manufacturers will all be interested in this project."

Along with Jain and Paulter, the study was co-authored by Sunpreet Arora, an MSU doctoral student. Their paper received the best paper award at the 15th International Conference of Biometrics Special Interest Group, 2016.

Novel design may make QCLs more efficient, easier to produce

ORLANDO, Fla. — A new method for producing quantum cascade lasers (QCLs) could lead to greater use of the lasers in portable health devices and in spectroscopy for remote sensing.

A previous approach to QCL production — one that produced the highest efficiency — required the infrared laser to be situated atop a substrate comprising more than 1,000 layers. Each layer, barely thicker than a single atom, was composed of one of five different materials, making production challenging and expensive.

Now, researchers at the University of Central Florida (UCF) have developed a simpler process for creating QCLs using just two materials, resulting in a design that is simpler to produce but is comparable in performance and higher in efficiency than QCLs made using more complex methods.

"The previous record was achieved using a design that's a little exotic, that's somewhat difficult to reproduce in real life," professor Arkadiy Lyakh said. "We improved on that record, but what's really important is that we did it in such a way

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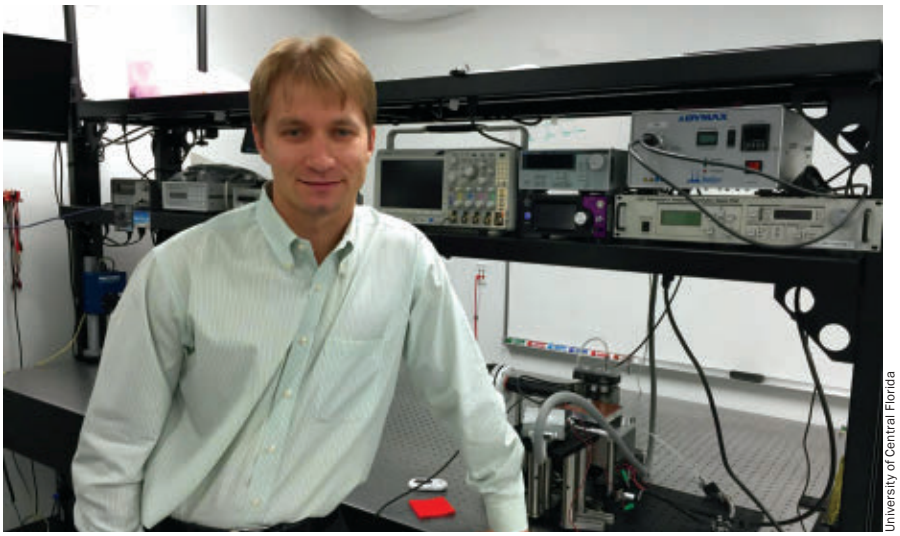
that it's easier to transition this technology to production. From a practical standpoint, it's an important result."

The research team produced 5.6-µm QCLs with a measured pulsed room temperature wall plug efficiency of 28.3 percent. They tested devices with variable cavity lengths and measured an injection efficiency of 75 percent for the upper laser level. They measured a threshold current density of 1.7 kA/cm^2 and a slope efficiency of 4.9 W/A for uncoated 3.15-mm × 9-µm lasers. Threshold current density and slope efficiency dependence on temperatures ranging from 288 to 348 K for the structure could be described by characteristic temperatures T0 ~ 140 K and T1 ~ 710 K, respectively.



University of Central Florida

Assistant professor Arkadiy Lyakh of UCF's NanoScience Technology Center has developed the most efficient quantum cascade laser ever.

The ability to produce QCLs more efficiently could lead to their greater use in spectroscopy, such as use of the IR lasers as remote sensors to detect gases and toxins in the atmosphere. Lyakh also envisions their use in portable health devices. For instance, a small QCL-embedded device could be plugged into a smartphone and used to diagnose health problems by simply analyzing one's exhaled breath.

"But for a handheld device, it has to be as efficient as possible so it doesn't drain your battery and it won't generate a lot of heat," Lyakh said.

The research was published in *Applied Physics Letters* (doi: 10.1063/1.4963233).

Fiber-Optics-Based System Monitors Structural Health

BLACKSBURG, Va. — An all-fiber-optics-based system for monitoring structure health shows promise as a reliable means to oversee structural soundness under extreme conditions. Active ultrasonic nondestructive evaluation (NDE), currently a widely used technique in structural health monitoring, has traditionally employed piezoelectric transducers (PZTs), which can be of limited use in corrosive environments or under extremely high temperatures.

Driven by the need for an ultrasonic NDE system that is more compact, multiplexable, and capable of working in harsh environments, researchers have studied the possibilities of using fiber optic technologies in ultrasonic NDE. One approach has been to use optical fibers to replace the PZTs in the traditional NDE system as broadband ultrasonic sources or broadband detectors.

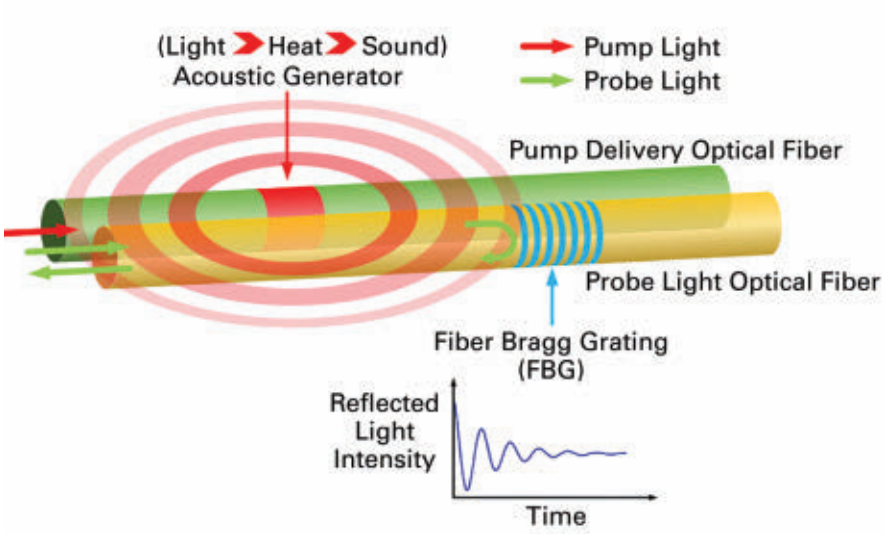
Researchers at Virginia Tech have designed, fabricated and demonstrated a multiplexable, all-fiber-optics-based system, which is known as an all-fiber-optics-based multiparameter structure-health-monitoring (AFO-SHM) network.

The system uses two optical fibers to serially connect multiple active fiber optic nondestructive evaluation (FO-NDE) elements, which are attached to the surface of the structure that is being monitored. Each sensing element consists of an acoustic-generation unit and an acoustic-detection unit.

The acoustic-generation unit is a micro structure fabricated in a multimode fiber, which serves to scatter light out of the optical fiber. The scattered light generates acoustic vibration on the surrounding material through a thermal-elastic effect. A consistent acoustic emission strength at different nodes can be achieved by the gradual increase of the scattering ratio of each node. The acoustic-detection unit is a 2-mm fiber Bragg grating (FBG) in a single-mode fiber, which detects the dynamic strain on the optical fiber. The vibrations are received by the FBG and the FBG forms the acoustic signature of the structure. The FBG also provides information about the strain and temperature of the structure.

The serially connected FBGs in the AFO-SHM network are fabricated with different center wavelengths. To obtain the acoustic signal of a certain sensing node, the wavelength of the probe light is tuned to the full width half maximum (FWHM) wavelength of the FBG in that node. By switching the probe light wavelength through all the FBGs in the network, multiplexed acoustic detection can be achieved.

The researchers demonstrated the system on an aluminum test piece, monitoring temperature, strain and thickness changes, and quantitatively associating the changes with the FBG spectrum shift and the peak shifts in the acoustic signature. The multiplexing capability was demonstrated by the acquisition of spectrum information and acoustic signatures from an AFO-SHM network containing two cascaded nodes.



The principle of operation for a single all-fiber-optics-based multiparameter structure-health-monitoring (AFO-SHM) sensing node.

"By analyzing the acoustic signature of the structure and the additional information from FBG, we can simultaneously monitor multiple environment parameters," researcher Chennan Hu said.

For their demonstration, the researchers used a temperature range from 24 to 60 °C, which is the allowed working temperature of the epoxy used in the AFO-SHM node.

The research did not demonstrate monitoring under high temperatures, "but we believe that this system could be used in high temperature when the low-temperature epoxy is replaced by high-temperature adhesive, and we have already acquired promising high-temperature monitoring results," Hu said.

One possible application of the distributed sensing system could be on the outer surface of P91 pipes, which are widely used in the power industry.

"These pipes are usually used to transmit corrosive high-temperature, high-pressure steam," Hu explained. "However, the integrity of these pipes and other critical materials involved in a power-generation system may deteriorate over time and the deterioration rate may pick up rapidly as the system operating temperature is pushed higher — so monitoring of these materials becomes more important."

The sensor system also could be used on an aircraft to monitor the health of multiple points in the gas turbine engine or other critical parts.

The research was published in *Optics Express*, a journal of OSA, The Optical Society of America (doi: 10.1364/OE.24.020287).

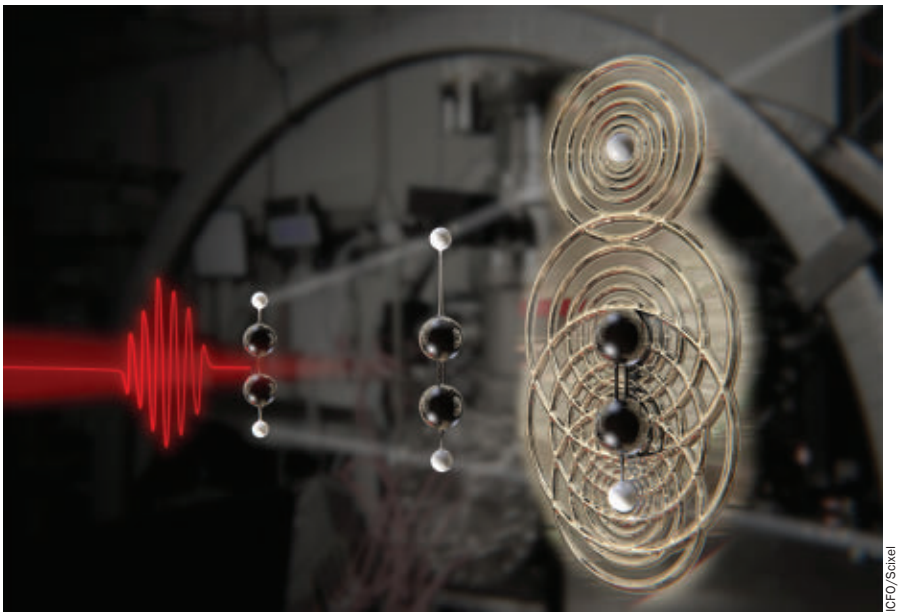
ICFO researchers image molecular bond breakup

BARCELONA, Spain — Researchers from the Institute of Photonic Sciences' (ICFO) Attoscience and Ultrafast Optics Group have reported on the imaging of molecular bond breakup in acetylene (C_2H_2) 9 fs after its ionization.

The team was able to track the individual atoms of the isolated acetylene molecule with a spatial resolution of 0.05 Å and a temporal resolution of 0.6 fs. They were also able to trigger the breakup of one molecule bond and see how one proton leaves the molecule.

"Our method has finally achieved the required space and time resolution to take snapshots of molecular dynamics without missing any of its events, and we are eager to try it out on other molecular systems such as chemical catalysts and bio-relevant systems" said Jens Biegert, ICFO professor and research leader.

The team developed a world-leading ultrafast mid-IR laser source and combined it with a reaction microscope to detect the 3D momentum distribution of electrons and ions in full kinematic coincidence. In the experiment, a single isolated acetylene



ICFO/Scixel

Illustration of laser-induced diffraction imaging of a molecular bond breakup in acetylene.

molecule was oriented in space with a short laser pulse. A strong infrared pulse liberated one electron from the molecule, accelerated it on a returning trajectory and forced it to scatter off its own parent molecular ion, all within only 9 fs.

"The flight path and kinetic energy of all collision fragments were recorded with the reaction microscope similar to a big particle physics experiment," said researcher Benjamin Wolter.

The team was able to extract the entire molecular structure and show that orienting the molecule along the electric field of the laser, or perpendicular to it, completely changed its dynamics. In one case, the molecule underwent vibrational motion with the laser field, while in the other case a C-H bond was clearly broken. The experiment is the first direct visualization of bond cleavage and observation of the proton during its departure from the $[C_2H_2]_2+$ ion, something that has never been seen before.

"We took one electron, steered it along a specific path with the laser and scattered it off an isolated molecule to record its diffraction pattern," Biegert said. "It is mind-boggling to imagine the length and time scales of the experiment." The experiment involved cooperation between experimentalists and theorists, atomic physicists and quantum chemists from ICFO-The Institute of Photonic Sciences, Kansas State University, Max Planck Institute for Nuclear Physics, National Metrology Institute of the Federal Republic of Germany, Center for Free Electron Laser Science/DESY/CUI, Aarhus University, Friedrich-Schiller University Jena, Leiden University and University of Kassel.

South Korea researchers produce tabletop hologram system

SEOUL, South Korea — Researchers at the 5G Giga Communication Research Laboratory of South Korea's Electronics and Telecommunications Research Institute have developed a novel tabletop display system for holographic images.

The system allows multiple viewers to simultaneously look at a hologram showing a full 3D image as they walk around the tabletop, giving complete 360° access.

"In the past, researchers interested in holographic display systems proposed or focused on methods for overcoming limitations in the combined spatial resolution and speed of commercially available, spatial light modulators," said Yongjun Lim, researcher at the 5G Giga Communication Research Laboratory. "Representative

techniques included space-division multiplexing, time-division multiplexing and [a] combination of those two techniques."

Lim and his team took a different approach by devising and adding a novel viewing window design and paying close attention to the optical image system.

"With a tabletop display, a viewing window can be created by using a magnified virtual hologram, but the plane of the image is tilted with respect to the rotational axis and is projected using two parabolic mirrors," Lim said. "But because the parabolic mirrors do not have an optically flat surface, visual distortion can result. We needed to solve the visual distortion by designing an aspheric lens. As a result, multiple viewers are able to observe 3.2-in. size holograms from any position around the table without visual distortion."

Currently, the system produces a monochrome green color. Next, the team aims to produce a full-color experience and resolve issues related to undesirable aberration and brightness mismatch among the four digital micromirror devices used in the display.

Collaborators on the project include colleagues from the Department of Electronics and Information Engineering of Korea University, and the School of Electronics Engineering at Kyungpook National University, South Korea.

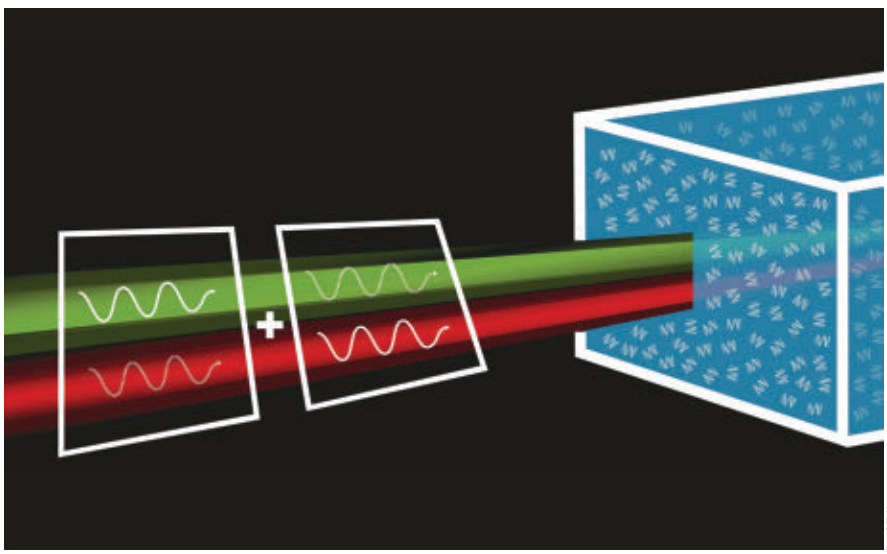
Quantum approach measures optical molecular activity with precision

SYDNEY — Quantum optical rotatory dispersion, a technique that uses quantum methods to differentiate and measure molecules when light passes through chiral media, could offer a precise way to measure intricate molecular properties, even when low light or a low concentration of the molecule is used.

Using multi-wavelength entangled photon pairs, researchers at Macquarie University and the University of Vienna measured the optical activity and optical rotatory dispersion exhibited by a solution of chiral molecules. The entangled photon states were used for quantum-enhanced measurements between different wavelengths and for measuring the dependence of optical activity on wavelength.

The researchers' scheme for probing wavelength dependence surpassed the information extracted per photon in a classical measurement, and could be used for more general differential measurements.

"We sought out to understand how light couples to matter — which is at the core of many common instruments. Ultimately, we hope our findings can be used to find new ways to improve instruments like optical sensors and telescopes," said associate professor Gabriel Molina-Terriza.



Ralf Erlinger

An illustration of the quantum measurement of optical rotatory dispersion.

The technique could be appropriate for analysis of samples that could be damaged by intense light, a potential concern for chiroptical studies.

"We've found a way to analyze delicate samples by using less light," said researcher Nora Tischler. "We hope to see this proof of concept built upon to eventually see efficiencies in the pharmaceutical sector, to more efficiently develop new medicines."

The researchers' work paves the way for quantum-enhanced measurements of chirality, with potential applications in chemistry, biology, materials science and the pharmaceutical industry.

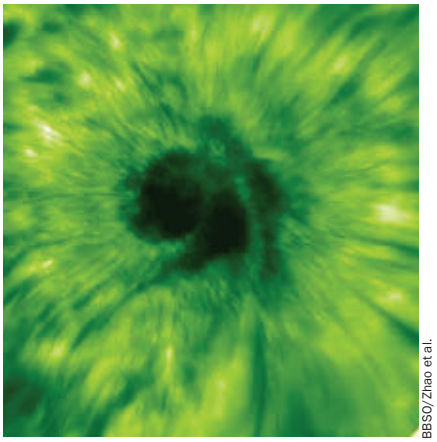
The research was published in *Science Advances* (doi: 10.1126/sciadv.1601306).

Solar imaging tool enables better understanding of sun's atmosphere

GREENBELT, Md. — The ability to track a particular kind of solar wave as it sweeps upward from the sun's surface through the sun's atmosphere is widening astrophysics' understanding of how solar material travels throughout the sun.

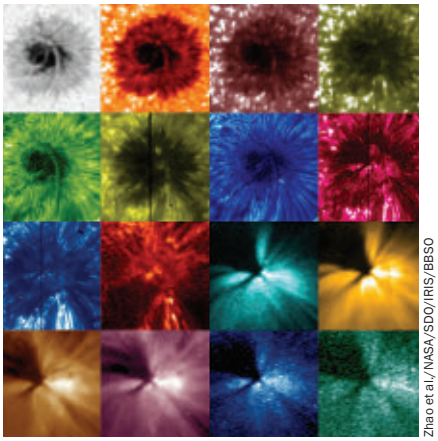
Though scientists have long suspected that the waves they spot in the sun's photosphere are linked to those seen in the sun's chromosphere, novel imaging tools have now enabled scientists to actually watch the wave travel up through the various layers into the sun's atmosphere.

By applying a time-distance helioseismic analysis over a suite of multi-wavelength observations above a sunspot, scientists at NASA's Goddard Space Flight Center and Stanford University



BBSO/Zhao et al.

Scientists analyzed sunspot images from a trio of observatories — including the Big Bear Solar Observatory, which captured this footage — to make the first-ever observations of a solar wave traveling up into the sun's atmosphere from a sunspot.



Zhao et al./NASA/SDO/IRIS/BBSO

Scientists used data from NASA's Solar Dynamics Observatory, NASA's Interface Region Imaging Spectrograph and the Big Bear Solar Observatory to track a solar wave as it channeled upward from the sun's surface into the atmosphere.

have demonstrated that helioseismic p-mode waves were able to channel up from the sun's photosphere through the chromosphere and transition region into the corona.

The scientists' numerical simulation of the traveling of waves from a sub-photospheric source qualitatively resembled the observed properties of the waves and offered an interpretation of the shapes of the wavefronts above the photosphere.

The study used data captured by NASA's Solar Dynamics Observatory (SDO), NASA's Interface Region Imaging Spectrograph and the Big Bear Solar Observatory. Together, these observatories watch the sun in 16 wavelengths of light that show the sun's surface and lower atmosphere. SDO alone captures 11 of these wavelengths.

"SDO takes images of the sun in many different wavelengths at a high time resolution," said Dean Pesnell, SDO project scientist at Goddard. "That lets you see the frequencies of these waves. If you didn't have such rapid-fire images, you'd lose track of the waves from one image to the next."

In addition to providing scientists with a novel tool for studying the sun's atmosphere, the ability to track the progress of solar waves is helping scientists pinpoint the mechanism that moves energy into the sun's corona.

"We see certain kinds of solar seismic waves channeling upwards into the lower

atmosphere, called the chromosphere, and from there, into the corona," said Junwei Zhao, a solar scientist at Stanford University. "This research gives us a new viewpoint to look at waves that can contribute to the energy of the atmosphere."

The research was published in *The Astrophysical Journal Letters* (doi: 10.3847/2041-8205/830/1/L17).

MSI camera to track potential dangers in low-visibility areas

O PORRIÑO, Spain — A surveillance camera now under development will use a multispectral imaging (MSI) platform to capture and reveal information about coastal, road and environmental situations, such as invisible gases or fire sources, through dense fog. This device will be designed to weigh less than 2 kg and will be able to capture images of moving objects in real time.

The device, known as SEERS (Snapshot Spectral Imager for IR Surveillance), will incorporate a multi-aperture, multisensory camera capable of capturing several wavelengths simultaneously in one place. The camera will provide a modular, compact snapshot spectral imaging system in the IR wavelength range of 0.7 to 14 µm, based on low-cost, uncooled focal plane arrays (FPAs), with embedded processing capabilities. The targeted range includes NIR, SWIR, MWIR and LWIR. The development of SEERS is being led by Aimen Technology Centre.

Development will begin with the design of a snapshot MSI imager in the IR domain. An embedded processing architecture will be used for vision and cognitive image fusion capabilities.

"The SEERS device is equipped with integrated computational imaging," said project coordinator Anton Garcia-Diaz. "It has no need for cooling and can process the images in real time, meaning key parts of processing are embedded within the device."

Use of CMOS-compatible FPA manufacturing technology is expected to significantly reduce the cost of SEERS, compared to a commercial monochromatic camera working in the mid-IR range of 3- to 5-µm wavelengths.

"Few imaging systems exist with the capability to identify gases, but even they can cost over €100,000 [about $107,000]. The SEERS project aims to deliver MSI technology in an extended infrared domain at under €40,000 [about $42,800] with improved persistence and gas identification capabilities," said Garcia-Diaz.

The SEERS project, which is expected to run until 2018, is supported by Europe's Horizon 2020 research program via the Photonics Public Private Partnership.

An 18-inch rolled OLED display made on a plastic substrate by LG Display.

OLEDs Step In Where Design Matters

The near-ideal visual characteristics of OLED displays mean OLEDs will thrive as a mainstream display technology in coming years, while their compatibility with flexible and transparent materials is creating a new market for displays.

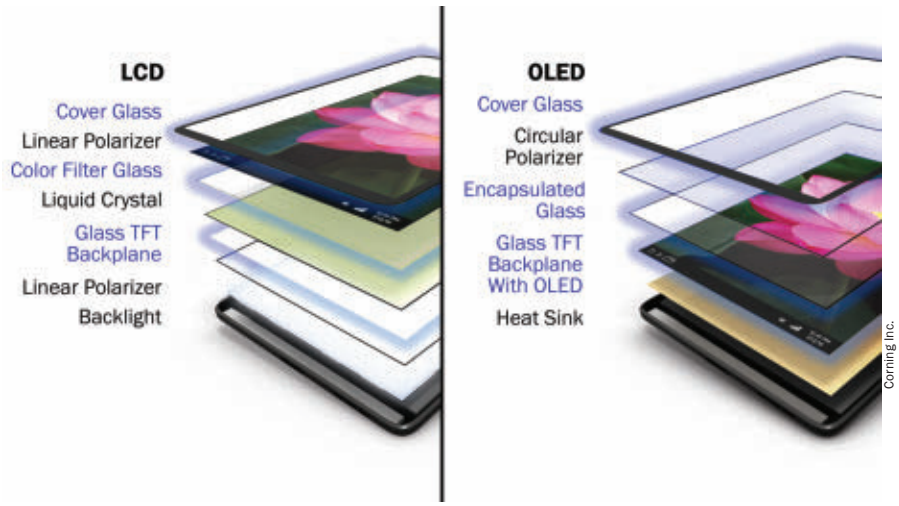
BY MARIE FREEBODY
CONTRIBUTING EDITOR

From the Apple watch to Samsung smartphones, LG televisions, virtual reality headsets and the first laptop screen, organic light-emitting diodes (OLEDs) are set to disrupt the display market. In addition, progress is underway as BMW and Audi release their first cars with OLED brake lights with more carmakers set to follow.

There's big money associated with OLEDs: For manufacturers, production is expensive and the resulting item often carries with it a high price tag. But consumer demand for luxury products and significant price reductions mean that OLED technology is cropping up in an increasing array of high-end goods.

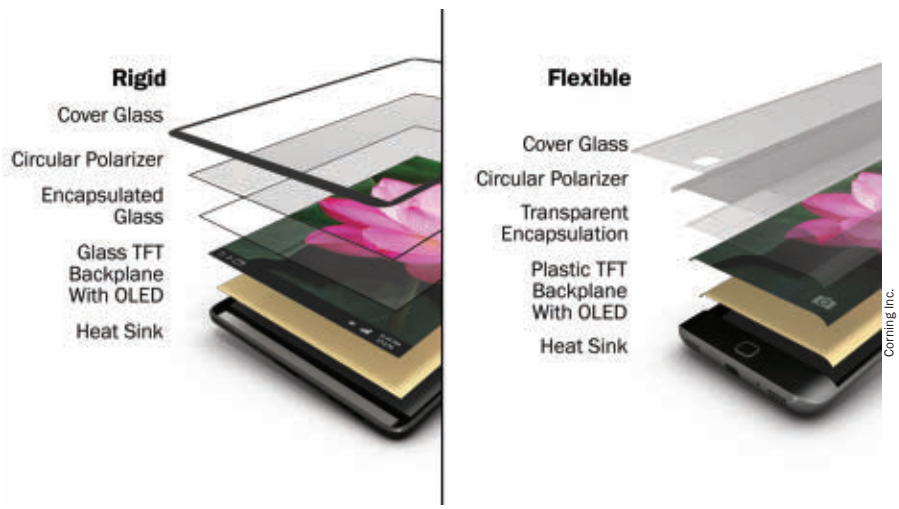
Samsung Display

A flexible AMOLED along with a Galaxy S7, which incorporates a flexible display for its "edge-type display."



Corning Inc.

Both OLED and LCD display panels serve important roles depending on the attributes a device maker wants to provide to consumers. Key differences lie in how light is emitted through each panel to create each pixel of light in a display. While LCDs use a backlight to project light through a color filter, OLEDs use organic, self-emitting diodes to create images.



Corning Inc.

An OLED display panel can be made either rigid or flexible, depending on the desired use. A flexible OLED display generally uses a plastic substrate and requires a display-quality carrier glass to take it through a demanding manufacturing process. The carrier glass is removed once the panel is complete.

Substantial improvements to lifetime, energy efficiency and price mean that OLEDs are now enjoying a growing share of markets that had been solely the domain of LEDs and other light sources. With more manufacturers interested in investing, one of the remaining hurdles is spreading awareness of the merits of OLEDs to producers and consumers alike.

Mobile displays and flexible substrates

Apple has made a number of initiatives in mobile display technology, but rather than OLED screens, the company introduced very high resolution with its "Retina" concept in its iPhones in collaboration with display companies such as LG Display. Speculation is rife as to whether iPhones will eventually use OLEDs, with many believing it's a case of "when," not "if" — particularly as we now see OLEDs on the Apple watch.

"As a planar, rigid display, both AMOLED [active matrix OLED] and IPS [in-plane switching]-based LCD displays have a comparable performance and characteristics, at least for ordinary users. This was particularly the case until recent years," said Seunghyup Yoo, a professor from the Korea Advanced Institute of Science and Technology (KAIST) based in South Korea. "Times are changing, however, as AMOLED displays are becoming more cost-effective and their characteristics such as fast response time are making it easier to embrace emerging applications like virtual reality."

What's more, when prepared on a plastic substrate, AMOLEDs can provide a design freedom such as a bent-edge display as well as being lightweight, leading eventually to flexible or bendable displays.

Michael Kunigonis, business director of high-performance displays at Corning Inc., with headquarters in Corning, N.Y., points out that the challenge with using plastic substrates is they are not dimensionally stable enough to endure the high-temperature manufacturing process required to build these panels.

A display-quality carrier glass like Corning Lotus NXT Glass that features dimensional stability enables efficient manufacturing of flexible OLED panels. These flexible OLED display panels can be bent and conformed to create curved displays.

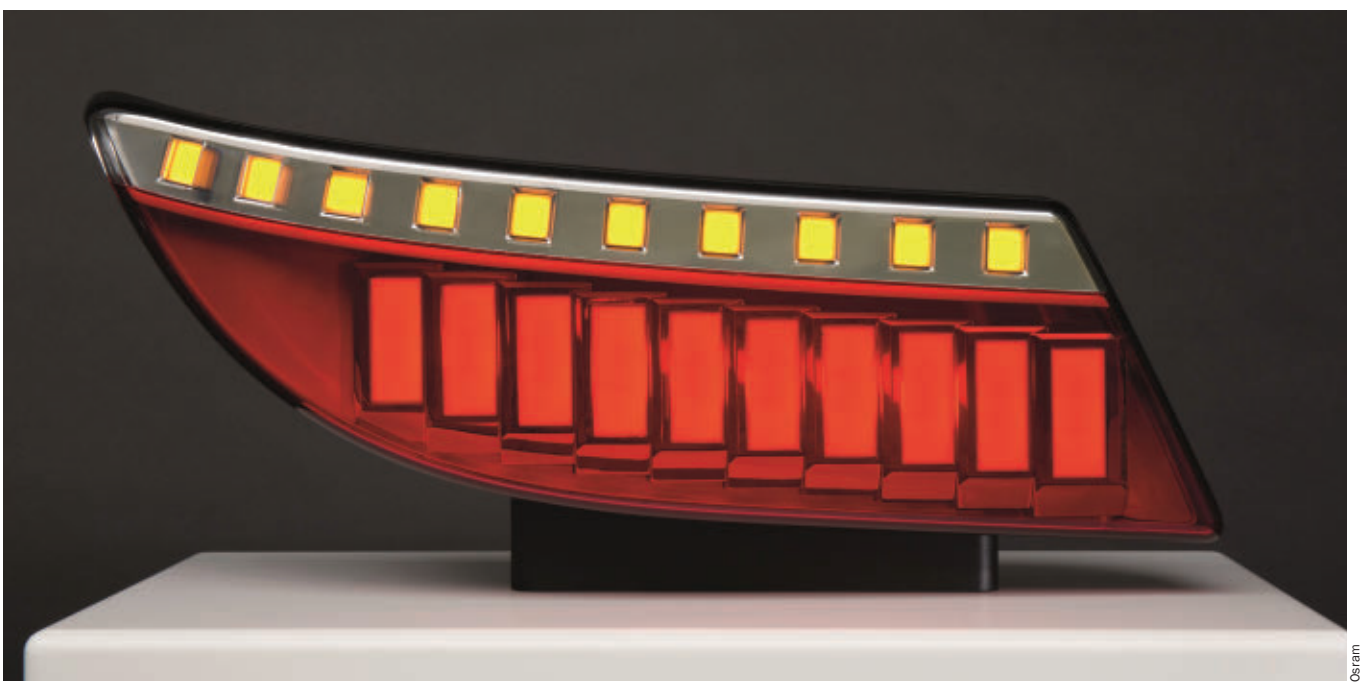
"A dimensionally stable carrier glass

Osram

A rear light module from a single flexible OLED produced as part of the R2D2 project in cooperation with Audi, Osram and Hella. Two such modules are installed in a complete rear light unit.

Latest advances in OLED lighting technology:

- High-brightness (8300 cd/m^2) panels capable of generating 300 lm from an emitting area of only 100 cm^2 while still providing a lifetime of over 10,000 hr.
- OLED lighting panels with lifetimes over 50,000 hr at a brightness of 3000 cd/m^2 and 100 lm.
- Ultra-thin OLED lighting panels of less than 1-mm thickness.
- Large area OLED lighting panels (up to 30 × 30 cm).
- Bendable and flexible OLED lighting panels.
- Panel efficiency of over 60 lm/W, with 80 lm/W in development.



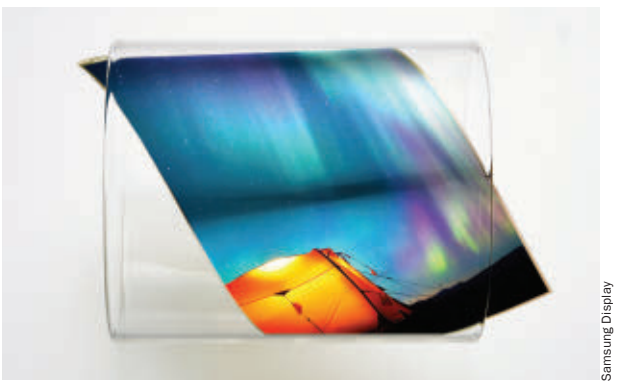
Osram

Osram's taillight is able to play special light sequences thanks to segmentation.

— with low total pitch variation and low total thickness variation — enables a well-aligned TFT [thin-film transistor] array and an even deposition of OLED material, overall contributing to a well-constructed panel that helps panel makers avoid yield loss," said Kunigonis. "A carrier glass should also have a high UV transmission, allowing a large amount of light through the carrier at an even distribution, enabling efficient laser lift-off, a vital step in the flexible OLED panel-making process."

A flexible OLED panel begins with a glass substrate, used as a carrier glass. A plastic layer is deposited and cured onto the carrier. At the end of the panel-making process, a UV laser shines through the display-glass carrier to debond it from the flexible OLED panel. The panel can then be conformed to create unique device designs. So far, Samsung has been the main manufacturer of mobile OLED displays. OLED displays on plastics, used in Samsung's Galaxy Gear series and in its edge-bent displays in its Galaxy Note Edge series, are ex-

EMDE



Samsung Display

Samsung Display

Osram

With significant price reduction, there is increased interest in more traditional markets such as task lighting. The OMLED from EMDE Design GmbH is a platform product that used between one and five Lumiblade panels from OLEDWorks LLC in a desk lamp configuration **(top left)**. LG boldly stepped out as the first and only supplier of large OLED televisions in its 4K OLED TV products **(top right)**. Flexible active matrix OLED (AMOLED) displays in operation **(middle** and **lower left)**. This OLED flower is part of Osram's OLYMP project, which aims to make OLEDs attractive for the mass-market general lighting sector **(above)**.

amples of successful commercialization of AMOLEDs, but carrying forward this technology to large-size TVs and plastic substrates is considered the next level of challenges.

"For OLED displays, manufacturers are still working on ways to make them bigger and cheaper. This year, we have the first generation of laptops with OLED screens, but they cost a premium," said Guillaume Chansin, Ph.D., senior technology analyst and lead author of the OLEDs Displays Forecast 2016-2026 at IDTechEx (www.idtechex.com), a market analysis and consulting firm with headquarters in Cambridge, England. "Investing in a new technology is always risky. LG has been very bold and now they are the only supplier of large OLED screens.

Consumers seem to be very enthusiastic about OLED, so I think other manufacturers will follow."

LG Displays came up with a subpixel structure in which white OLEDs (WOLEDs) are combined with RGB color filters. WOLEDs are by themselves individual pixels and thus can be addressed independently — the image is in black and white, and color is rendered using color filters on each pixel.

Samsung Display

A 55-in. transparent AMOLED display.

This means that there must be a compromise in efficiency since a significant portion of white light should be filtered out to define a specific primary color. Even so, the simplified manufacturing process for RGB pixel patterning has led to successful commercialization of OLED TVs that are 55 inches or larger in diagonal.

"LG was the first TV manufacturer to commit and invest in OLED technology a few years ago and we are now reaping the rewards with sales of LG OLED TVs continuing to increase," said Robert Taylor, product manager at LG Electronics UK. "Other TV manufacturers have been more cautious, likely to be down to the significant investment in the production facilities needed to create OLED panels, ultimately resulting in a more expensive consumer product."

As LG points out, OLED technology is expensive to produce and it's a technology that not all consumers are familiar with.

"While demand for OLED TVs is increasing there is still some work to do in educating consumers on the benefits of OLED," Taylor said. "However, with LG making more OLED TVs in its range than ever before this year, the price points for LG's OLED TVs have become more varied, which is encouraging for other manufacturers to see."

Architectural lighting and automotive opportunities

Lighting devices are generally much easier to fabricate than display devices because they do not involve integrated thin-film transistors and high-resolution patterning. Nevertheless, they typically require higher brightness levels than display applications, which makes practical deployment of OLED lighting much more challenging as efficiency and lifetime can degrade rather significantly when brightness level increases.

While OLEDs have not yet significantly entered the residential or office lighting market due to performance and cost, a healthy market does exist in targeted segments where "design" matters and where lighting solutions can tolerate a price premium — such as in architectural lighting.

"Architectural lighting is indeed one of the opportunities for OLED lighting. Technology, however, is not driven by power consumption but by design.

“We see the growth related to our product performance; our panels are substantially the brightest available and this enables affordable functional light, with superb light quality, in elegant OLED fixture designs.”

Giana Phelan, director of business development at light engine and panel manufacturer OLEDWorks LLC

Samsung Display

Samsung Display

A mirror display based on AMOLED technology.

Growth in general has been delayed due to the cost position,” said Nadine Schian, head of communications for Specialty Lighting at OSRAM GmbH, Munich. “Cost reduction can be achieved by, for example, upscaling and acceleration of the production. However, huge investments are needed for this.”

With cost and performance parameters improving slowly, more manufacturers view OLEDs as a way to complement and differentiate with respect to LEDs.

“The technology and integration requirements of LEDs were at first very demanding for manufacturers and they did not have the energy or time for OLEDs — that is no longer true,” said Giana Phelan, director of business development at light engine and panel manufacturer OLEDWorks LLC, located in Rochester, N.Y. “We see the growth related to our product performance; our panels are substantially the brightest available and this enables affordable functional light, with superb light quality, in elegant OLED fixture designs.”

The automotive industry is a promising new market, with OLEDs giving car makers another technology that can reinforce their brand through design. One aim is to replace some of the lights with OLEDs and another is to improve the driving experience with beautiful displays.

“If one looks at the cars released these days, there are more and more IT devices being added and their tachometers are now displays, rather than needles over a printed scale,” said KAIST’s Yoo. “Lightweight, free-form design features of OLED displays on plastics can become very promising for such futuristic automobiles, and some high-end automakers are considering using OLED technologies for the tail lamp of their cars.”

In fact, BMW’s M4 GTS and Audi’s soon-to-be-released TT RS coupe have adopted Osram’s OLED lighting technology in their rear lights.

“We improved the OLED performance, such as the encapsulation, heavily, in order to meet strict automotive requirements,” Schian said. “We see a huge interest from automotive industry in this technology and expect a fast penetration, especially in the more luxury vehicles.”

BMW has opted for a fanlike design, which takes advantage of the flatness of OLEDs and acts as a design highlight, particularly when viewed slightly from the side. With a total of 15 OLEDs per taillight and a brightness of 1200 cd/m^2, a 3D effect can be created by segmentation. The possibility of controlling individual light modules separately opens up even more design options such as dynamic functionality.

In a short space of time OLED technology has advanced rapidly, offering consumers a wide range of options from curved and flat screen designs to elegant, on-brand motifs. The innovations are a result of consumer demand for the latest technology that takes advantage of their thinness and flexibility. OLED devices will continue to improve, and as consumers become increasingly aware of the technology, there is no doubt that adoption will be on the up.

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Medical Lasers Cut and Heal

New innovations in medical lasers allow for greater control of wavelength, power and pulse duration, expanding applications beyond ablation and tissue removal to include bioresponse and drug delivery.

BY HANK HOGAN
CONTRIBUTING EDITOR

For medical lasers, the future may include both addition and subtraction.

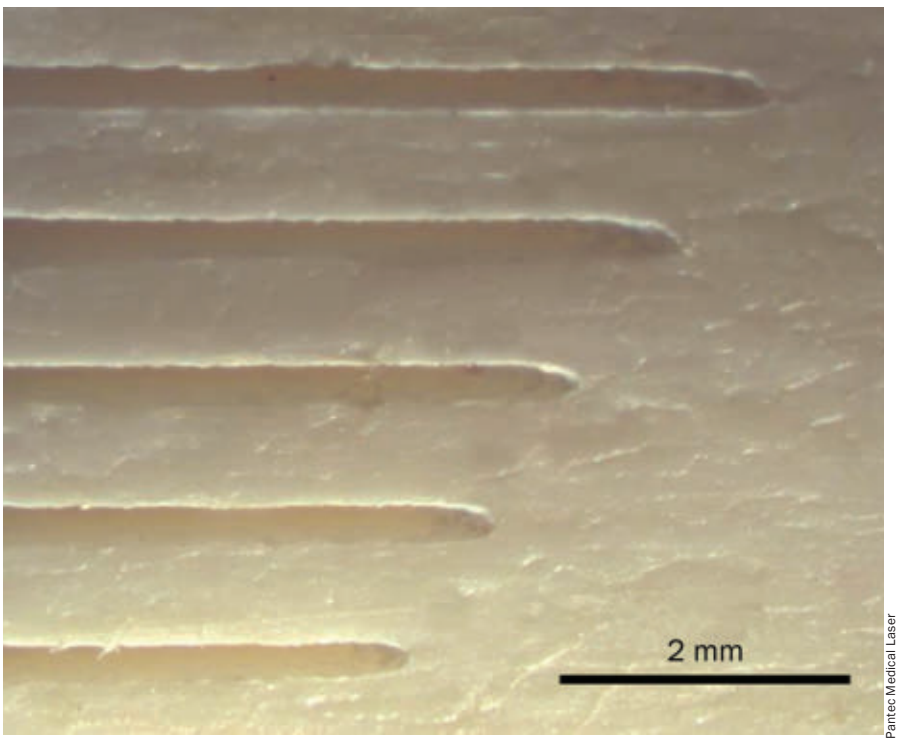
That's because, in medicine, lasers have traditionally been used for ablation, cutting and other processes that remove tissue. Now researchers and companies are looking into harnessing the power of light to stimulate a bioresponse, thereby triggering growth and an ushering in of an additive approach.

The key for either subtraction, addition or a combination is to get the right wavelength at the right intensity and duration to the right spot. Beyond that, systems have to allow a fast learning curve so that they're usable by a broad audience of nonlaser experts. They also have to be the right cost.

"In order to enable a higher penetration of our technologies, we must strive to make them even more affordable and intuitive for new users," said Amir Lichter, vice president of product delivery and life cycle at Yokneam, Israel-based Lumenis Ltd., a laser- and energy-based medical device supplier.

One key to cutting costs is complete control over the manufacturing cycle, Lichter said. Another is to seek alternative energy-based technologies for some clinical applications that can deliver results at a lower cost than lasers. Lumenis, which is celebrating a half century in medical lasers, also offers intense pulsed light and radio-frequency-energy-based solutions, with these used in an array of medical applications.

With regard to lasers, Lumenis uses CO_2 lasers, which emit at 10 microns in ear, nose and throat, as well as gynecological and dermatological applications.



Pantec Medical Laser

Lasers cut bone to a depth greater than 6 mm with a high aspect ratio.

Lumenis employs holmium solid-state lasers, with a wavelength of 2.04 µm, for the treatment of benign prostatic hypertrophy, stone dusting or the breaking up of stones and other urology applications. When it comes to aesthetic and dermatology procedures, Lumenis turns to 1064-nm wavelength Nd:YAG lasers to treat vascular conditions, while employing CO_2 and 1565-nm Erbium lasers for skin resurfacing and diode lasers for hair removal. Doubling the Nd:YAG to the green by passing the light through a KTP crystal yields devices used in ophthalmic treatment.

The power ranges from a watt for retinal treatments on up to 120 watts for urology applications. Some of these are pulsed while others are continuous wave, with the specific treatment dictating which approach is best.

Two different laser sources = better results

As for the future, Lichter pointed to a trend that will push laser innovation. "More effective solutions can be obtained by combining two different sources of lasers or even two different energy-based technologies," he said.

An example includes the use of radio frequency to pretreat an area, thereby boosting laser penetration. Another possibility is the use of one laser to make a smooth ablative cut while a second at a different wavelength stops bleeding, possible because of differing blood absorption characteristics of the two beams.

‘More effective solutions can be obtained by combining two different sources of lasers or even two different energy-based technologies.’

Amir Lichter, vice president of product delivery and life cycle at Yokneam, Israel-based Lumenis Ltd.

To do this the lasers must be integrated into a system while taking up less space, power and other resources. They also need to be more robust in order to achieve an acceptable uptime.

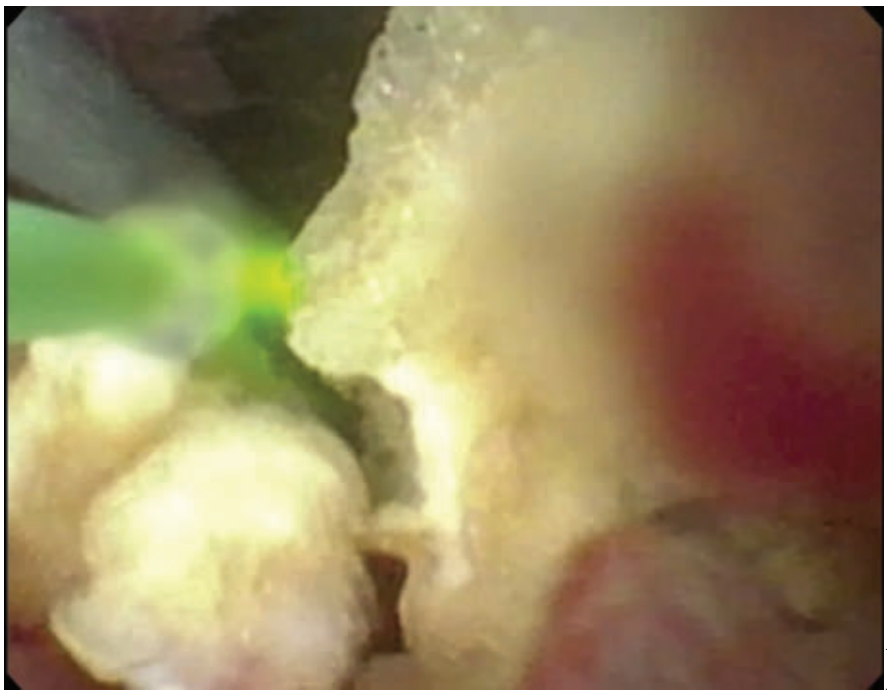
Further changes that Lichter sees coming include guided real-time imaging to increase the effectiveness of treatment and improve the safety of an operation. Again, this integration will be aided by laser improvement. So, too, will creating more cost-effective solutions, a third future trend.

Laser parameters such as wavelength, power and pulse duration are important and must fit the desired application, according to Lichter. Just as critical, though, is that the systems be reliable, intuitive to operate and easy to use, because ultimately the devices will be operated by medical and not laser professionals.

As for biostimulation, Lumenis has research activities underway in this area, Lichter said. At the moment, though, the company has nothing that can be publicly shared.

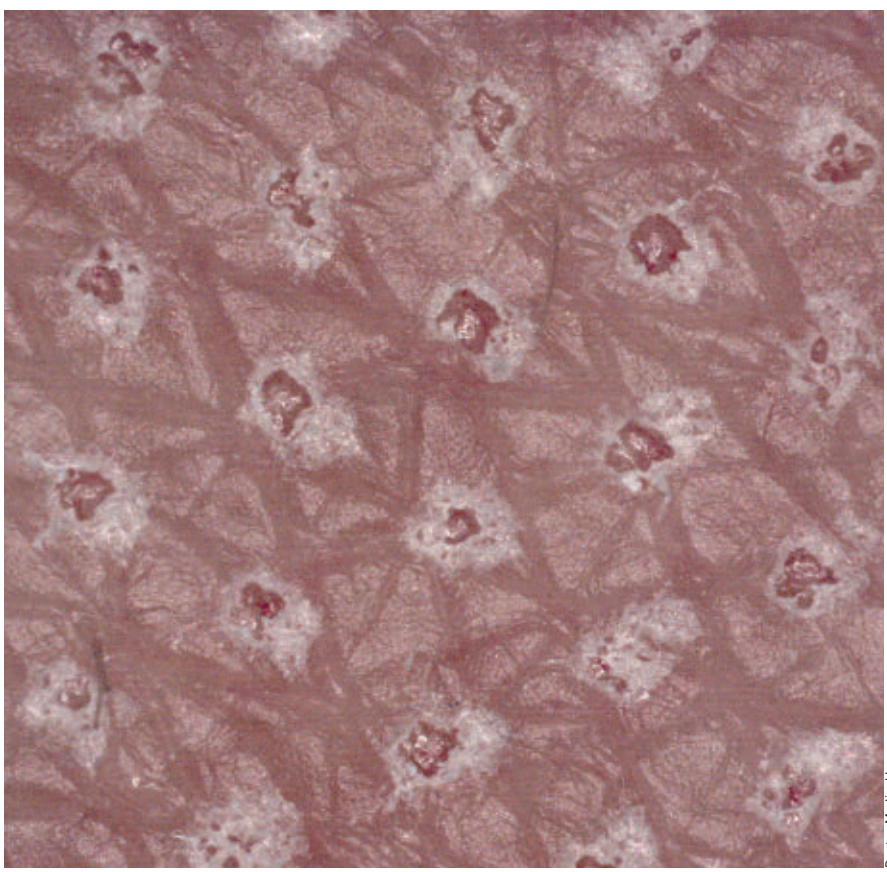
Healing effects

The case for the healing effects of medical lasers seems sound, based on preliminary evidence and the physics involved. With regard to the evidence, studies at Careggi Hospital in Florence, Italy, have reportedly shown that women who have undergone laser-based cervical disease treatment get pregnant at a greater rate than the normal populace. A study of patients at Kaiser Permanente Northwest[1] found the same, with laser and nonlaser



Lumenis

A laser breaks up urinary stones.



Pantec Medical Laser

Skin perforated by laser shows no blood. This treatment can ease the delivery of drugs through the skin.

treatments included in the evaluation.

As for the physics rationale, that arises from the fact that, at the focus, the power of a laser can heat tissue to thousands of degrees but does so for only microseconds if it is pulsed. As a result, diseased tissue is destroyed but the surrounding healthy tissue is unharmed. However, the surrounding tissue is still exposed to intense and potentially healing light, with this falling off with distance from the focal point.

Proving that benefit scientifically is difficult and the burden of evidence for a medical claim is high. Biostimulation is an area of great interest, however, and so it may not be long before there are confirming studies.

For example, according to DEKA, a spinoff of the El.En. Group S.p.a. of Florence, Italy, studies are underway of the wound-healing effects of its CO_2 laser system. These are being conducted to examine the effects of the laser, which the company stated "appears to induce a significant response in terms of inflammation, growth factors expression, collagen regeneration, immune-modulation and neo-angiogenesis (new blood vessel formation)."

The laser scheme allows different output wavelengths by careful crystal absorption and pump wavelength matching.

The El.En. Group makes medical systems based on CO_2, Nd:YAG, holmium, and diode lasers for a variety of medical treatments. Currently, these are used for ablation, cutting or coagulating, depending on the energy density. There is the possibility they will be used for biostimulation in the future.

In the meantime, Luca Giannoni, medical R&D product manager, said some of the company's improvement efforts are centered on scanners, the systems that deliver the laser to the desired spot while moving the beam very rapidly. Scanners need to be both precise in targeting and quick in their response.

Another area of improvement involves various system modules. A laser, unlike a blade, has multiple parameters that can be tuned to give the optimum result. Some of this tuning may not be intuitive to medical professionals.

One such adjustment is focus, which Giannoni noted is an acquired skill that takes time to develop. So the El.En. Group is attempting to make focusing simpler and more effective for professionals who are not experts.

"We are working to make something that is more friendly for them to focus and for them to understand if things are working correctly or not," Giannoni said.

A much smaller company, Pantec Medical Laser of Ruggell, Liechtenstein, got into the medical laser business as a way to make drug delivery painless, according to Manuel Messner, application and sales engineer. The firm, a division of Pantec Engineering, wanted to use a

laser to produce tiny holes in the skin. On top of this would go a patch bearing the drug of interest. The medicine would penetrate the skin and provide a therapeutic effect, courtesy of the laser-drilled perforations.

Ideal wavelength for tissue absorption

Due to the presence of water in biological tissue, Pantec looked at its absorption spectra and decided where the laser output should sit. "Around 3-µm wavelength you see a very high absorption. Meaning if you manage to get a laser at that wavelength, all the laser power, all the laser energy is absorbed by the water, giving you desired effects like ablation or coagulation of your soft or hard tissue," Messner said.

Pantec opted to use an Er:YAG crystal for its optical gain medium, which led to a 2.94-µm wavelength beam. The company went with a direct diode pump instead of flash lamps and chose a monolithic resonator design, leading to better pump light matching and the elimination of external cavity mirrors. This monolithic diode-pumped solid-state design enables the lasers to be compact and robust, opening up the possibility of integration into a handheld unit, Messner said. He added that it also made the lasers efficient and almost maintenance-free.

According to Messner, the chosen laser scheme allows different output wavelengths by careful crystal absorption and pump wavelength matching. The design also makes upping the power output easier.

What Pantec had at the end was a system that worked well for treating the skin to make it easier to do drug delivery. The company put the design to use in other medical procedures.

"We took this Er:YAG laser and power scaled it. We started with 2-watt laser modules 10 years ago and now we are at over 100 watts output power. That opened the way for all kinds of medical applications," Messner said.

Today, the lasers are used for minimally invasive surgery, dentistry, ophthalmology and dermatology applications, he said. Pantec has added other wavelengths by using Thulium:YAG crystals, which lase at 2.02 microns. The company is also looking into visible wavelength applications, with one planned application being photocoagulation of the retina.

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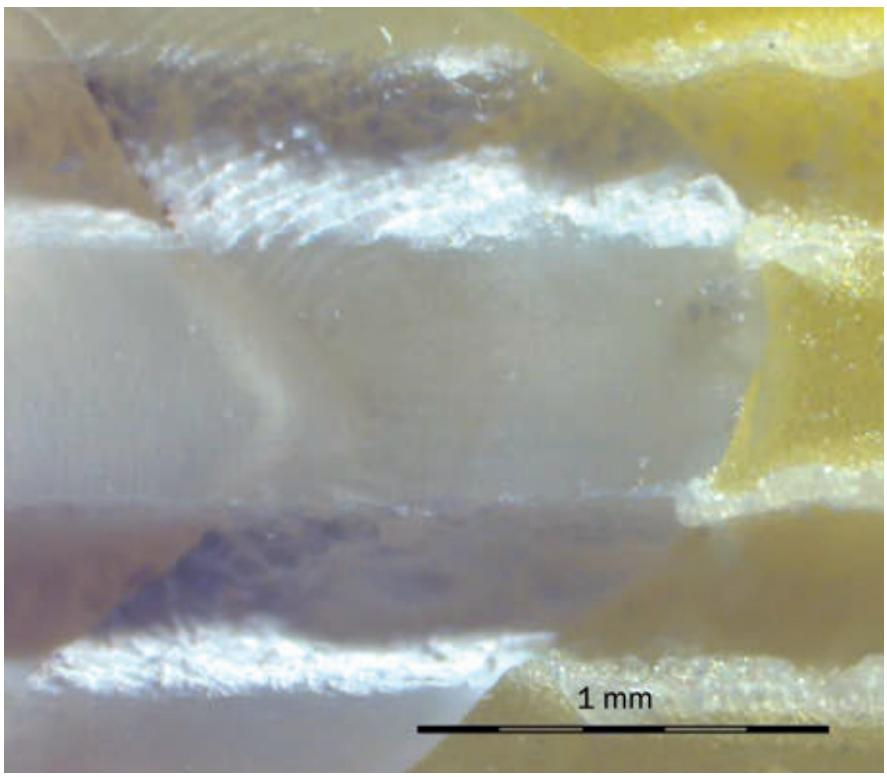


Pantec Medical Laser

Lasers efficiently cut enamel and dentin.

Lumenis

Scar revision using an ultrafast CO_2 laser before **(left)** and after **(right)**.

Reference

1. A. L. Naleway and Sheila Weinmann et al. (2015). Pregnancy after treatment for cervical cancer precursor lesions in a retrospective matched cohort. *PLOS One*, http://dx.doi.org/10.1371/journal.pone.0117525.

No One-Size-Fits-All Approach to Selecting **Optical Coatings**

To maximize the performance of a coating for a given application, a better understanding of coating design and deposition technique is a must.

BY STEFAAN VANDENDRIESSCHE
EDMUND OPTICS INC.

Optical coating design and performance are critical for a growing number of applications in fields as diverse as biomedicine and astronomy. Coatings can perform a variety of functions, from imparting high reflectivity on telescope mirrors, to controlling polarization and removing unwanted reflections. As laser usage continues to increase globally, the use of laser-specific optical coatings increases in tandem. The ongoing improvements in laser power, pulse length and wavelengths have resulted in new coating requirements, spurring the development of novel coating technologies.

The interactions of high-power lasers and optical coatings are complex and depend on the laser's wavelength, pulse length and intensity. On the other side, coating performance is impacted by the uncoated substrate, coating design and deposition technique.

There are many methods for manufacturing optical coatings; therefore, a solid understanding of the benefits and disadvantages of each technique, along with the interplay of the laser with the design of the coating and the uncoated substrate, helps in the selection of the proper substrate, coating technology and requirements for the given application. Achieving the required performance without over-specifying the optic or choosing an unnecessarily expensive substrate or coating technique can save on cost and provide engineering benefits that directly impact the bottom line (Table 1).

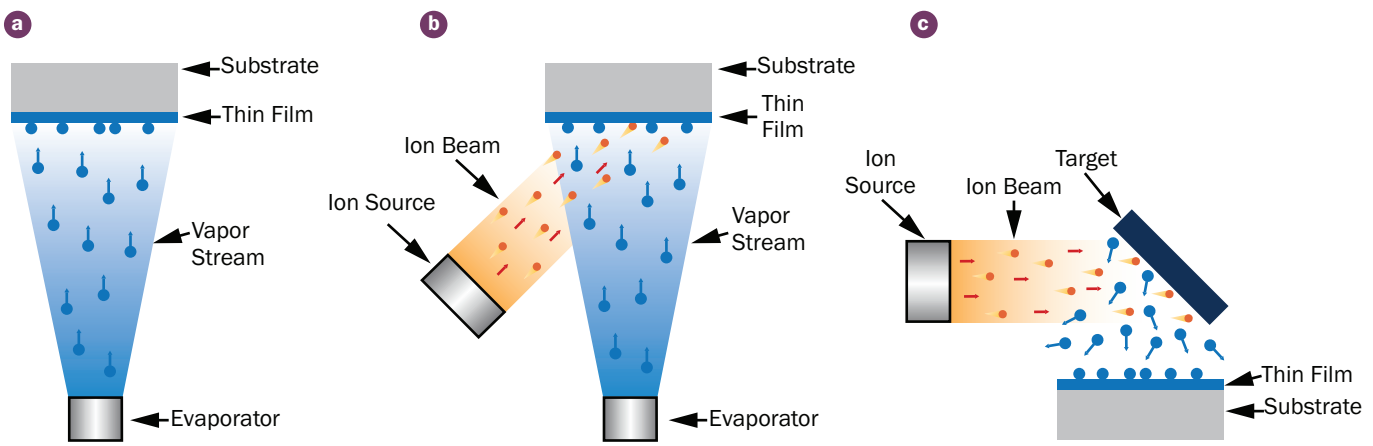
Specifying a substrate

Often the first material that comes to mind for laser optical applications is fused silica, favored for its low coefficient of thermal expansion. For that reason, it is often the best choice for an application, yet it typically comes at a price premium compared with other materials.

The common misconception is that fused silica is the only choice due to its high laser-induced damage threshold (LIDT). This is a pitfall to avoid when specifying laser optical substrates, as many other common materials exhibit similar bulk material LIDT as fused silica in the correct material purity grade[1]. Generally the bulk material LIDT is irrelevant as the coating or coating-substrate interface will fail at laser fluences many times lower than that of the bulk material.

Another commonly misunderstood requirement for optical coatings is surface roughness. While it's important for laser optical performance, including scatter and laser damage threshold, specifying roughness correctly without unnecessary over-specifications and associated costs is often difficult. A useful surface roughness specification includes the maximum value of a measured metric, such as R_a or R_q, as well as the area over which the roughness is to be measured.

Subsurface damage is not often specified in substrate requirements despite the fact that it is an important factor in LIDT. The main reason to avoid specifying it is the difficulty in both controlling and mea-



Various coating technologies: electron-beam physical vapor deposition **(a)**, ion-beam-assisted electron beam physical vapor deposition **(b)**, ion-beam sputtering **(c)**.

Images couresty of **Edmund Optics**.

Table 1.
A comparison of the main laser optical coating technologies shows that the choice of technology is heavily dependent on the specific coating requirements.[2]

	Evaporative	Evaporative with IAD	Plasma Sputtering	IBS	ALD	Subwavelength Structured Surfaces
Performance						
Antireflection Performance	Low	Medium	High	High	Very high	Very high
Reflective Performance	Low	Medium	Medium	High	Very high	Potentially Very high
Edge Performance (Notch, Short and Longpass)	Low	Medium	Very high	Very high	Very high	Poor
Wavelengths						
Durability	Low	Medium-high	High	High	High	Medium-high
LIDT						
Coating Stress	Low	Medium	High	High	Medium	Not applicable
Coating Loss (Scatter, Absorption)	High	Medium	Low	Very low	Very low	Low
Process						
Process Stability, Reproducibility	Stable	Stable	Extremely stable, reproducible	Extremely stable, reproducible	Extremely stable, reproducible	Difficult to control
Process Time	Slow	Slow	Intermediate	Very slow	Very slow	Fast
Optic Shape Flexibility	Flexible	Flexible	Intermediate	Inflexible	Very flexible	Very flexible
Unit Coating Price	$	$	$$	$$$	$$$	$
Conformal	No	No	Yes	Yes	Yes	Yes
Technical Maturity	Established	Established	Established	Established	Emerging-established*	Emerging
Equipment						
Equipment Investment	$	$$	$$$	$$$$	$$$$	$$
Equipment Size	Large	Large	Large	Large	Large	Small

*Emerging within the optical coatings industry but established in the semiconductor industry

IAD = ion-assisted deposition IBS = ion-beam sputtering ALD = atomic layer depostion LIDT = laser-induced damage threshold

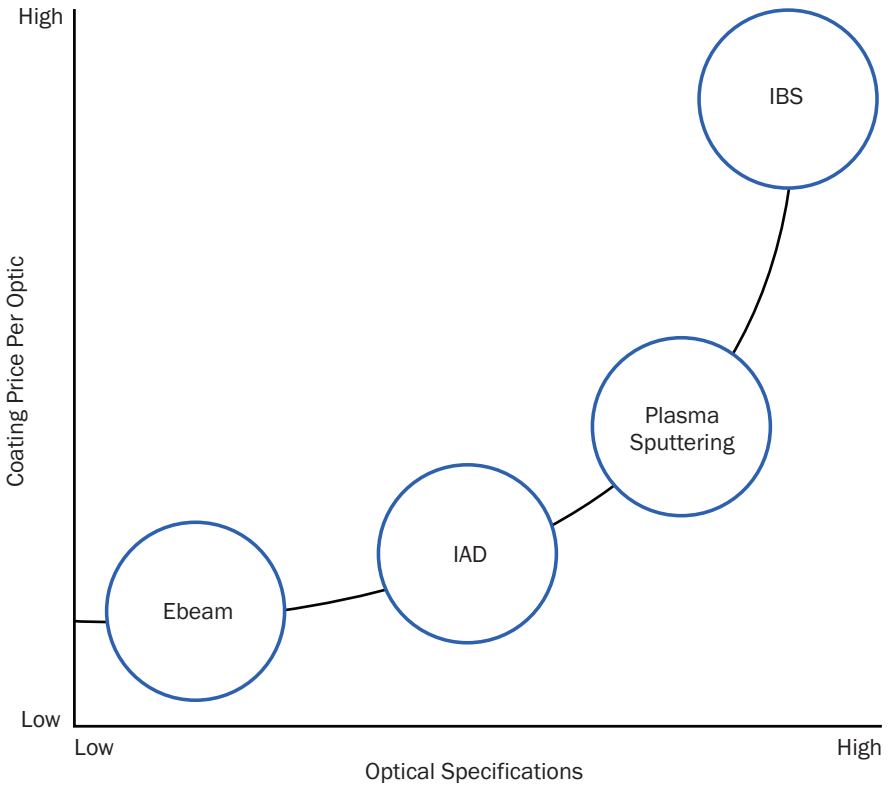
suring it. Often a process is developed that results in an acceptable laser optical performance and this process is carefully repeated to ensure the same subsurface damage without measuring or knowing what the actual subsurface damage is.

Specifying a coating

Typically a reflectivity is specified over a wavelength range, either close to 100 percent for mirror or reflective coatings or close to 0 percent for antireflective coatings. Specific reflection requirements are given for more specialized coatings such as notch, bandpass and edge filters, and these often include the slope: the degree that the reflectivity changes over a specific wavelength.

Environmental requirements include abrasion resistance and performance tolerances during humidity and heat changes. These are often important for laser applications in more demanding environments, such as laser steel welding.

Surface quality, similar to nonlaser optical coatings, is most often specified using either the MIL standard (MIL-PRF-13830B) or the ISO standard (ISO 10110-7:2008). When using lasers, slight surface imperfections generate highly detrimental



Choosing between the established coating techniques requires an understanding of the cost/performance ratios and trade-offs. This chart does not include emerging technologies, as their cost and performance metrics are not sufficiently determined for a general comparison with established technologies.

Applications Determine Coating Choices

For high-reflectivity wavefront-critical mirrors used in cavity ring-down spectroscopy, the high reflectivity requirements narrow the coating technology selection down to plasma sputtering, ion-beam sputtering or atomic layer deposition, with the final choice often dictated by price, volume and batch sizes. The laser-induced damage threshold (LIDT) is not significant for this application, so the subsurface damage in the substrate is of lesser importance, too. To achieve the required reflectivity, the surface roughness will need to be very low. A super-polished fused silica substrate would be the recommended substrate and, due to the stress caused by the possible coating technologies, coating the nonreflective side may be required to balance out the stress.

In another case, a polarization critical lens for chemical analysis mandated that residual stress in the coating could distort the polarization and must be avoided at all costs. For this reason, the coating technology of choice is evaporative deposition. The fused silica must be specified to be low-birefringence fused silica, as standard fused silica would cause polarization distortion due to birefringence.

A third example involves high laser-induced damage threshold mirrors for a fiber optical laser machining application. Other than the LIDT, this mirror does not have very tight specifications that could be met with most coating technologies. Price becomes the most important remaining parameter, and the recommended coating technology is either evaporative deposition with ion-assisted deposition or plasma sputtering. The substrate can be any of the common optical materials, including N-BK7, fused silica and Zerodur, depending on the thermal specifications and material availability at the correct size and polishing price and time.

scattering and are potential nucleation sites for laser damage, and for this reason laser optics are usually specified with 20-10 or less surface quality, and quite often 10-5 or lower.

LIDT is a seemingly simple specification that is very often misused and misunderstood. A properly defined LIDT establishes a maximum irradiance (for continuous wave lasers, typically in kW or MW/cm^2) or fluence (for pulsed lasers, typically in J/cm^2) at a specific wavelength, pulse duration and repetition rate if applicable, laser beam spot size and beam profile. While it may seem straightforward, the existence of an entire ISO standard (ISO 21254-1:2011) of over 75 pages devoted to characterizing LIDT demonstrates that it is not as straightforward as it appears to be. Achieving a certain LIDT depends on the chosen coating technology[3], the coating design[4], coating materials chosen, process control and cleanliness during coating, as well as the substrate on which the coating is deposited. Moreover, the damage mechanisms depend on wavelength as well as pulse duration[5]. Damage either occurs within the bulk material, or at the surfaces and interfaces that include the thin-film coating.

Damage to bulk material and coatings

Damage to the bulk material most often occurs in uncoated laser optics. This is because the bulk material typically has a 3 to 10 times higher LIDT than the coating does. Bulk material failure can occur due to material impurities or inclusions, but this damage can be avoided by selecting the correct optical material for the required wavelength, and specifying the correct grade of optical material to avoid inclusions and impurities.

Damage most often occurs in the thin-film coating or at the surfaces and interfaces. Within the thin-film coating, it can be minimized with the correct coating materials and coating design. The electronic bandgap of the chosen materials influences the LIDT, and the purity of the coating materials is also an important factor. The design of the coating determines what the distribution of electric fields will be during irradiation, and an ideal design minimizes peak electric fields and places the highest electric field values as far from interfaces as possible.

TECHSPEC Nd:YAG Laser Line Mirrors offer the high reflectance and superior surface quality and accuracy needed for demanding laser applications.

Damage occurring at the coating-substrate interface can often be mitigated by correct substrate specification[6]. Often this damage is initiated by subsurface damage present in the substrate and could have been avoided by using substrates with less subsurface damage. This region is often the most important in determining LIDT.Damage occurring in this region is the reason transmissive coatings typically have significantly lower LIDT values than reflective coatings; most of the laser beam energy never reaches this relatively fragile region in reflective designs, whereas most of it does for transmissive coatings.

The exact mechanisms of laser-induced damage are the subject of countless articles and technical conferences and are beyond the scope of this article[7]. It's important to understand how coating, substrate and process parameters influence LIDT in a given application, and this requires an in-depth discussion with your optical manufacturer.

Evaluating coating techniques

In evaporative deposition, source materials are vaporized using either resistive heating or electron-beam bombardment inside a vacuum chamber. These vaporized materials condense onto the optical surfaces and, through the careful control of vaporization rates, vacuum and substrate rotation, uniform optical coatings of specific designed thicknesses result.

Because of the relatively gentle nature of vaporization, the resulting coatings are loosely packed or porous. These loose coatings suffer from water absorption, which changes the effective refractive index of the layers and result in a degradation of performance.

Evaporative coatings can be enhanced using ion-beam-assisted deposition, where an ion beam is directed at the substrate surface. This increases the energy of the source material when it adheres to the surface, resulting in stronger adhesion. The resulting coating is denser but also contains more stress.

Another coating technology is plasma sputtering, which covers a range of technologies encompassing advanced plasma sputtering to magnetron sputtering. All involve the generation of a plasma. The ions in this plasma are accelerated into the source material, striking loose energetic source ions. These then sputter onto the target optic. While each type of plasma sputtering has its own specific properties, advantages and disadvantages, these technologies are grouped together as they have a common operating concept and the differences among them are much smaller than the differences with the other coating technologies discussed here.

With ion-beam sputtering (IBS), a beam of ions is accelerated through a high-energy electric field. The beam then hits the source material with significant kinetic energy, "sputtering" the source material loose from the target. These sputtered source material ions are energetic and impinge on the substrate surface, creating a dense film. While IBS is well-established in the laser optical coating space, it is overused due to a lack in understanding the capabilities of the other coating technologies.

In atomic layer deposition, optical coatings are built layer by layer from gas precursors. Unlike evaporative deposition, the source material doesn't need to be evaporated from a solid, but can originate directly from a gas. Despite this, the coating is often still performed at an elevated temperature. The key differentiator for atomic layer deposition (ALD) is that the precursors are delivered in non-overlapping pulses, and that each pulse is self-limiting. The chemical design of the precursors and the coated surface is such that only a single layer can adhere per pulse. This provides an extraordinary level of control for layer thicknesses and designs, but also results in a slow rate of deposition.

Clues from a moth's eyes

Surfaces with structures smaller than the wavelength of light have been of interest ever since the discovery of the textured pattern on moths' eyes. While this approach is still evolving, it consists of modifying the structure of a substrate's surface as opposed to depositing alternating layers of high- and low-refractive index materials traditionally used in thin-film coatings. The features on the textured surfaces can be periodic such as the moth's eye pattern, or random in nature. These structures can be manufactured using photolithography or using modified plasma etching.

Translating an application's requirements to substrate and coating specifications is a crucial step in selecting the right coating technology. There is no single technology best suited for all applications; while some applications can be served by multiple coating technologies, generally it is possible to identify one most suitable method to deliver the necessary performance at the right price.

Meet the author

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References

1. C.J. Stolz (Nov. 28, 2012). Boulder Damage Symposium annual thin-film laser damage competition. *Opt Eng.* Vol. 51, Issue 12, 121818.
2. R. Jedamzik and F. Elsmann (Feb. 22, 2013). Recent results on bulk laser damage threshold of optical glasses. *Proc SPIE*, Vol. 8603, High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications II, 860305.
3. J. Shao and K. Yi, et al. (July 2011). Filters & coatings: Laser advances drive development of specialized optical coatings. *Laser Focus World.*
4. P. Kupinski and M. Thomas (September 2014). Transmissive high-energy laser optics: Manufacturing and testing considerations. *Laser Focus World.*
5. N. Bloembergen (1973). Roles of cracks, pores and absorbing inclusions on laser induced damage threshold at surfaces of transparent dielectrics. *Applied Optics*, Vol. 12, pp. 661-664.
6. A.A. Manenkov (January 2014). Fundamental mechanisms of laser induced damage in optical materials: Today's state of understanding and problems. *Optical Engineering*, Vol. 53, Issue 1, 010901.
7. A. Czajkowski (2010). Optical coating technology and applications: Past and present to future. *Photonik International.*

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Wavefront Sensing
Under Unique Lighting Conditions

Shack-Hartmann wavefront sensors prove critical in detecting light propagation properties of noncoherent light sources.

BY JOHANNES PFUND, RALF DORN and CHRISTIAN BROCK, OPTOCRAFT GmbH

While the invention of the general principle of Hartmann wavefront sensing goes back to the beginning of the 20th century[1], the advent of industrial cameras and micro lenses in the 1970s facilitated broader applications[2]. Nowadays, Shack-Hartmann wavefront sensors (SHWFSs) have made their way into numerous applications in R&D, medicine and manufacturing.

Certain applications, however, require light sources with unique coherence or phase distribution properties. LEDs have an interesting degree of partial temporal and spatial coherence but are difficult to use with interferometric methods. Optical vortex beams, with their helical phase distribution, are common in research where the angular momentum properties of these beams are harnessed. For a growing number of cases, SHWFSs are the preferred choice when other interferometric tools come up short, such as when the light of LEDs is used for metrology or for LED-based optical systems.

Shack-Hartmann principle

Shack-Hartmann wavefront sensors comprise a 2D array of micro lenses and a detector, typically a CCD or CMOS camera. After passing through the micro lens field, a flat wavefront generates a regular spot matrix on the detector. If the wavefront is curved, the spots generated are shifted correspondingly from their local optical axis. From these displacements, the wavefront is reconstructed (Figure 1).

The measurement process requires only a single camera image and is thus fast and makes for simple application. Using associated software, a large number of optical variables can be measured, such as wavefront aberrations and intensity profile. Based on the wavefront, a Zernike expansion, a calculation of the point spread function, the Strehl ratio and the modulation transfer function may help to get more detailed insight into the behavior of optical systems. When using the intensity profile in addition to the wavefront, laser beam parameters can be calculated.

Two classical applications of SHWFSs are the adjustment of a lens system and the analysis of laser beams. The double pass configuration offers high accuracy, sensitivity and greater flexibility in lens production (Figure 2). Figure 3 shows the measurement result of a photographic lens performed at a wavelength of 540 nm using a SHWFS with 60 × 60 micro lenses.

Measuring lasers and LEDs

The SHWFS measures the intensity and phase distribution of a laser beam on one position along the beam axis. The wavefront curvature radius R, the $1/e^2$-diameter of the beam $d(z_m)$ and the beam propagation factor M^2 can be calculated from the second spatial/angular moments of the measured intensity distribution/wavefront.

To analyze the stability of the beam parameter measurement, continuous measurements of the position of the beam waist z_0, the beam waist diameter d_{bw} and the Rayleigh length z_R were taken over a period of 30 minutes at a frame rate of

Table 1.

	$d(z_m)$	M^2	d_{bw}	z_0	z_R
Mean/mm	2.13	1.17	0.07	148.5	5.14
rms/mm	0.005	0.029	0.0024	3.86	0.28
rms/%	0.2	2.3	3.3	2.6	5.5

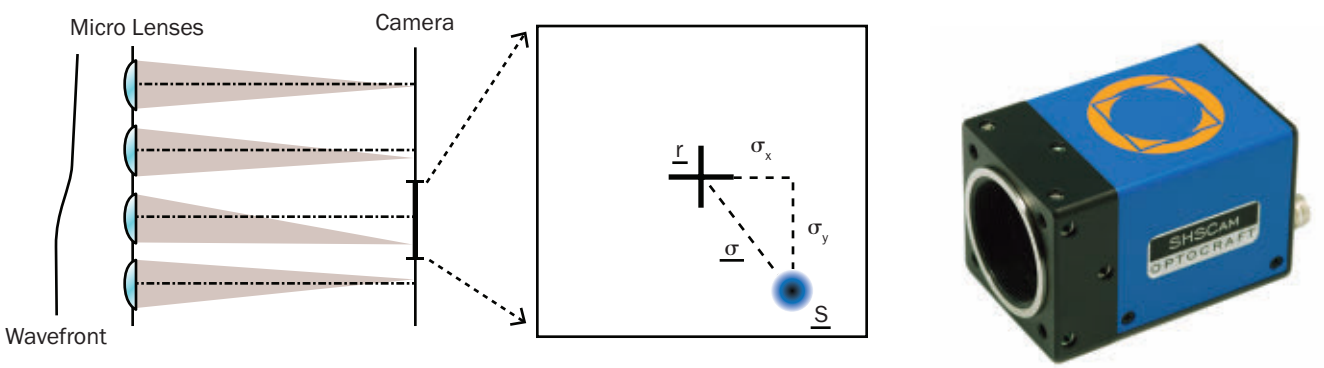


Figure 1. Shack-Hartmann wavefront sensor principle and typical form factor.

Images courtesy of Optocraft GmbH.

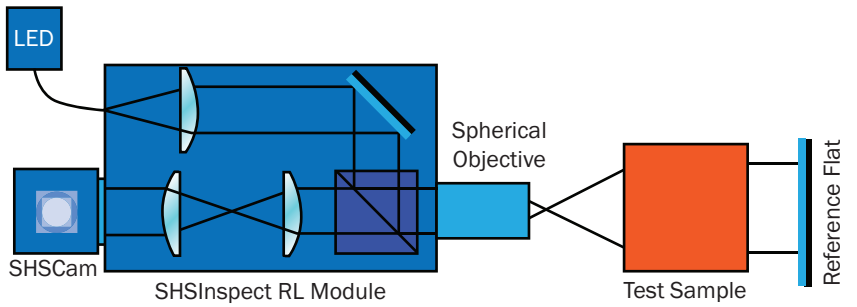


Figure 2. Double pass configuration for lens testing.

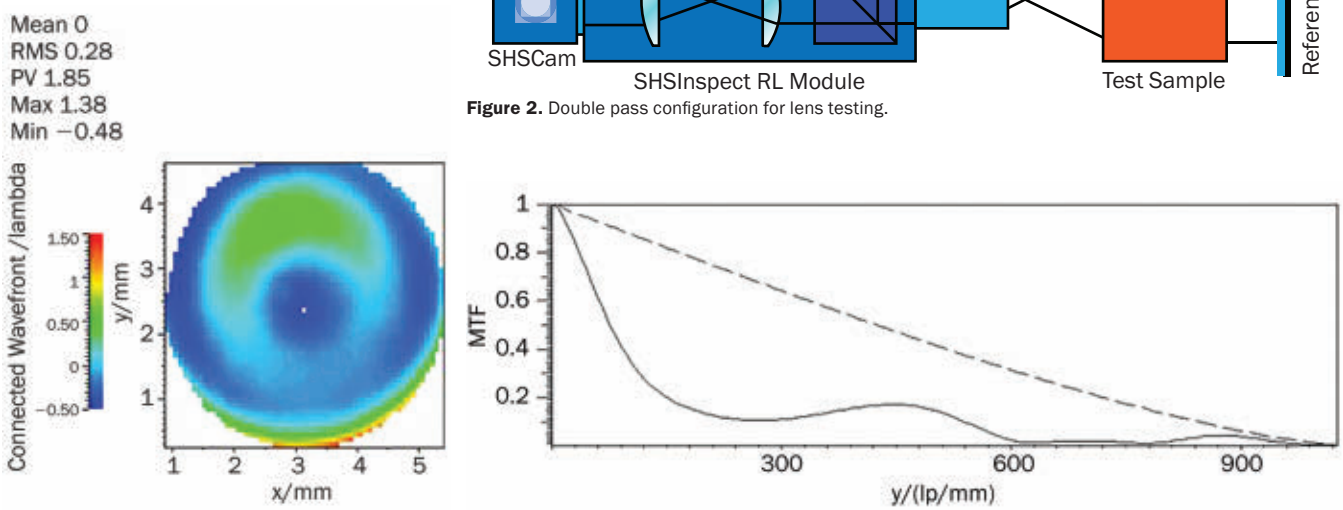


Figure 3. Example measurement results of a photographic lens 1.8/50 mm.

10 Hz. The resulting mean values and standard deviations (root mean square) of the respective beam parameters are shown in Table 1.

The complex amplitude of the electromagnetic field describes the propagation of light from a single point of a monochromatic light source. It contains the intensity distribution and phase of the light beam. Beams from classical laser sources such as HeNe and Nd:YAG lasers resemble this model. These coherent properties may represent a requirement or an advantage in many applications. However, there are also applications in metrology where they even prohibit a proper solution. Coherent noise, for example, might degrade the measurement repeatability or accuracy due to dust and dirt in the setup. SHWFSs do not require coherence — either temporal or spatial — of the light source to retrieve a wavefront measurement.

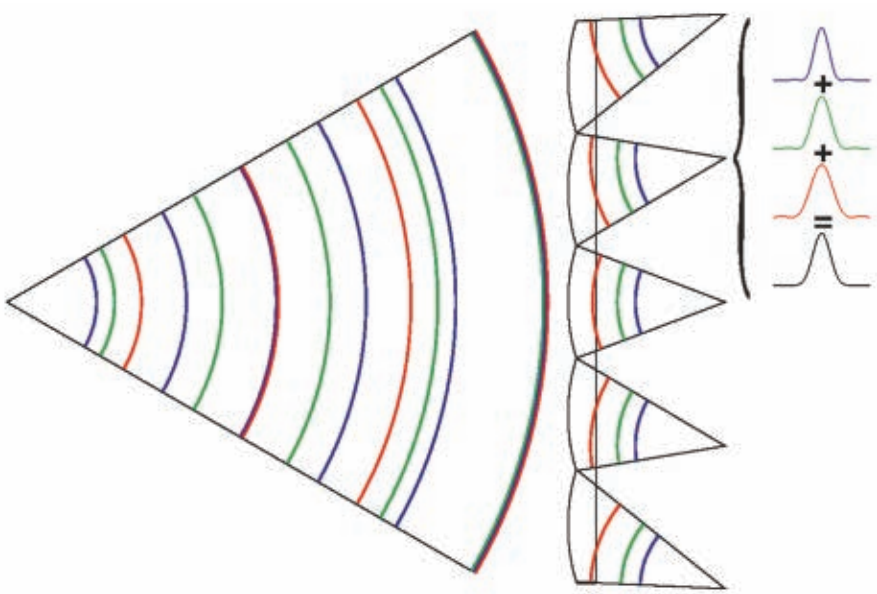


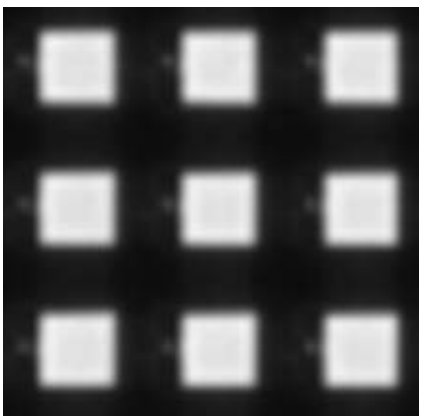
Figure 4. Wavefronts with different wavelengths emanating from one light source point.

Temporal and spatial coherence

The Shack-Hartmann principle can be understood as a geometric measurement principle: The final intensity distribution of the polychromatic spot can be considered as the incoherent superposition of the intensity distributions of "many" monochromatic spots; for example, the sum of the intensity Airy patterns of each monochromatic component or "color" (Figure 4).

One of the first applications of the SHWFS was in astronomy[3], where white light from stars is routinely used. The metrological problem is less an issue to retrieve a geometrical wavefront shape from a white light or polychromatic spectrum and more the somewhat philosophical matter of associating this retrieved shape from such a superposition of monochromatic waves with one single wavefront.

The situation is further compounded if each monochromatic component of a spectral distribution contributes a wave with a different geometrical shape to the total electric field, such as when measuring objectives with strong chromatic aberrations.



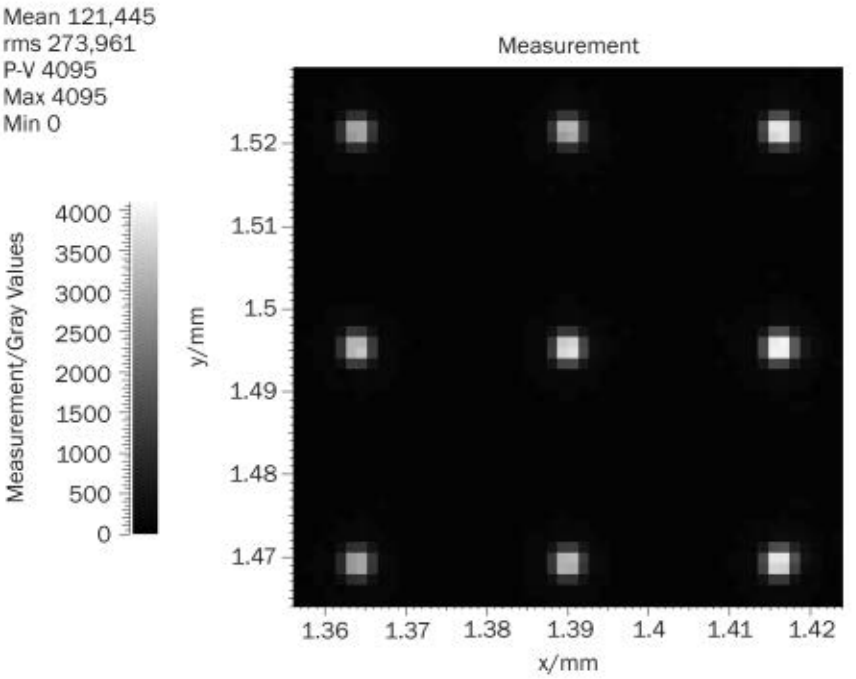


Figure 5. With LED illumination, each spot is an image of the emitter surface, **above**. LED spot pattern in a coherent situation, **right**.

Should the light source no longer be a quasi point source, as in the case of a small pinhole or the end of a monomode fiber, spatial coherence requires special consideration.

An extended light source can be understood as an ensemble of source points. Each emits a wavefront not necessarily requiring a constant phase relation relative to the wavefronts emitted by other source points. On the camera chip of the SHWFS these different wavefronts each form slightly different spot patterns that are superposed, culminating in one "spot" per micro lens.

Accordingly, the wavefront sensor measures an averaged wavefront even in the case of an extended light source. If the distance z between the light source and the wavefront sensor is long, the different wavefronts from the various source points of the extended light source differ by less than a fraction of a wavelength over the detection area — the light source is then spatially coherent from the perspective of the wavefront sensor. For short distances z, the wavefronts from the various source points take a significantly different optical path across the area of a micro lens — the light source is spatially incoherent.

The van Cittert-Zernike theorem relates the size d_{LS} of the light source, the distance z between the light source and the sensor, and the diameter of the coherence area d_{coh} over which the wavefront can be considered to be spatially coherent. Applied to the measurement situation of a Shack-Hartmann wavefront sensor, the following is derived:

$$d_{coh} = \frac{4\lambda z}{\pi d_{LS}}$$

With decreasing spatial coherence, the size and shape of the spots generated by each micro lens are no longer limited by diffraction at the rim of the micro lens and each spot evolves into a small (geometric) image of the light source (Figure 5).

Partially coherent light sources

With a decreasing degree of spatial coherence, the term wavefront becomes less and less well defined. However, in such applications, the "wavefront" evaluated by the SHWFS still contains valuable information.

A practical application is the automated alignment of a plastic asphere in front of an LED source as used in medical or mobile devices. The LED light spot is projected onto a position at a well-defined distance XYZ with respect to the LED.

The measurement system consists of the SHWFS, a Keplerian telescope and a collimation lens acting as a null lens. The alignment is performed in four steps (Figure 6).

a. Reference position: The measurement system is axially aligned so that the null lens collimates the divergent beam emitted from the LED, (reference position z=0).

b. Target position: Starting from the reference position z=0, the system is axially moved by Δz.

c. Asphere alignment: The asphere (red) is inserted. The tilt and defocus signals are used to calculate a correction vector to the ideal lens position. The wavefront information is not only used to shift the asphere to its correct position, but also describes the wave aberrations introduced into the beam by the asphere.

d. Gluing process and final inspection: To fix the asphere onto a holder, UV-curing polymer is applied.

Under such conditions, the spot pattern to be evaluated (Figure 5) is clearly spatially and temporally incoherent. To evaluate the data, a special SHWFS layout and evaluation algorithms are required (Figure 5). In this example, aspheres with a focal length in the millimeter range can be positioned with micrometer precision in a cycle time of 2 to 3 seconds.

Measurement of helical light beams

Laser beams with an orbital angular momentum, or optical vortex beams, are lightwaves capable of transducing rotational transversal forces. The corresponding wavefront exhibits a helical structure and is usually described by Laguerre-Gaussian modes. Figure 7 shows examples of helical mode wavefronts with different helicity or topological charge.

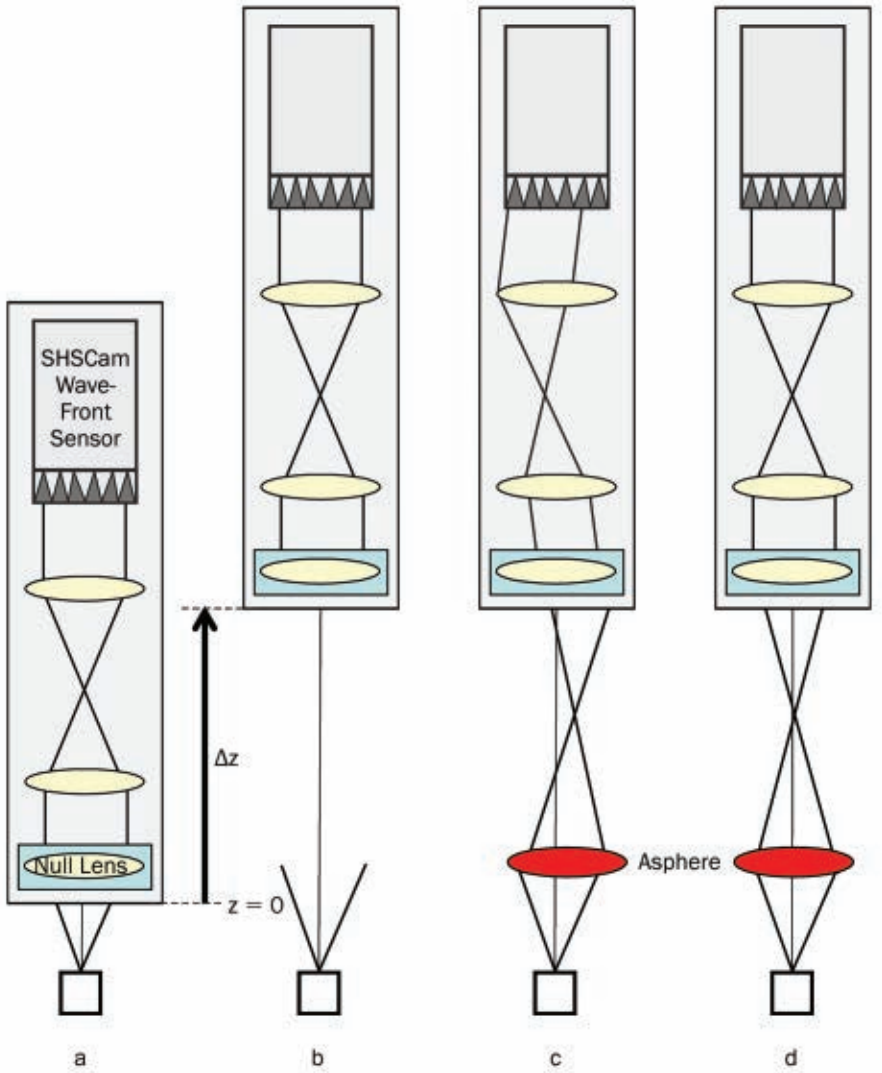


Figure 6. Alignment of an asphere relative to an LED source.

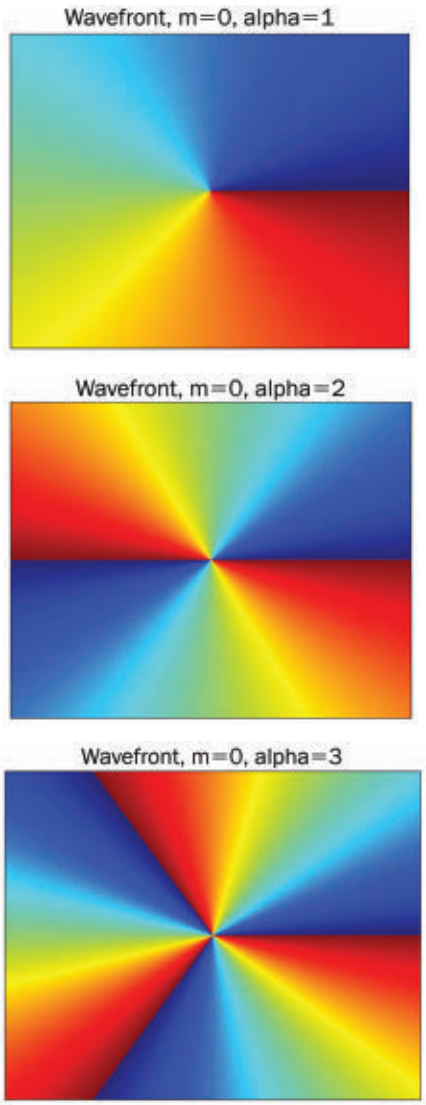


Figure 7. Simulated helical modes with topological charge 1, 2 and 3. The simulation uses the Laguerre-Gaussian modes described by M. Chen and C. Dainty in their 2009 paper: Reliability of detecting optical vortex with a Shack-Hartmann wavefront sensor in a scintillated vortex beam. *Proc SPIE*, Vol. 7476.

Orbital angular momentum beams can be formed by spiral phase plates, computer-generated holograms, spatial light modulators, optical nano-antenna arrays or ring resonators. Moreover, a laser beam with a high degree of coherence is required. Applications include the rotation of particles trapped in an optical tweezers, the generation of weak microfluidic currents, stimulated emission depletion microscopy, edge filtering by spiral phase contrast imaging, and improved optical data transmission and quantum cryptography[4]. When measuring orbital angular momentum beams with SHWFS, difficulties like phase discontinuities present in the corresponding helical wavefronts need to be addressed.

The light from a fiber-coupled laser diode emitting at a wavelength of 635 nm is collimated and passed through a spiral phase plate (Figure 8). A SHWFS with a lateral resolution of 58 × 43 micro lenses is placed directly behind the phase plate to minimize wavefront propagation effects. For simplicity, no relay optics are used. At first, a measurement with the phase plate removed from the beam path is taken and used as a reference for subsequent measurements. Then, spiral phase plates with different topological charges of 1, 2 and 3 are measured.

Due to the phase discontinuity present in helical wavefronts, classic Shack-Hartmann wavefront reconstruction algorithms fail to calculate the helical wavefront. However, to analyze the influence of the spiral phase plate on the transmitted wave, it is usually sufficient to evaluate the spot displacement distribution detected by the wavefront sensor, which represents the gradient field of the corresponding wavefront.

The relevant information on the optical vortex is not readily accessible in the spot field measured. Removing tilt and defocus from the spot field allows the analysis of the helical gradient field and enables a comparison with simulation results (Figure 9).

An important quantity characterizing

an optical angular momentum beam is the topological charge l. It can be calculated from the measured gradient field by evaluating the following path integral $\oint \nabla \perp W \cdot \mathrm{d}\,\vec{r} = l \cdot \lambda$, where $\nabla \perp W$ denotes the gradient of the wavefront and the wavelength of the orbital angular momentum beam. Table 2 shows the topological charges resulting from the measurement of 15 different spiral phase plates, each comprising three subgroups with a topological charge of 1, 2 and 3, respectively. The deviation of $l_{measured}$ from l_{design} results from the discretization due to the limited number of sampling points.

In contrast to typical interferometers, SHWFSs can deal with spatially and temporally incoherent light. Besides standard applications where measurement conditions with large van Cittert-Zernike coherence areas are present, the authors demonstrated that the precise alignment of an asphere in front of a LED is possible in low coherence situations. SHWFSs can also measure a highly coherent optical vortex beam generated by a spiral phase plate. The phase discontinuities inherent in such beams prevent a direct reconstruction of the helical shape of the wavefront. But, when processed properly, the spot field analysis provides valuable information such as the topological charge calculated from the SHWFS measurement.

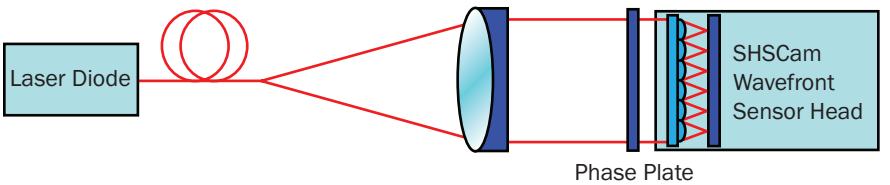


Figure 8. Experimental setup for helical wavefront measurements.

Table 2.

l_{design}	$l_{measured}$				
1	0.91	0.90	0.93	0.96	0.98
2	1.83	1.79	1.87	1.94	1.75
3	3.00	2.92	3.03	2.97	3.05

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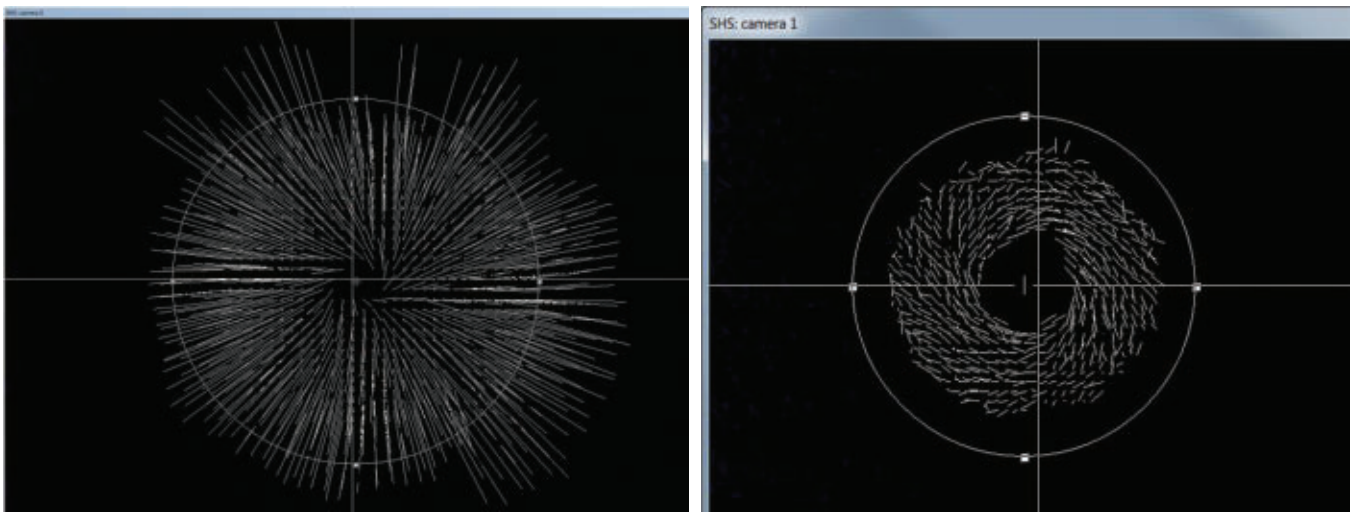

Figure 9. Measured spot displacements, **left**. Tilt and defocus subtracted from measurement. Enlarged spot displacement for visibility, **right**.

Acknowledgments

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References

1. J. Hartmann (1904). Objektivuntersuchungen, Zeitschrift für Instrumentenkunde, 1-21.
2. R.V. Shack and B.C. Platt. (1971). Production and use of lenticular Hartmann screen. *J Opt Soc Am*, Vol. 61.
3. J.W. Hardy. (1978). Active optics: A new technology for the control of light, *Proc IEEE*, Vol. 66, pp. 651-697.
4. M. Ritsch-Marte. (2015). Der Dreh mit dem Licht - Optische Spiralwellen und ihre Anwendungen, in *Physik Journal* 14, Nr.1, S.31.

Breakthroughs Bring **THz Spectroscopy, Sensing** Closer to Mainstream

Advances in terahertz optical frequency comb operations have helped make possible single-mode THz emission in a wide spectral range at high powers.

BY MANIJEH RAZEGHI, QUANYONG LU, SANTANU MANNA, DONGHAI WU AND STEVEN SLIVKEN, NORTHWESTERN UNIVERSITY

The terahertz (THz) electromagnetic spectrum (1 to 10 THz), sitting between the infrared wavelengths on the higher frequency side and microwaves on the lower frequency side, has unique and important properties. THz waves can pass through a number of materials, including synthetics, textiles, paper and cardboard. Many biomolecules, proteins, explosives or narcotics feature characteristic absorption lines — so-called spectral "fingerprints" — at frequencies between 1 and 10 THz. The two main advantages of THz radiation are the penetration of conventionally opaque materials and high chemical selectivity.

The major applications of THz radiation are imaging, sensing, spectroscopy and communication (Figure 1). Unlike x-rays, THz waves do not have any ionizing effects and are generally considered biologically innocuous. This makes THz waves much safer than x-rays when used for airport security and medical diagnosis.

Thanks to the rapid development of THz technologies in recent decades, there has been exponential growth in companies, products and research. In fact, BCC Research expects the market to reach $195.3 million by 2018. The diversification of the THz market is expected to accelerate after 2018, and the total market value should exceed $942 million by 2023[1].

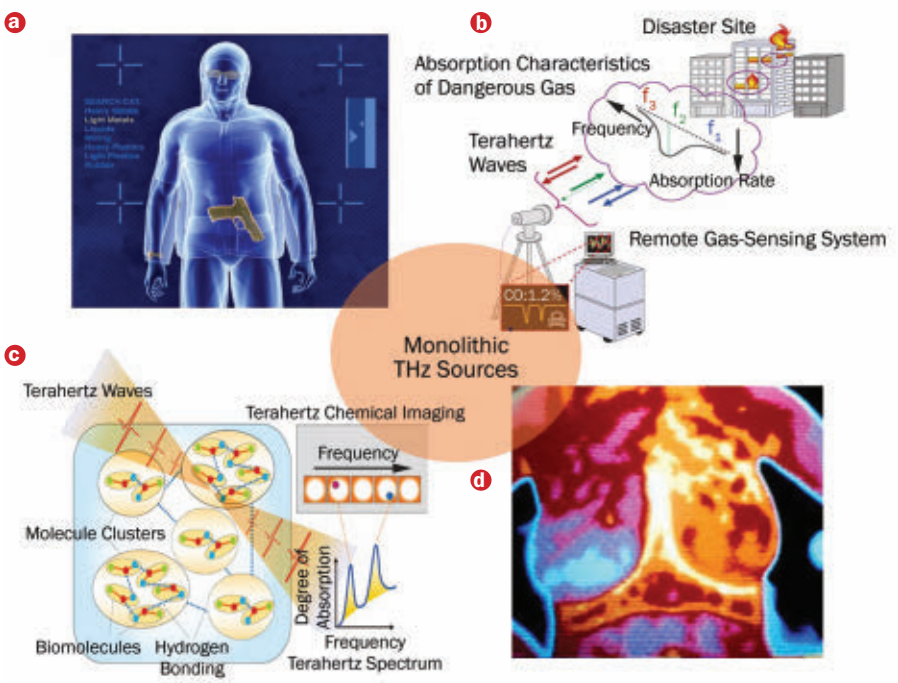

Figure 1. Applications of THz source technology.

Wanted: high-power, compact THz sources

All of the previously mentioned applications stand to benefit from a compact THz source with high average THz power output. For example, if 100 µW of power images 1 cm^2 in five minutes, then 100 mW would image 200 cm^2 in just one minute, a number that might make it valuable for large-scale security or medical screening. However, the options in high-power compact THz sources are limited. The electronic devices on the lower THz frequency side — frequencies lower than 1 THz — such as Schottky-diode based multipliers, Gunn diodes, resonant-tunneling diodes and impact ionization avalanche transit-time diodes, can deliver a room temperature THz signal with a compact device size[2]. However, these sources have limited frequency coverage, poor power efficiency and low output power levels at the super THz frequencies, which have a frequency greater than 2 THz. At these higher frequencies, THz quantum cascade lasers (QCLs) have emerged as the most powerful semiconductor THz sources. However, the working temperature is still below 200 K[3].

Images on this page courtesy of iStockphoto/Cornishman **(a)**; Shimizu, NTT-technical review 2009 **(b)**; K.Ajito, NTT-technical review 2009 **(c)**; Terahertz Imaging and Cancer. *Journal of Physics*: Conference Series, 2014, 486 012014 **(d)**.

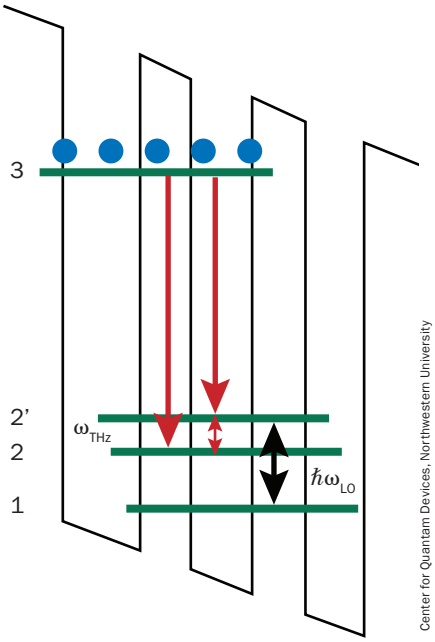

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Figure 2. The difference frequency generation (DFG) process between the electron states in a band structure of a quantum cascade laser.

Currently, difference frequency generation (DFG) in mid-IR QCLs, the intracavity nonlinear optical approach, has been able to deliver multi-mW THz power at room temperature[4]. When a QCL active region is designed with strong nonlinear coupling between the lower lasing levels and injector levels, the result is a large nonlinear susceptibility $\chi^{(2)}$, and THz emission can be generated within the cavity (Figure 2). When the lower level 2 is designed with a strong coupling with its neighboring level 2′, a large nonlinear susceptibility $\chi^{(2)}$ up to 10^4 pm/V will be created in the active region, which is more than two orders of magnitude higher than the nonlinear crystals.

With certain mode-selecting mechanisms, such as the composite distributed feedback grating[5], and certain phase-matching mechanisms, such as the modal or the Čerenkov phase-matching scheme with epi-down mounting[6], single mode THz emission in a wide spectral range can be generated. Therefore, this type of THz source inherits all of the advantages of the mid-IR QCLs, such as room temperature operation, electrical pumping and compact size, as well as the potential for high-power output and mass production.

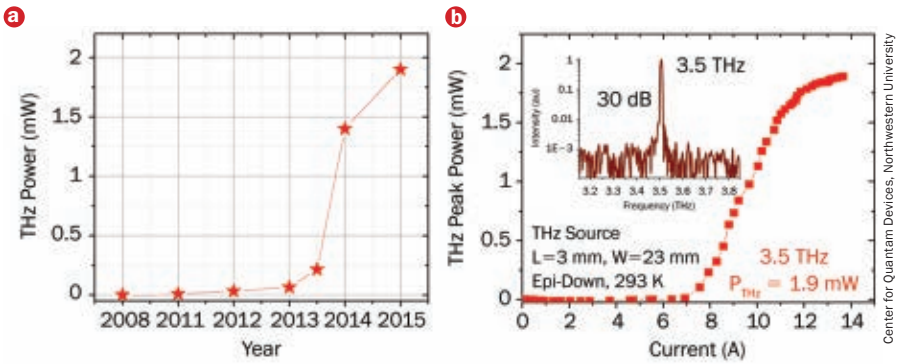

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Figure 3. Recently demonstrated THz power records of the THz sources based on DFG quantum cascade lasers (QCLs) at room temperature as a function of year **(a)**. THz power and spectra **(inset)** for a high power THz source based on DFG QCL **(b)**.

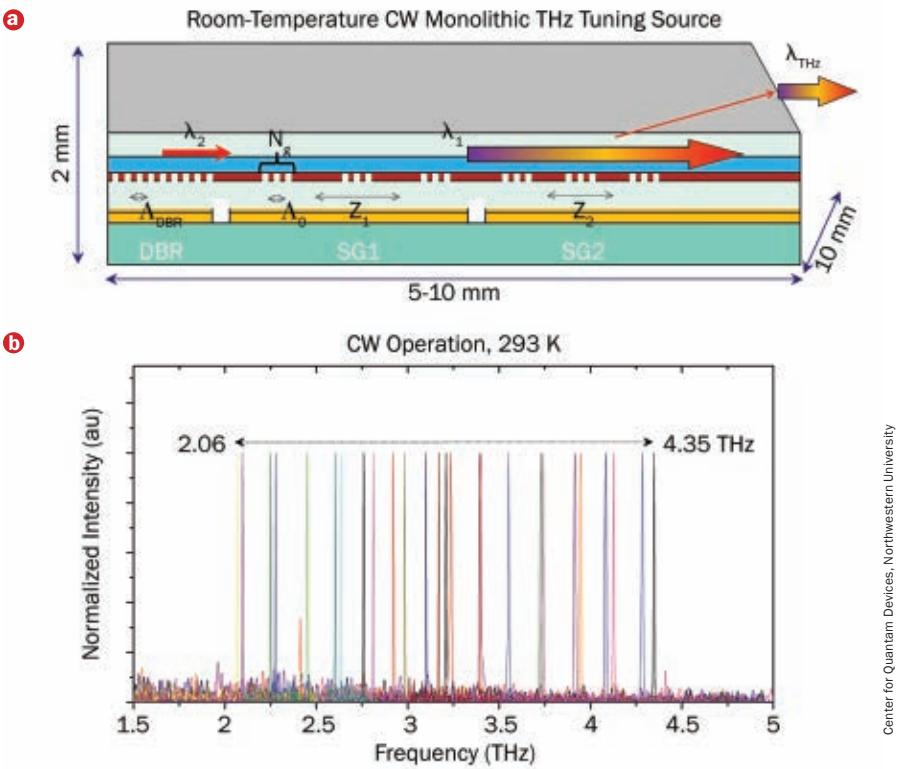

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Figure 4. A monolithically tunable THz source based on DFG QCL **(a)**. Tunable THz spectra at room temperature continuous wave operation **(b)**.

High-power QCL sources with wide frequency tuning

The past few years have seen the rapid development of room-temperature THz DFG QCL sources for higher power output, wider frequency tuning and continuous wave operation (Figure 3a). Currently, such devices can emit THz power up to 1.9 mW with a side mode suppression ratio of 30 decibel (dB) at 3.5 THz in pulsed mode operation (Figure 3b)[4]. In continuous wave operation, they can produce 0.014 mW, with a wide monolithic tuning frequency range of 2.06 to 4.35 THz at room temperature (Figure 4) by using a strain-balanced active region structure and sampled grating design[7,8].

Considering another 30 percent reflec-

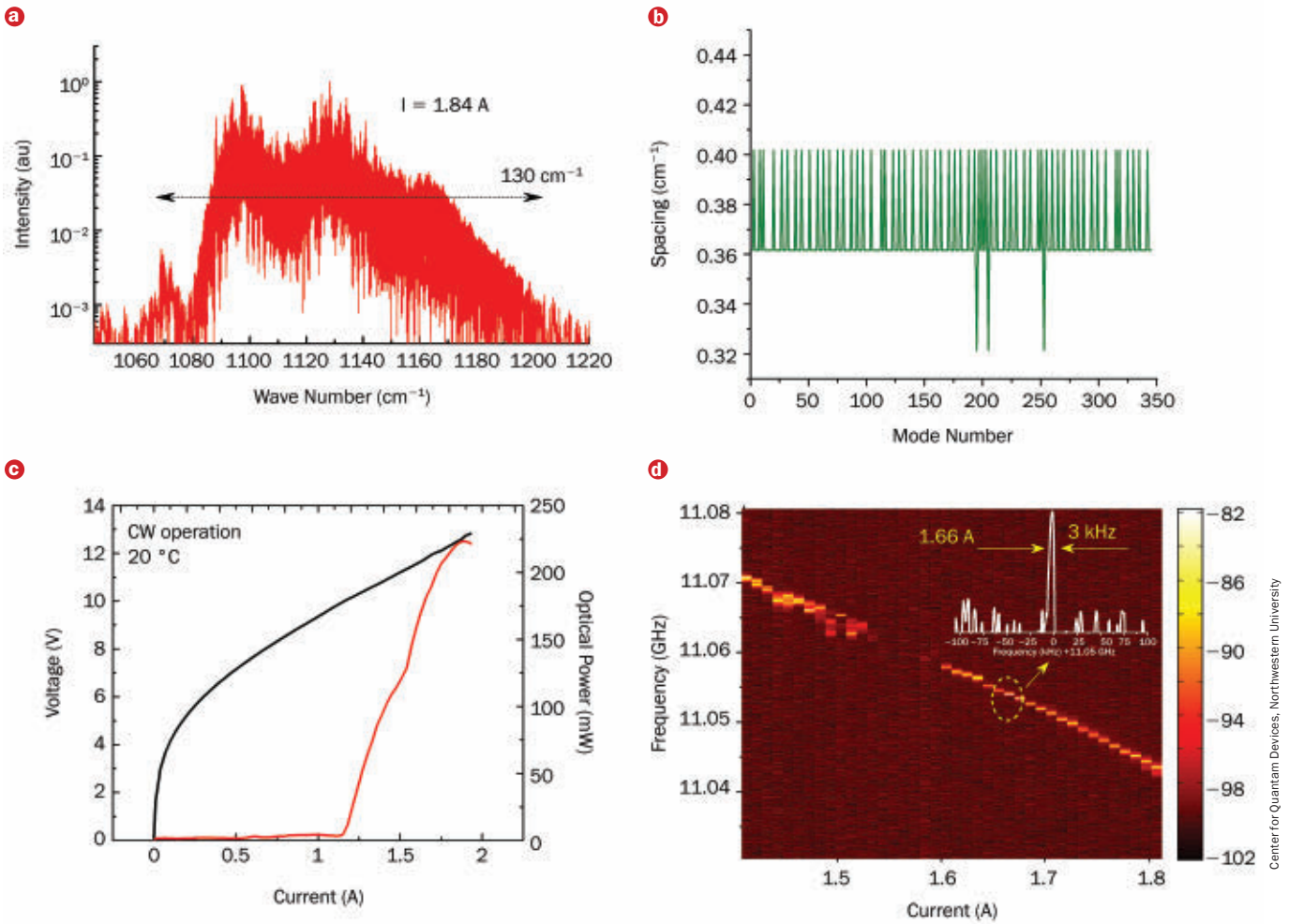

Figure 5. Lasing spectrum measured at a current of 1.84 A **(a)**. The adjacent mode spacing as a function of mode number **(b)**. P-I-V characterization of a 4-mm long Fabry-Perot QCL device in CW operation **(c)**. Intermode beatnote spectra at different current. (Inset) Intermode beatnote spectrum measured at a current of 1.66 A **(d)**.

tion of the THz emissions, the outcoupling efficiency of the emitted THz power with respect to the generated power is as low as 15 percent. Given the maximum recorded 1.9-mW output power, the total generated THz power in the device is estimated to be about 12 mW. Therefore, there is a great potential for THz power enhancement when an efficient THz outcoupler is applied to the THz waveguide. By enlarging the outcoupling aperture with a Si prism to allow for more THz light to be coupled out from the substrate or extracting the THz light from the entire cavity via diffraction grating, even higher THz power and efficiency in a wider spectral range in pulsed and CW modes can be obtained. This is of special importance to high THz frequency generation (>4.5 THz) where the phonon absorption in the semi-insulating InP substrate plays a leading role in the THz absorption prior to outcoupling. Currently, THz QCL sources with a diffraction grating outcoupler can produce THz surface emission with mW level power[9].

With further optimization to the diffraction grating design and fabrication, the THz outcoupling efficiency from the diffraction grating, much higher than that from the polished edge facet, has been recently demonstrated. Considering the fact that mid-IR QCLs operating up to 200 W have been demonstrated[10], by following a similar strategy, it may be possible to further enhance the THz power to tens of MW by scaling the device.

This revolutionary CW monolithic tunable THz source, which is also compact (packaging size of ~$10 \times 10 \times 2$ mm^3) and mass-producible, is becoming the ideal light source for emerging THz applications such as spectroscopy and sensing.

High-power QCL frequency comb sources

THz spectroscopy is a vital tool for detecting and quantifying many types of chemical molecules, and plays an important role in environmental monitoring, medical diagnosis, atmospheric chemistry and industrial quality control. Optical frequency combs have revolutionized metrology and spectroscopy with their extraordinary speed and precision. The evenly spaced modes in the frequency domain enable the frequency comb to act as a ruler and provide unprecedented precision and speed compared with other spectrometric techniques. Mode-locked femtosecond lasers have been used for the direct generation

of the mid-IR frequency comb; however, the wavelengths are mainly limited to 3 μm[11]. Deep in the mid-IR and THz wavelength range, QCL frequncy combs are the only monolithic solid-state optical comb sources[12,13]. As a QCL is engineered with a sufficiently low group velocity dispersion using a broadband heterogeneous active region design, the device can emit a frequency comb via four-wave mixing. Frequency comb operation was achieved from a free-running CW broadband QCL at λ~9.0 μm with a spectral range of 130 cm^{-1} and an output power of 220 mW for 350 modes (Figure 5a,c). All the lasing modes exhibit near identical frequency spacing of 0.38 cm^{-1} (11.04 GHz).

The intermode beatnote spectra were characterized with a high-speed quantum well infrared detector and the photoresponse was measured with a spectrum analyzer. A narrow intermode beating linewidth of 3 kHz (Figure 4d) was observed, which corresponds to a broad spectral coverage of 65 cm^{-1} and high CW power output of 180 mW for ~176 comb modes, nearly 1 mW power for most of the modes. The frequency comb power was recently enhanced up to 880 mW at λ~8.0 μm with a narrow intermode beatnote linewidth of only 50 Hz.

The demonstrated high-power frequency comb source is likely to find wide applications in chip-based spectroscopy and metrology. It also opens a way to THz optical frequency comb operation at room temperature based on intracavity DFG (down conversion) inside a mid-IR QCL.

Meet the authors

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References

1. BCC Research (July 2013). Terahertz radiation systems: Technologies and global markets (IAS029C).
2. H. Eisele and G. I. Haddad (1998). Two terminal millimeter-wave sources. *IEEE Trans Microwave Theory Tech*, Vol. 46, Issue 6, pp. 739–746.
3. S. Fathololoumi and E. Dupont, et al. (2012). Terahertz quantum cascade lasers operating up to ~200 K with optimized oscillator strength and improved injection tunnelling. *Opt Express*, Vol. 20, p. 3866.
4. M. Razeghi and Q. Y. Lu, et al. (2015). Quantum cascade lasers: from tool to product. *Opt Express*, Vol. 23, p. 8462.
5. Q. Y. Lu and N. Bandyopadhyay, et al. (2011). Room temperature single-mode terahertz sources based on intracavity difference-frequency generation in quantum cascade lasers. *Appl Phys Lett*, Vol. 99, 131106.
6. Q. Y. Lu and N. Bandyopadhyay, et al. (2013). Room temperature terahertz quantum cascade laser sources with 215 μW output power through epilayer-down mounting. *Appl Phys Lett*, Vol. 103, 011101.
7. Q. Y. Lu and N. Bandyopadhyay, et al. (2014). Continuous operation of a monolithic semiconductor terahertz source at room temperature. *Appl Phys Lett*, Vol. 104, 221105.
8. Q. Y. Lu and D. H. Wu, et al. (2016). Room temperature continuous wave, monolithic tunable THz sources based on highly efficient mid-infrared quantum cascade lasers. *Sci Reports*, Vol. 6, 23595.
9. M. Razeghi and Q. Y. Lu, et al. (2015). Recent development of high power, widely tunable THz quantum cascade laser sources based on difference-frequency generation. *Proc of SPIE*, Vol. 9585, 958502-1.
10. D. Heydari and Y. Bai, et al. (2015). High brightness angled cavity quantum cascade lasers. *Appl Phys Lett*, Vol. 106, 091105.
11. A. Schliesser and N. Picqué, et al. (2002). Mid-infrared frequency combs. *Nature Photon*, Vol. 6, p. 449.
12. A. Hugi and G. Villares, et al. (2012). Mid-infrared frequency comb based on a quantum cascade laser. *Nature*, Vol. 492, Issue 229.
13. Q. Y. Lu and M. Razeghi, et al. (2015). High power frequency comb based on mid-infrared quantum cascade laser at λ~ 9 μm. *Appl Phys Lett*, Vol. 106, 051105.

Photonics West 2017
Presents Largest Comprehensive Expos

SPIE Photonics West 2017 (Jan. 28 to Feb. 2, San Francisco), the largest exhibition and conference in the photonics industry, showcases the most innovative research, products and ideas in the field.

For many in the industry, the year truly begins with Photonics West. A symbol of the optimism and excitement for the potential of photonics and light-based technologies, the annual exhibition and conference highlights innovation in research, technology and more, through product demonstrations, courses and workshops, symposia and plenary talks.

"SPIE Photonics West … is the must-attend gathering place for the companies that are pushing the research into application areas and launching innovative products and services," said Marilyn Gorsuch, director of the show's technical programs.

Exhibitions

More than 1,300 companies are geared up to showcase their latest products, tools and applications in all fields. The general Photonics West Expo (Jan. 31 through Feb. 2) offers attendees face-to-face access to the world's top suppliers, hiring companies and business sessions. There will be 19 regional cluster and pavilion displays, including newcomer Regione Toscana. Nearly 250 new product launches will complement daily product demonstrations in various technologies and applications ranging from fiber optic components and systems to optical detectors, IR sources and detectors, and metrology.

Specifically and notably, some of the new products slated for reveal are:

- 4D InSpec for high-resolution surface defect measurement in shop floor environments, from **4D Technology Corp.**
- Yuja, an ultra-compact femtosecond laser for industrial microdrilling and microcutting, developed by **Amplitude Systèmes**.
- High-precision PMMA direct-cut lenses for trial production (Ra >10 nm), by **Circle and Square Co. Ltd.**
- The WERLLICHT PRO 3D laser projector, from **Extend3D GmbH**.
- **Hamamatsu Corp.**'s near-IR-enhanced photodetectors for automotive lidar.
- **Headwall Photonics**' VNIR-SWIR hyperspectral sensor for the 380- to 2500-nm range, suitable for small UAV deployment.
- Next-generation F-Theta Lens and Beam Expander for future technological requirements, developed by **Jenoptik Optical Systems**.
- **Optec spa**'s first-ever truly metric zoom lens for the short-wave IR range.
- USB3.0 SWIR 1024-pixel OEM linescan camera for spectroscopy and machine vision applications, from **Princeton Infrared Technologies Inc.**

"The R&D community knows Photonics West is the place to hear the newest breakthroughs and share ideas spanning engineering, physics, chemistry, biology, medicine and business growth," said Peter Hallett, director of Marketing and Industry Relations at SPIE.

Startup Challenge

Aspiring entrepreneurs and development-stage companies that have created new photonics products are the focus of the annual Startup Challenge. Organized and hosted by SPIE, and featured on the Expo floor, this annual competition is an opportunity for new photonics entrepreneurs to pitch their light-based technology product ideas to a team of business development experts and venture capitalists, and garner feedback while making new connections.

"Part of the value of the competition is that it teaches entrepreneurs about the differences in priority placed on commercialization as compared to academic research," said Adam Wax, a professor at Duke University who has served as a judge and mentor for the Startup Challenge. "This understanding is essential for connection with venture capitalists."

Cash prizes awarded — $10,000 for first place, $5,000 for second and $2,500 for third — are funded by founding partner Jenoptik. Trumpf, Open Photonics and Edmund Optics also contribute to the awards, providing the first-place winner with $5,000 in products. The U.S. National Science Foundation is a supporting sponsor of the competition, as well.

Twenty semifinalists each receive feedback from photonics industry leaders on their business model, a networking lunch with mentors and investors, and product demonstration time on the floor of the Photonics West Exhibition.

"While the money is important — to a startup, every dollar counts — one of the most important benefits is the mentoring, coaching and advice you get," said 2016 Startup Challenge winner Leslie Kimerling of Double Helix Optics. "Probably most important is the networking and the community that you continue to build."

Robert McLaughlin, of the University of Western Australia, the 2014 winner, agrees, noting that feedback from judges who "have been there, have done that" is very valuable.

"Especially as an engineer, there is a whole world of complexity in going from technical problems to commercialization," he said. "They taught me an awful lot about how I get from an idea to actually turning it into a company where I can get it out into the world and make a difference."

SPIE BiOS (Jan. 28-29)

The world's largest biophotonics, biomedical optics and imaging conference, held at Photonics West, includes more

Images courtesy of Doug Cody/SPIE.

Visitors talk with company representatives on opening day of the Photonics West 2016 Exhibition.

than 200 companies that will present daily product demonstrations and new technologies. Among them:

- **Biomedical optics components, products, instrumentation and applications**
- **Lasers**
- **Molecular imaging**
- **Therapeutic lasers**
- **Nano/biophotonics**
- **Biosensors**
- **Spectroscopic/microscopic imaging**

Forty-five conferences are held within BiOS, including the new "Visualizing and Quantifying Drug Distribution in Tissue." Symposium chairs are distinguished industry veterans James Fujimoto, a professor of electrical engineering and computer science at the Massachusetts Institute of Technology, and Dr. Rox Anderson, a professor at the Wellman Center for Photomedicine at Massachusetts General Hospital and Harvard School of Medicine.

The technical program heightens the BiOS exhibition as the largest symposium under the Photonics West umbrella. Scheduled are 2,300 technical presentations in tracks on photonic therapeutics and diagnostics, neurophotonics, neurosurgery, optogenetics, clinical technologies and systems, tissue optics, laser-tissue interaction, tissue engineering, biomedical spectroscopy, microscopy and imaging, nano/biophotonics, and brain research.

The Translational Research Applications track features the latest photonics technologies, tools and techniques that present high potential to impact health care, while the new Brain Applications track will focus on innovative technologies that will increase understanding of brain function.

BiOS Hot Topics

Featured sessions within BiOS will begin with the annual Hot Topics program. Some of the top industry researchers and scientists will present, including Christopher Contag — founding director of the Institute for Quantitative Health Science and Engineering at Michigan State University and inaugural chair of the Biomedical Engineering Department at Stanford University — who will

present "In Vivo Optical Imaging Using Bioluminescent Reporters." Earning the 2017 Britton Chance Biomedical Optics Award that will be presented at Photonics West, Contag will share his extensive expertise in the way biology in living tissue is studied. His work in this area has been noted by the awards committee as "the most significant advances in biomedical research in recent history."

Robert R. Alfano, a professor at the City College of New York and pioneer in ultrafast optical science and engineering, will also present during the BiOS Hot Topics, focusing on advances in non-invasive optical biopsy. Other Hot Topics presenters include Emilia Entcheva, a professor at George Washington University, discussing cardiac optogenetics; Dr. Richard Levenson, professor and vice chair of strategic technologies in the Department of Pathology and Laboratory Medicine at the University of California, Davis, Medical Center, featuring UV surface excitation for slide-free tissue microscopy; Lev Perelman, director of the Center for Advanced Biomedical Imaging and Photonics at Harvard University's Beth Israel Deaconess Medical Center, presenting on biomedical imaging and spectroscopy with scattered light; Zhongping Chen, a professor of biomedical, electrical and chemical engineering, and computer and materials sciences in the Samueli School of Engineering at the University of California, Irvine, focusing on frontiers in functional optical coherence tomography; Hideaki Koizumi, of Hitachi Ltd., sharing his knowledge of diffuse optics; Alberto Diaspro, director of the Istituto Italiano di Tecnologia's Department of Nanophysics and a professor of applied physics at the University of Genova, focusing on nonlinear microscopy; and Enrico Gratton, professor of biomedical engineering and physics at the University of California, Irvine, is discussing fluorescence spectroscopy and microscopy in imaging live cells.

Plenary presentations will round out the BiOS expo. The session on nano/biophotonics will feature Michael Sailor, a professor of chemistry and biochemistry at the University of California, San Diego, speaking on porous silicon nanoparticles as self-reporting drug delivery vehicles.

The neurotechnologies plenary will showcase a number of industry experts:

- **Robert Campbell**, University of Alberta: Genetically encoded indicators of neuronal activity.
- **Francesco Pavone**, Università degli Studi di Firenze: Optical detection of spatial-temporal correlations in whole-brain activity.
- **Valentina Emiliani**, Université Paris Descartes: Two-photon optogenetics with millisecond temporal precision and cellular resolution.
- **Peter So**, Massachusetts Institute of Technology: A strategy for monitoring synaptic activity across the full dendritic arbor.
- **Chris Xu**, Cornell University: 3-photon microscopy for deep brain imaging.
- **Shaoqun Zeng**, Wuhan National Lab for Optoelectronics: Chemical sectioning — high-throughput ex-vivo brain imaging.
- **Adam Bauer**, Washington University School of Medicine in St. Louis: Mapping functional connections in the mouse brain — insight to understanding and treating disease.

- **Maria Angela Franceschini**, Athinoula A. Martinos Center for Biomedical Imaging: Clinical neuro-monitoring with NIRS-DCS.
- **Rafael Yuste**, Columbia University: The novel neurotechnologies — impact in science, medicine and society.
- **Edmund Talley**, National Institutes of Health: NIH funding report.

Symposiums, workshops, courses

"New this year we have free workshops on specifying lasers and detectors, applications of 3D printing, optical design software and entrepreneurship, so technical professionals can continue learning and innovating," Hallett said. "Wise people will use their training budget to attend one of 70 courses spanning laser systems engineering, silicon photonics, OCT and virtual reality taught by the people who invented the technology. Add the ability to discuss product requirements face-to-face with any of the 1,300 exhibitors and Photonics West becomes so valuable professionally that for many people, it is the most important event of the year."

Winners and judges show some of the prizes awarded in the 2016 SPIE Startup Challenge.

LASE (the industrial laser, laser source, and laser application conference) will offer plenary presentations in areas such as gravitational wave astronomy, micro 3D structures, extreme ultraviolet lithography, and innovative ways to apply multidimensional, multidisciplinary 3D technology. In addition, 16 conferences within LASE provide more opportunity to showcase industry expertise.

There are 34 conferences scheduled within OPTO (the optoelectronics, photonics materials, and devices conference), as well as plenary talks, including "Non-reciprocal Photonic Gauge Potential and Non-equilibrium Thermal Metaphotonics for the Control of Light and Heat," "Quantum-Dot-Based Photonics: Fundamental Advantages and Applications for Energy-Efficient and Secure Information Systems," and "LiFi: Transforming Fiber Into Wireless."

For more information about Photonics West 2017, visit www.spie.org.

justine.murphy@photonics.com

PROFILE

Manufacturer of new generation of optical components – diffractive waveplates – utilizing geometrical phase modulation to make nearly 100% efficient micrometer thin film coatings acting as lenses, prisms, spiral phase plates, arrays, beam shapers, etc.

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20 Years of Solving Extraordinary Problems in Optics

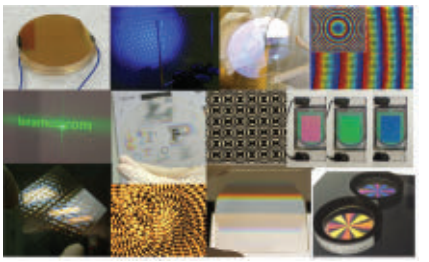
BEAM Engineering for Advanced Measurements Corporation was founded in 1996 for developing and commercializing unique liquid crystal photonics devices.

BEAM's Crystal-Scan Optical Multimeter won the Photonics Circle of Excellence Award in 2001.

BEAM has 17,000-sq.-ft. facilities and a world-class staff including 14 outstanding researchers and engineers with Ph.D. degrees.

The Fourth Generation (4G) optics developed by BEAM are coatings capable of performing the same functions as lenses, prisms, spiral phase plates, and axicons.

BEAM's 4G optics are enabling breakthroughs in numerous fields: ultralight large lenses and mirrors and high contrast coronagraphs for astronomy, all-electronic beam steering and variable divergence beam control systems, switchable beam shapers, tunable spectral filters, shutters, and attenuators, adaptive ophthalmic optics, high power laser components, imaging optics, solar energy concentrators, etc.



BEAM is a pioneering leader of the 4G optics technology, and is vertically integrated to complete the cycle from chemical synthesis to optical systems.

BEAM

PROFILE

Manufacturer of a diverse range of high precision optical components and systems for imaging and laser-based applications.

BMV Optical Technologies Inc.
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www.bmvoptical.com

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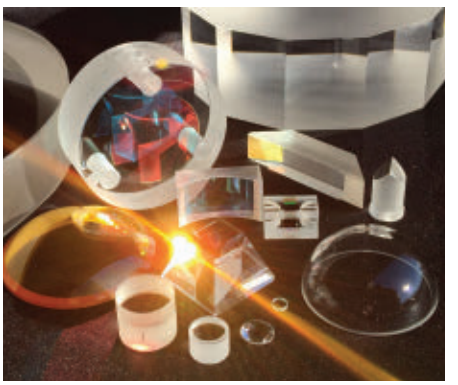
Custom Optics – Prototype to Volume Manufacturing – Rapid Turnaround

Established in 2001, BMV is a manufacturer of precision optical components and systems for R & D, Military, Medical, Aerospace, Telecom and Industrial applications. A complete solution provider, BMV also provides complete optical, thin film and mechanical design complemented with complete in house Opto-electronic assembly, metrology and machine shop. Manufacturing from prototype to volume quantities, our products include: spherical/cylindrical lenses and lens systems, graded reflectivity mirrors, ultra-precision flats, etalons, sapphire optics, laser windows, wedges, beam splitters, polished metal optics, precision glass machining, etc. Thin-film coatings for the UV, VIS and IR include: anti-reflection; single/dual wavelength and broadband, high reflectors; all dielectric or metallic, beam splitting, high pass/low pass filters, beam combining and laser output couplers. BMV's continued success is based on commitment to Excellent Quality, Quick Turnaround and Unsurpassed Customer Service.



BMV is ISO 9001:2008 certified and registered under the Controlled Goods Program.

BMVOPTICAL TECHNOLOGIES

PCO – Leading Manufacturer of sCMOS, CMOS & CCD Camera Systems

Excellence in development, production, sales & support

PCO cameras combine the best characteristics of high quality cameras and scientific measuring instruments. For nearly three decades our highly trained specialized team members have developed and handcrafted PCO cameras. Excellent performance and reliability are guaranteed by using sophisticated technologies in design, high production standards and strict quality controls. PCO-owned subsidiaries in America, Europe (headquarters) and Asia provide a strong support network for our customers worldwide. Our factory-owned distribution channels ensure that PCO cameras are developed and supported in a manner that meets our customer applications with customer input having a direct path back to our product development and support teams.

Pioneer of sCMOS sensor technology

PCO is one of the three inventors and developers of the sCMOS sensor. The pco.edge sCMOS camera family has been a breakthrough in scientific imaging ever since its introduction to the market. The value of the cameras is justified by their distinctive ability to simultaneously deliver lowest noise levels, fast frame rates, wide dynamic range, high quantum efficiency and a large field of view – all in one image.

PRODUCT RANGE

sCMOS cameras – pco.edge family

PCO's scientific CMOS camera systems provide up to 82% quantum efficiency, 16 bit dynamic range and up to 5.5 MPixel with special microscopy readout modes combined in a light and compact camera body. All pco.edge cameras are available with a variety of interface options, Camera Link HS interface being the latest and fastest addition. It enables ultra-fast data transmission up to 1.1 GByte/s and is the perfect complement to the high data rates of the pco.edge family.

High-speed cameras – pco.dimax family

PCO's high-speed cameras offer resolutions up to 4 MPixel at maximum frame rates, best light sensitivity and real 12 bit dynamic range with leading image and color quality. All models come with a variety of trigger options and can be easily synchronized between each other.

Luminescence decay time microscopy camera – pco.flim

The pco.flim camera system is the first luminescence decay time microscopy camera using a two tap CMOS image sensor. Synchronized modulation of pixels and stimulated light enables the analysis of decay times in the range of 100 ps to 100 µs. A broad variety of trigger options allows the camera's integration in versatile fields of applications.

Intensified cameras

PCO offers high resolution MCP (multichannel plate) image intensifier camera systems and also develops customer specific solutions (OEM) such as camera systems for industrial applications where high dynamics, extreme offset stability or other special features are relevant issues.

Specialized cameras

PCO carries a large selection of different scientific and industrial CCD cameras with interline transfer CCD image sensor technology. The camera systems have dynamics in the range of 12 to 14 bit and are designed for thermo-electrical cooling for extra-long exposure performance, visible NIR and UV light detection or further specified fields of application.

Commitment to excellence

Founded in 1987, PCO has three decades of technical know-how and expert knowledge in the development of high performing camera systems. In-house competence of all significant technical disciplines and partnering with leading image sensors manufacturers ensures cutting edge sCMOS, CMOS and CCD technology for all PCO cameras. Constant advancement of hardware and software not only guarantee profound innovational strength but also enables powerful competitive capacity. Headquarters in Kelheim (Germany) with a worldwide network of trained sales partners, PCO also operates subsidiaries in America and Asia to support its customers and meet their individual needs throughout the global market.

pco.

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Admesy: Colour and Light Measurement for R&D and Production

PROFILE

Founded in 2006, Admesy provides our customers with innovative Test & Measurement solutions tailored for color and light measurement in production processes. Our products are innovative, compact, fast, user-friendly and robust.

info@admesy.com
www.admesy.com

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Admesy offers a broad range of test and measurement instruments focused on colour and light measurements for R&D and inline production process environments.

All products are developed and produced in-house based on a long history of inline testing. Admesy measurement devices are developed for R&D and industrial use and combine high speed accurate measurements with a robust device and low maintenance needs. Our product range includes spectrometers, colorimeters, light meters, 2D spectral vision systems and numerous accessories.

Our wide product range offers solutions for various measurement questions in display, lighting, analysis and OEM integration ranging from optical characteristics such as brightness, spectral power distribution, whitepoint adjustment and colour and flicker behaviour to OEm integration of spectrometers for analysis purposes.

Admesy was founded in 2006 in the Netherlands and has quickly grown into an international company serving customers all over the world from its headquarters near Maastricht, The Netherlands. Besides our office in the Netherlands we have a support office near Seoul in South Korea and near Shengzhen in China allowing us to quickly assist and support our numerous Asian customers.

admesy
ADVANCED MEASUREMENT SYSTEMS

1 Dispensing Components

Intertronics' QuantX range of premium dispensing components delivers dispense quality, efficiency and economy, providing optimized yields and minimum material waste. The syringe barrel range covers all commonly used sizes, including amber and black variants, for protection of light-sensitive materials. They are manufactured from premium-grade polypropylene under stringent conditions to ensure minimal resistance and parallel uniformity for accuracy and repeatability when dispensing dots, lines or doses. Barrels feature an industry-standard Luer lock fitting.
info@intertronics.co.uk

2 Duplex Carts

MV Products has released a new line of high-capacity, dual-vacuum inlet traps mounted on carts for large substrate vacuum deposition processes used in manufacturing thin-film transistor LCDs, organic LEDs, solar cells and crystal-growing. MV MultiTrap Duplex Carts feature two 16-in., high-capacity vacuum inlet traps supplied with a broad selection of filter cartridges to meet specific customer requirements for high flow vacuum deposition processes. They provide up to 160 sq ft of filtration surface area, 60 grams per sq ft of particle retention, and permit easy access to process components for maintenance. The carts can be equipped with internally cooled baffles with up to 30 sq ft of cooling surface area. Each MultiTrap unit can be mounted vertically or horizontally and can be supplied with NW-40 to ISO-160 ports.
www.massvac.com

3 Front Haul Test Solution

Anritsu Co. has announced the Network Master Pro MT1000A front haul test solution with common public radio interface (CPRI) radio frequency (RF) module. The Network Master Pro MT1000A with CPRI RF module has a fast sweep speed, allowing it to conduct measurements up to 10× faster than comparable handheld test solutions. Users can capture all interfering signals including intermittent interferers missed by current alternatives. Incorporating a spectrum/spectrogram tune and zoom feature, the device allows users to zoom in on an area of interest to provide more detailed information for better identification of an interfering signal's origin.
www.anritsu.com

4 Aspheric Lenses

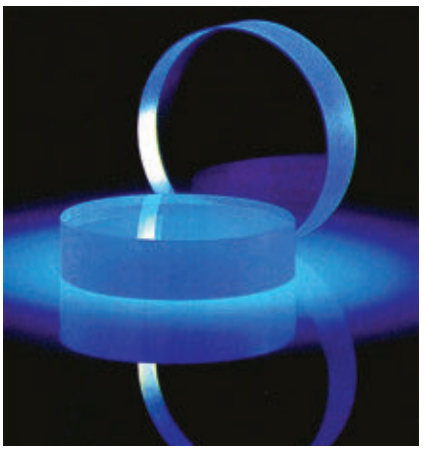
The TECHSPEC Precision Aspheric Lenses from **Edmund Optics Inc.**, designed to focus light while eliminating spherical aberration from divergent light sources, have been computer optimized. The lenses decrease laser spot size and maintain high power per area. Aspheric lenses can increase the numerical aperture of a lens and may also reduce the number of elements needed in a multi-element system, potentially reducing overall system weight, increasing throughput and simplifying assembly. Featuring low f/numbers for optimal light-gathering performance, the lenses offer available prescription data for easy integration into a wide range of optical systems. The lenses are available uncoated or with a VIS coating, which provides less than 1.5 percent reflection from 425 to 675 nm, and a NIR coating, providing <1.5 percent reflection from 600 to 1050 nm.
www.edmundoptics.com

5 USB Fiber Extender

Phrontier Technologies LLC has announced a stand-alone USB 3.0 fiber extender to its PHORCE family of devices. The new model features a sleek, compact gold housing that directly connects to USB applications with no drivers or additional programming required. It extends USB over the user's choice of single mode, multimode or coarse wavelength division multiplexing fiber up to 300 m. The stand-alone PHORCE consists of a PC module that connects to any USB 3.0 port on a host and a separate remote module that connects to devices such as a camera, control panel or external hard drive. The model provides 5 GB/s of transmission bandwidth and a power consumption of approximately 2W, excluding USB bus-powered devices.
info@phrontier-tech.com

6 Entertainment Lasers

Coherent Inc.'s Genesis Taipan HD lasers, an expanded series of light show and entertainment lasers, enable show designers to produce sophisticated visual displays and effects with increased brightness and better definition. The devices offer TE00 output beam characteristics and are available with powers between 2 and 5 W at six standard Taipan wavelengths of 460, 480, 488, 532, 577 and 590 nm.
www.coherent.com



Etalon Plates

Optical Surfaces Ltd. has announced precision etalon plates for use in Fabry-Perot interferometers. Etalons are available in air-spaced or solid forms. Designed for use at customer-defined wavelengths within the range of 190 nm to about 2 µm, the etalons are supplied with wedge angles of 5 minutes of arc for smaller diameters, rising in steps to a wedge angle of 40 minutes of arc for diameters greater than 70 mm. The plates are available as standard with UV-grade silica and germanium.
www.optisurf.com

Board Probes

Oxford Instruments Asylum Research Inc. has released SurfRider Econo Board Probes for routine atomic force microscope (AFM) measurements. The budget-priced probes can be used by all AFM users and are available in eight different models covering resonance frequencies from 13 to 300 kHz. They come in PtIr-coated and noncoated models. The SurfRider Econo Board Probes are ideal for all AFM brands, models and modes, including nanoelectrical and nanomechanical characterization modes, tapping mode, force modulation and contact mode.
sales@asylumresearch.com

Benchtop Goniometer

SphereOptics GmbH's new benchtop goniometer, with the capability to fit into almost every optical laboratory, provides measurement data on a concise level. The detector head of the goniometer is a high-quality, visible-range spectrometer equipped with diffuser optics to collect all-important measurement quantities over the required angular range. Data such as luminous intensity distribution, peak intensity, cone illuminance, beam angle, color data, spectral power distribution and total luminous flux is provided in a customizable report. In addition to the source output data, ambient temperature during the measurement is reported, as well as source-specific data such as power, power factor,

lumen/W or the orientation of the source during measurement, burn-in and stabilization time.
info@sphereoptics.de

VCSEL Driver

Macom Technology Solutions Inc. has announced the MALD-37345 quad 28-G VCSEL driver with input equalizer and the MATA-37344 quad 28-G transimpedance amplifiers. The solutions are targeted for short-reach, VCSEL-based 1000-Gbps onboard optics, as well as optical modules and active optical cable applications. The new chipset eliminates the need for clock data recovery with backward pin compatibility with the MALD-37045 and MATA-37044 devices, giving customers the ability to mix and match parts. The VCSEL driver of the MALD-37345 includes programmable eye-shaping features and an input equalizer. The high-sensitivity transimpedance amplifier of the MATA-37344 features selectable bandwidth to

support up to 28.05 Gbps and lower speed legacy data rates, as well as an output driver with programmable output swing and 2-tap de-emphasis. Both devices are available in 2 × 3-mm die form, supplied in waffle packs, whole wafers or quartered wafers.
marketing@macom.com

LWIR Imager

Flir Systems Inc. has announced the Lepton longwave infrared imager, a device that is 10 times less expensive than traditional thermal cameras. With a resolution of 80 × 60 active pixels in a camera core smaller than a dime, Lepton brings thermal imaging to a new generation of electronic devices for work, play and mission-critical applications.
www.flir.com

VCSEL Chip

The V50-850M and V100-850M vertical-cavity surface-emitting laser (VCSEL) fiber-coupled modules from **VI Systems GmbH** obtains a data rate of up to 108 Gbps over above 100 m. The data rate was demonstrated using pulsed amplitude modulation (PAM) with four or eight levels. A discrete multitone modulation can be applied to the device for data transmission of 112 Gbps over 100 m of multimode fiber. With duo binary 4-PAM modulation technology, a maximum data rate of 160 or 150 Gbps over 100 m of multimode fiber using multimode VCSELs has been demonstrated.
www.v-i-systems.com

Camera Lenses

Sigma Corp. of America has released its Sport Global Vision lenses with the 85-mm F1.4 DG HSM Art, a portrait lens; the 12- to 24-mm F4 DG HSM Art, an ultrawide angle zoom lens meant for high-resolution digital cameras; and the 500-mm F4 DG OS HSM, a sport lens featuring a fast aperture for prime super telephoto. The lenses can be updated with the latest lens firmware from a workstation or

laptop using the Sigma Optimization Pro software and Sigma USB Dock.
www.sigmaphoto.com

Frequency Divider

Valon Technology LLC has announced the Valon 3010 Programmable Frequency Divider. The device accepts a wide range of input frequencies and provides three independent, user-selectable, divided outputs. The 3010 is useful for extending the low-frequency range of any signal source down to 5 MHz as a 50 Ω output or down to 0 Hz as a transistor-transistor logic (TTL) output. The 16 available output division ratios are set by the user with hardware jumpers. Division ratios of 1 to 10, 12, 15, 16, 18, 24, 30 and 32 are available. The divide-by-one setting is useful for buffering and squaring a low-level radio frequency signal. The two 50 Ω outputs and the TTL output can be independently programmed to any of the divider ratios. The third divider output also drives a cascade of four divide-by-two stages, providing an additional

new products

divide by 2, 4, 8 and 16, with an overall maximum divide by 512. The divider is suited for frequency synthesis, clock division, clock distribution in electro-optical, molecular spectroscopy, particle physics and general lab use.
sales@valontechnology.com

Optical Transport Network Solution

PacketLight Networks Ltd.'s fully integrated PL-2000AD optical transport network solution equips enterprises and carriers with extended point-to-point Layer-1 encryption capabilities across metro and long-haul routes. The device protects in-transit data at the physical layer, where lesser known but dangerous breaches are increasingly seen. The PL-2000AD encryption can interconnect with any layer-2/3 switches or to existing DWDM infrastructure. It supports protocols such as Ethernet, Fiber Channel, SONET/SDH and OTN that are ideal for data centers and carrier networks.
www.packetlight.com

Underground Cable Terminal

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

Amplifier Detectors

Newport Corp. has released the LIAD series of Lock-In Amplifier Detectors for calibrated power measurement low-level light sources. The detectors

use a pyroelectric or photodiode sensor in combination with a built-in lock-in amplifier to reduce noise and drift. They are capable of measuring power down to 300 fW for pulsed light sources with frequencies of 200 Hz or higher. All LIAD Series Lock-in Amplifier Detectors include an 18-Hz chopper that must be placed close to the signal source. The sensor detects the chopped signal only, suppressing all signals not at 18 Hz. The LIAD series features the photodiode-based model LIAD-PD-300N, which covers wavelengths between 200 and 1100 nm, as well as the pyroelectric detector-based LIAD-PY-100M, covering the range between 0.15 and 12 µm. Both models are compatible with Newport 843-R Series, 1919-R and 841-PE- USB power meters.
www.newport.com

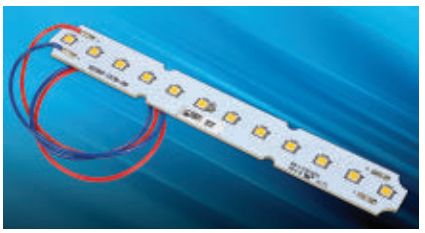
Diamond-Turned Optics

For a wide range of precision applications, Diamond Turned Optics from **Rocky Mountain Instrument Co.** features three-axis turning. The equipment can generate spherical, aspherical, cylindrical, acylindrical, off-axis parabolic, hyperbolic, conical, toroidal and lens array surface figures with superior accuracy. The diamond-turned optics can be manufactured from a wide range of metal and infrared substrates including silicon, germanium, zinc selenide, zinc sulfide, chalcogenide, amtir, copper, aluminum, brass and more. The diamond-turning capabilities have a tight form accuracy of <20 nm, high surface figure quality and capacity for sizes up to 350 mm in diameter.
www.rmico.com

Vibration Isolators

The MicroDamp series of vibration isolators from **Herzan LLC** offers an affordable and efficient means of vibration isolation tailored to the weight of any instrument. The devices utilize a damped composite material at their core with an aluminum casing to create an economical solution for applications not requiring low-frequency vibration isolation. They often utilize three to four isolators within a vibration isolation platform, depending on the supported instrument's dimension profile and

overall weight distribution. The isolators can be easily configured to individual instrument weights and weight distribution profiles, offering a widely applicable solution for instruments between 8 and 3,600 lbs. With no air or electricity required, the MicroDamp Series is an easy-to-install, maintenance-free solution that can be designed into a variety of instrument configurations.
www.herzan.com



Linear Light Engine Modules

Thomas Research Products has announced a series of linear light engine modules designed for OEMs. The 5.5-in modules are optimized for use in conjunction with the company's existing linear 11- and 22-in. engines for a greater variety of applications. They can also be utilized individually for small luminaires. The linear light engines are engineered for troffer applications, whether retrofit or new manufacturing. The light engines provide color temperature options from 2700 to 5000 K, with 83 CRI or better. They offer high lumen output using standard 350- or 700-mA LED drivers.
info@trpssl.com

Laser Marking System

The LaserTowerPRO RT from **Laser Photonics**, a laser marking system for high-volume applications, supports continuous laser marking applications with a dedicated operator. A 24-in. rotary dial table is positioned with half the table located inside the processing chamber and the other half outside the processing chamber. While a batch of units are under laser processing, the operator unloads/loads the next batch allowing for continuous volume production. The LaserTowerPRO RT is an industrial-grade system designed to operate under high-vibration, shock and dust conditions with a mean time between failures of >50,000 hours. The device requires no consumables.
www.laserphotonics.com

Piezo Scanner

The P-616 NanoCube XYZ piezo scanner from **Physik Instrumente LP**, based on a parallel-kinematic design, is a redesign of the P-611 3D positioning stage. The device features one lightweight moving platform for all three axes, high precision and dynamics in a compact package. It is the company's smallest and lightest system with capacitive feedback delivering 100-µm travel range. The XYZ stage is driven by ceramic-encapsulated, preloaded PICMA piezo actuators that provide better performance and reliability than conventionally insulated piezo actuators. Applications include photonics alignment, microscopy, 3D imaging, screening, surface analysis and wafer inspection.
info@pi-usa.us

Spectrophotometer

McPherson Inc. has announced the VUVAS-10X spectrophotometer system to develop and test optical materials and coatings for high-altitude and extraterrestrial science missions. The system is designed for optimal performance in the 90- to 160-nm wavelength range — the deep or vacuum ultraviolet region — and specially built with a windowless hydrogen plasma light source and differential pumping. The system uses a 1-m focal length high-resolution monochromator with special light source, scintillated detector and goniometric sample chamber.
sales@mcphersoninc.com

Happenings

DECEMBER

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

PHOTONICS 2016 (Dec. 4-8) Kanpur, India. The International Conference on Fiber Optics and Photonics. Contact Indian Institute of Technology Kanpur, +91 512-259-7187, photonics2016iitk@gmail.com; www.iitk.ac.in/photonics2016/.

Nanophotonics and Micro/Nano Optics International Conference 2016 (Dec. 7-9) Paris. Contact Charif Bouchemat, +33 7-81-20-11-82, nanop2016@premc.org; www.premc.org/nanop2016.

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

SEMICON Japan 2016 (Dec. 14-16) Tokyo. Contact SEMI Japan, jcustomer@semi.org; www.semiconjapan.org.

JANUARY

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

● **BiOS (Jan. 28-29)** San Francisco. Colocated with SPIE Photonics West. Contact SPIE, +1 (360) 676-3290, customerservice@spie.org; www.spie.org/conferences-and-exhibitions/photonics-west/bios-expo.

● **SPIE Photonics West 2017 (Jan. 28-Feb. 2)** San Francisco. Contact Cathy DeVries, +1 (360) 676-3290, customerservice@spie.org; www.spie.org/SPIE-PHOTONICS-WEST-Exhibition.

Photons Plus Ultrasound: Imaging and Sensing - 2017 (Jan. 28-Feb. 2) San Francisco. Contact SPIE, +1 (360) 676-3290; www.spie.org/pwb/conferencedetails/photons-plus-ultrasound.

FEBRUARY

MD&M West (Feb. 7-9) Anaheim, Calif. Medtech. Contact UBM, +1 (310) 445-4200, TSOperations@ubm.com; http://events.ubm.com/event/3242/mdm-west.

● **Advanced Manufacturing Expo & Conference (Feb. 7-9)** Anaheim, Calif. Contact UBM, +1 (310) 445-4200, tshowreg@ubm.com; www. anaheim.ubmcanon.com.

SPIE Medical Imaging (Feb. 11-16) Orlando, Fla. Contact SPIE, +1 (360) 676-3290; www.spie.org/conferences-and-exhibitions/medical-imaging.

Biophysical Society 61st Annual Meeting (Feb. 11-15) New Orleans. Contact Biophysical Society, +1 (240) 290-5600, society@biophysics.org; www.biophysics.org/2017meeting.

PAPERS

SPIE Technologies and Applications of Structured Light (April 18-21) Yokohama, Japan
Deadline: Abstracts, Dec. 12
TASL '17 is accepting papers for two parallel conferences. The Optical Manipulation Conference (OMC) will include the latest research and new technologies for optical radiation forces in the field of optical trappings and manipulations, as well as related topics. The Biomedical Imaging and Sensing Conference (BISC) will provide an international forum for reporting recent progress in imaging and sensing in biology and medicine, as well as related areas. Contact Annie Gerstl, +1 360-676-3290, annieg@spie.org; www.spie.org/TSLcall.

CYTO 2017 (June 10-14) Boston
Deadline: Oral presentations, Jan. 19; poster and multimedia presentations, Feb. 16
Submission of abstracts is encouraged in all aspects of cytometry. To aid placement in the program, each submission should identify a topic category that is most relevant to the abstract. The review committee reserves the right to reclassify abstracts during the review process. Contact International Society for the Advancement of Cytometry (ISAC), +1 301-634-7017, info@cytoconference.org; cytoconference.org.

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

IPC Apex Expo 2017 (Feb. 11-16) San Diego. Contact IPC, +1 (877) 472-4724, registration@ipc.org; www.ipcapexexpo.org.

● **Laser Additive Manufacturing workshop (LAM) (Feb. 21-22)** Houston. Contact Laser Institute of America, +1 (407) 380-1553; www.lia.org/conferences/lam.

SPIE Advanced Lithography (Feb. 26-March 2) San Jose, Calif. Contact SPIE, +1 (360) 676-3290, customerservice@spie.org; www.spie.org/x10942.xml.

PHOTOPTICS 2017 (Feb. 27-March 1) Porto, Portugal. Fifth International Conference on Photonics, Optics and Laser Technology. Contact PHOTOPTICS Secretariat, +351 265-520-185, photoptics.secretariat@insticc.org; www.photoptics.org.

● **Photonics. World of Lasers and Optics 2017 (Feb. 28-March 3)** Moscow. Contact Ms. Margarita Semyakina, +7 499-795-29-06, ms@expocentr.ru; www.photonics-expo.ru.

MARCH

● **PITTCON 2017 (March 5-9)** Chicago. The Pittsburgh Conference on Analytical and Applied Spectroscopy. Contact The Pittsburgh Conference, +1 (412) 825-3220, info@pittcon.org; www.pittcon.org.

● **AeroDef Manufacturing Conference and Exhibition (March 6-8)** Fort Worth, Texas. Contact SME, +1 (866) 635-4692, service@sme.org; www.aerodefevent.com.

PIC International Conference (March 7-8) Brussels. The Photonics Integrated Circuits Conference is colocated with the Seventh CS International Conference focusing on the compound semiconductor industry. Contact Angel Business Communications, +44 0-2476-718-970, info@picinternational.net; www.picinternational.net.

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

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

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

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

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TS Queen Mary to get facelift thanks to laser scanning

Shipbuilders of the historic TS Queen Mary, the famous British turbine excursion steamer built in 1933, would probably be perplexed to learn that researchers hoping to restore the ship would be firing 1 million laser beams per second at her. But that is exactly what the School of Simulation and Visualisation at the Glasgow School of Art, in Glasgow, Scotland, did in order to create a precise 3D image, which will be compared to future scans to monitor rates of decay and damage over the years.

The school has been using laser scanning for over a decade, having scanned five Scottish World Heritage sites as well as five international sites, which include the Sydney Opera House and Mt. Rushmore. Through those projects they took an interest in Scotland's industrial heritage and laser-scanned a giant cantilever crane in Nagasaki, Japan, that was designed and built in Glasgow.

When the TS Queen Mary was in dry dock only 25 miles away from the school in Greenock, Scotland, Al Rawlinson, head of data acquisition at the school, couldn't pass up the chance to get a scan.

"The TS Queen Mary struck a chord with us. It's a ship of historical importance in the U.K. and right here on our doorstep. The first time she was dry-docked in almost 20 years was an unmissable opportunity for us to get down there and scan her," he said.

Laser scans provide the most complete and precise three-dimensional models; they are millions of times more accurate and detailed than photographs, and their precision can be marked down to the nearest millimeter.

While the school has access to several different laser scanners, Rawlinson chose to use a Zoller and Frohlich (Z+F) Imager 5010C with a maximum data acquisition rate of 1.016 million pixels per second.

"Given the limited access I had to the ship in terms of time, I needed to use a scanner which was highly portable, very quick to use, and which could capture large amounts of high quality data very quickly," said Rawlinson.

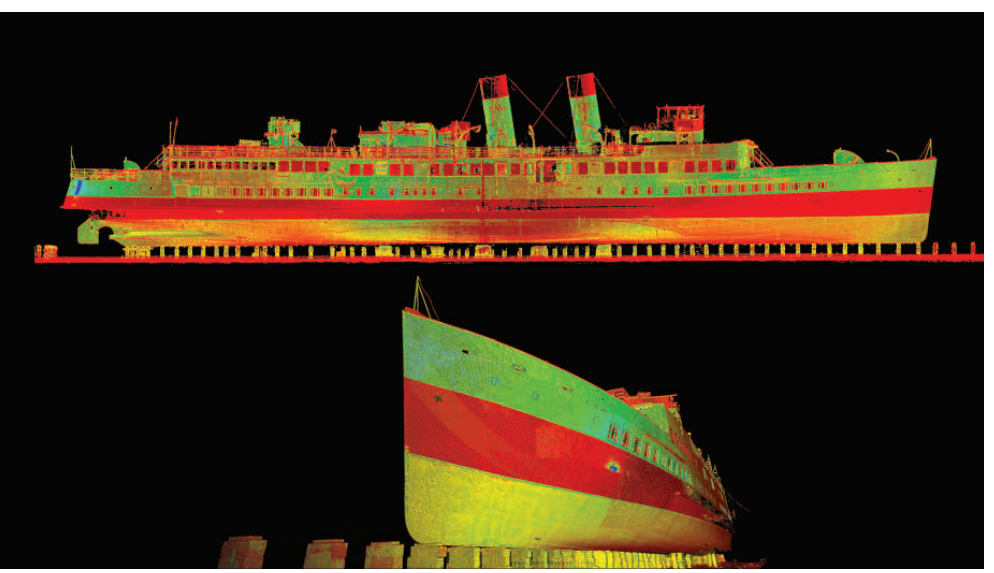
The precise measurements produced from the stand-alone laser scanner will be used to accurately repair and conserve the 1930s steamship.

The steamship, built by William Denny and Brothers Ltd. in Dumbarton, Scotland, was purchased last year by the charity Friends of TS Queen Mary; now, the group is raising £2 million to restore her.

"It's fantastic to work with such a well-respected art school to marry old with new," said Iain Sim, a Friends of TS Queen Mary trustee. "It's a real credit to the quality of engineering that went into her, and we want to preserve that."

The 3D images of the TS Queen Mary will be featured as part of an interactive exhibition planned for the ship once she is fully restored.

Autum Pylant
autum.pylant@photonics.com



3D laser-generated image of the TS Queen Mary.

Zoller and Frohlich Imager 5010C alongside the TS Queen Mary.

Images courtesy of the **School of Simulation and Visualisation** at the **Glasgow School of Art**.

Industrial Automation Webinar Series

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COMING SOON

Laser Additive Manufacturing (LAM)

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

Wayne Penn of Alabama Specialty Products Inc. will provide an in-depth introduction to LAM and the open source world of 3D printing. He will discuss the challenges of additive manufacturing, including quality control and the role of laser welding and cladding technology in additive manufacturing. He will present examples of industrial applications showing the use of additive manufacturing and conclude with a look at future initiatives.

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

Available on Demand

Vision Guided Robotics (VGR)

David Bruce of FANUC America will discuss the steps required to set up and execute 2D and 3D VGR, including 2D pick and place and 3D bin picking. He will review the advantages of using virtual VGR in the engineering phase of large and small automation projects and provide real-world examples. Bruce will also discuss the different software packages that can be used for VGR and the trade-offs to consider when selecting a VGR system.

To watch this webinar and others, visit **www.photonics.com/webinars**.

Robotic Collision Avoidance: When Accidents Are Not an Option

Available on Demand

Tim Dykstra of Concept Systems Inc. discusses how to manage the interface between robots and their active, changing environments, and recent advances in robotics that make robots less vulnerable to collisions. He reviews the role of vision systems and sensors in collision avoidance and how to integrate computers and vision technology. He also discusses the benefits of a collision avoidance module (CAM), and how collaborative robots are being used to achieve a safer production environment. He concludes with a look at the future of path planning and collision avoidance.

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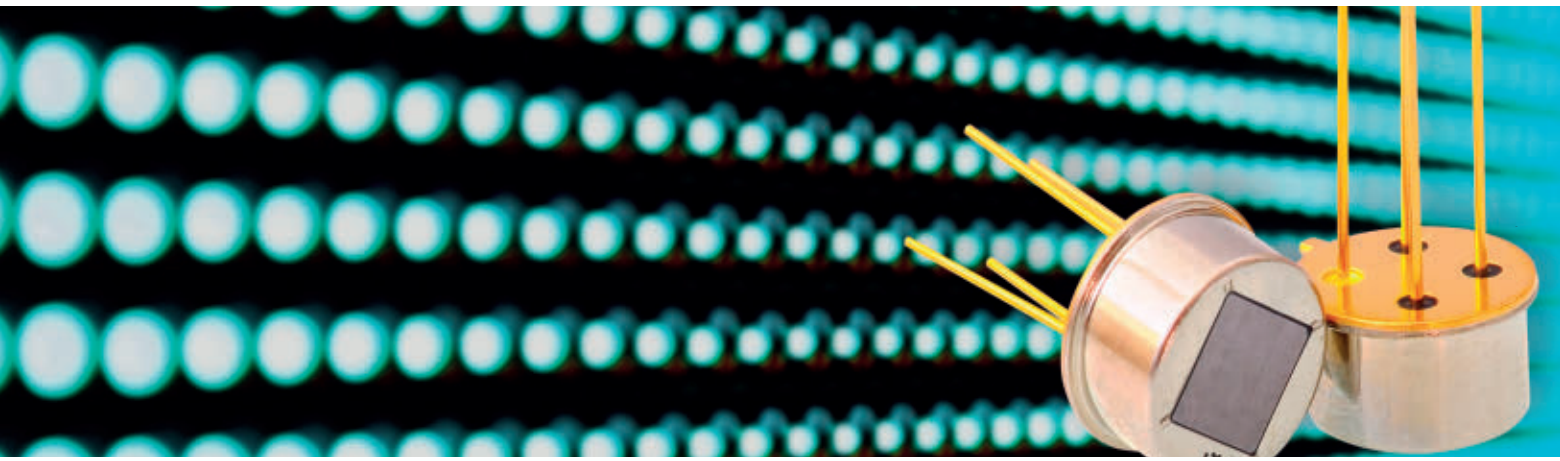

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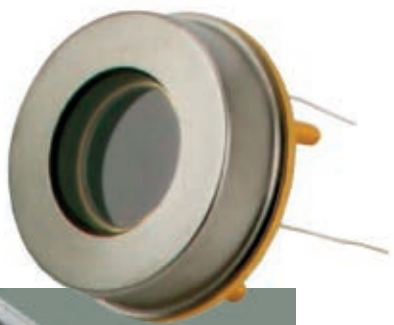

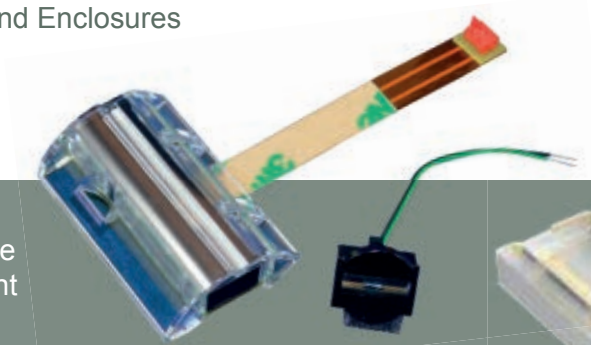

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- Position sensing
- Proximity sensing
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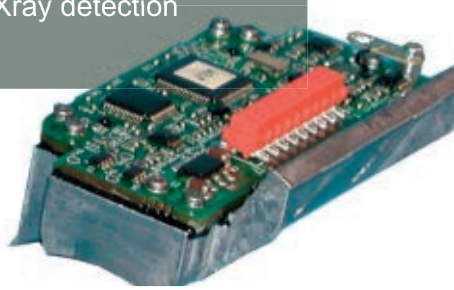
- Colorimetry
- Spectroscopy
- Pulse oximetry
- Fluorescence detection
- Xray detection



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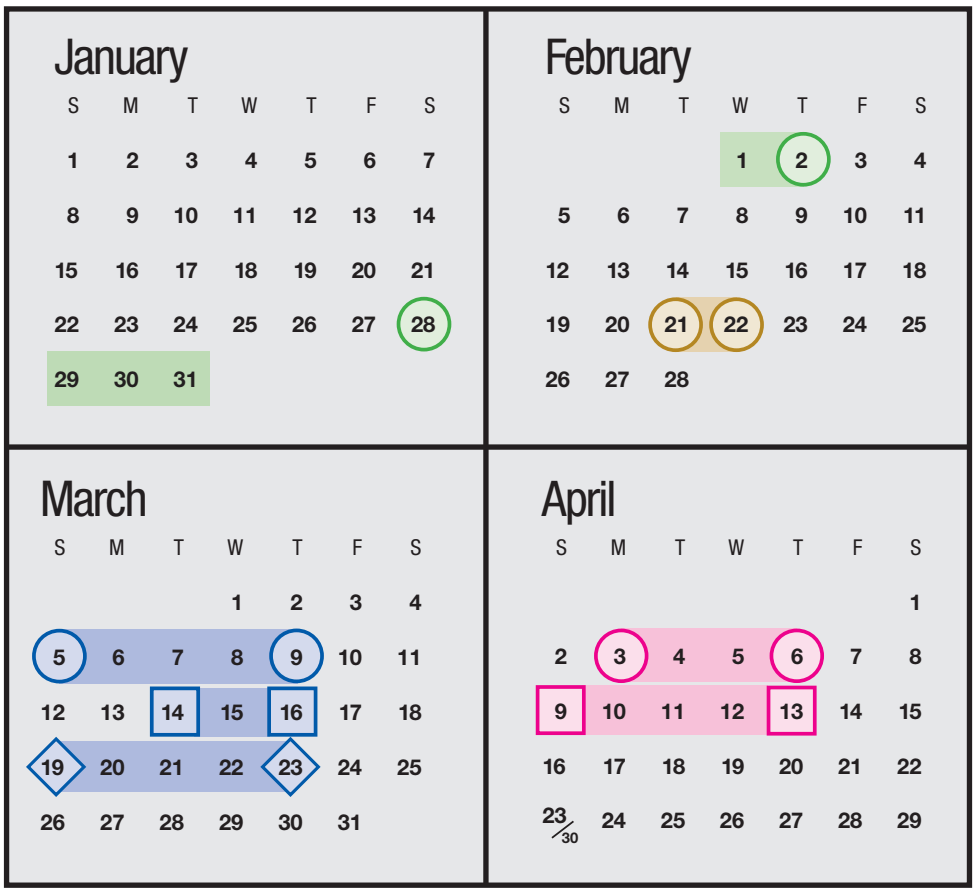

- SPIE BiOS/Photonics West, January 28-February 2
- Laser Additive Manufacturing, February 21-22
- PITTCON, March 5-9
- LASER World of PHOTONICS CHINA, March 14-16
- OFC, March 19-23
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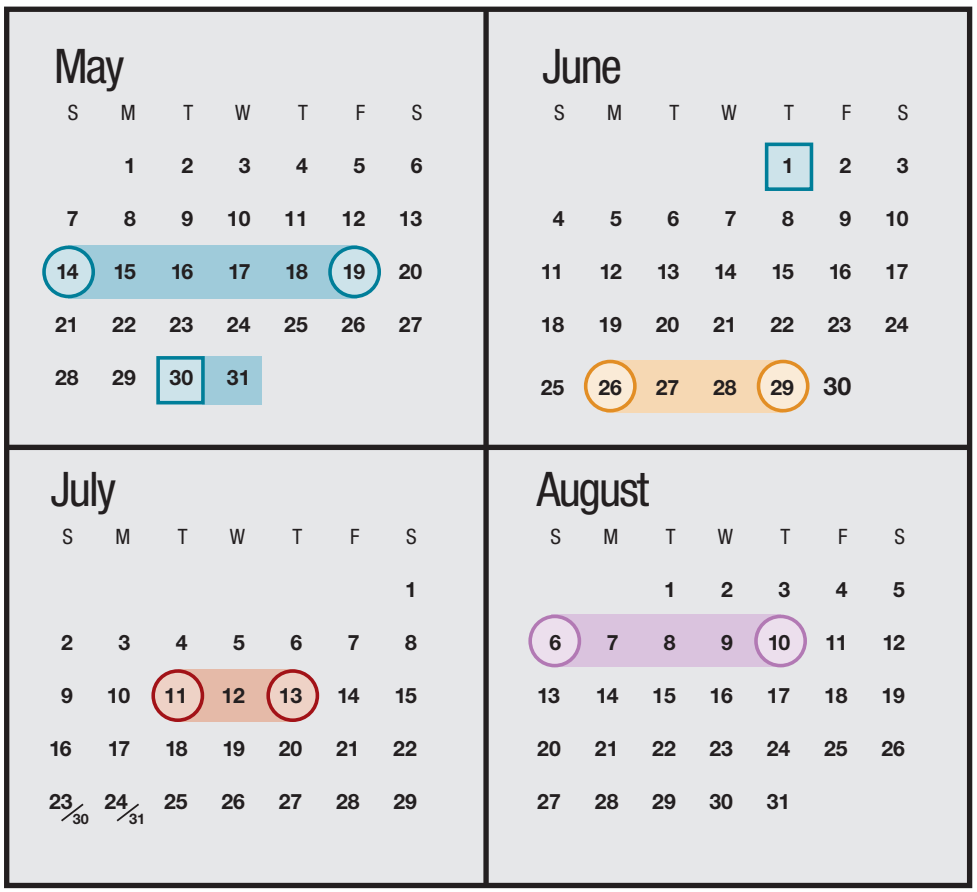

- CLEO, May 14-19
- SENSOR + TEST, May 30-June 1
- LASER World of PHOTONICS, June 26-29
- SEMICON West, July 11-13
- SPIE Optics + Photonics, August 6-10

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September

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- **Frontiers in Optics, September 17-21**
- **SPIE Optifab, October 16-19**
- **ICALEO, October 22-26**
- **FABTECH, November 6-9**
- **Neuroscience, November 11-15**