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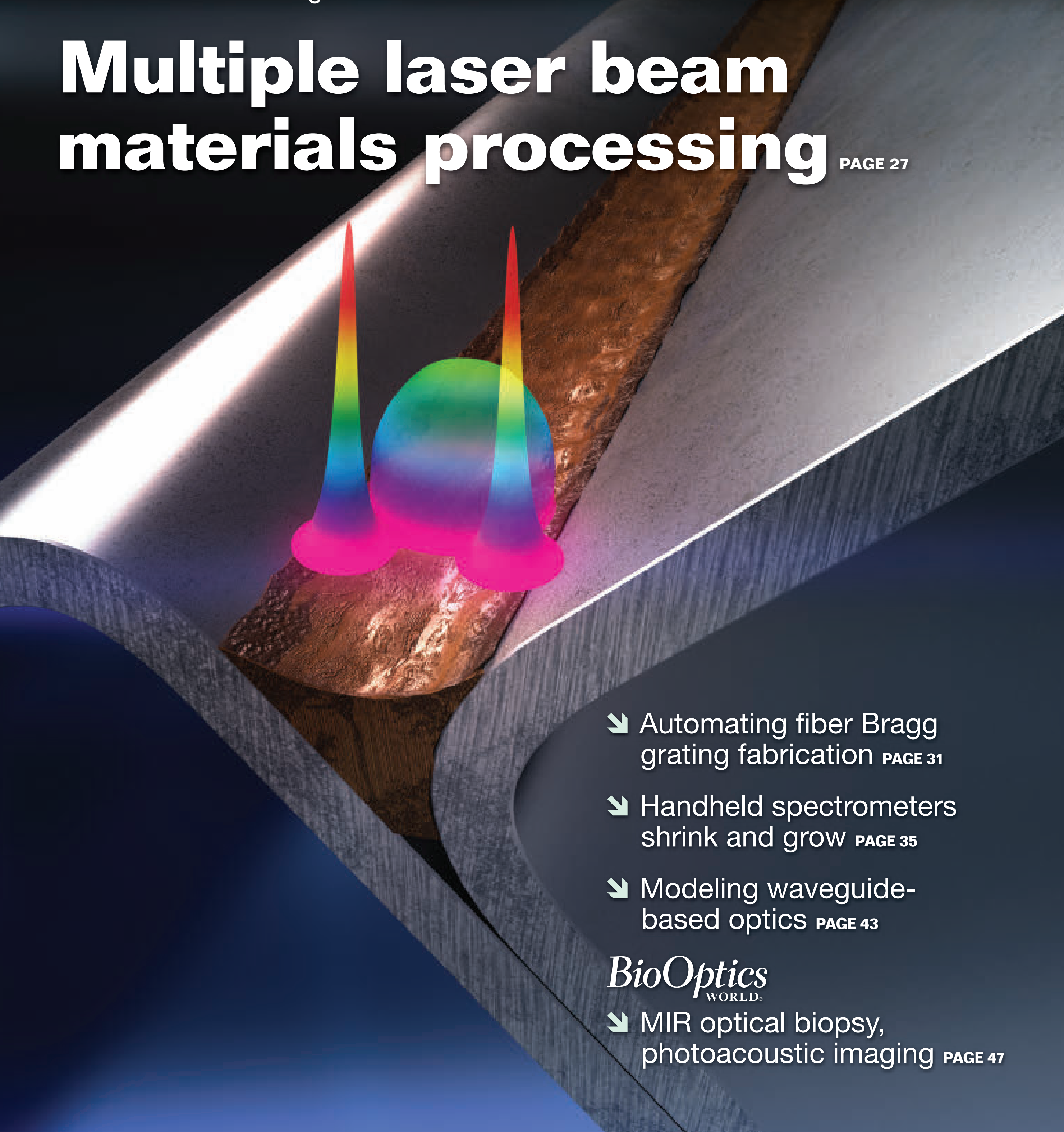

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FEBRUARY 2016 ▪ VOL. 52, NO. 2

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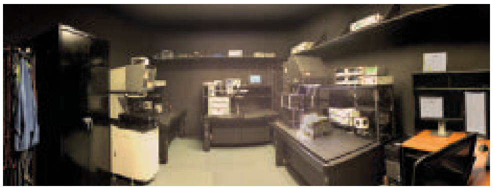

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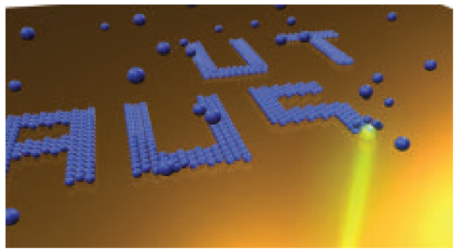

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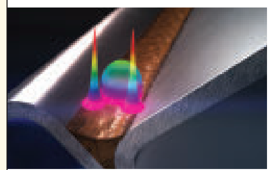

Trifocal brazing involves two lead beams that clean and pre-heat steel edge surfaces to promote wetting. *(Courtesy of IPG Photonics)*

LASER FOCUS WORLD PRESENTS

BioOptics WORLD

Coming in March

Next month includes special articles to highlight what's hot in many important areas:

- Contributing editor Jeff Hecht continues his Photonic Frontiers series by discussing optical communication beyond 100 Gbits/s.
- Articles on new silicon photonics designs, high-power fiber lasers, laser light shows, molded optics, and ultrafast sampling for time-domain spectroscopy.

In *BioOptics World*, we will have articles on near-infrared deep-tissue imaging and Raman spectroscopy.

cool content

Blog: Photon Focus

Senior editor John Wallace provides some analysis and commentary on China's strong presence in photonics. Keep coming back to our blog for more hot topics, cool commentary, and other events-related musings!
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http://bit.ly/1OPCBvC

Lasers and light sources keep finding new markets

Conard Holton
Associate Publisher/ Editor in Chief
cholton@pennwell.com

Since the dawn of the 21st century, fiber lasers have been the fastest growing segment of the laser markets, adopted into applications ranging from biomedicine to defense and research. The market where the technology has had the greatest impact by far is industrial materials processing, where Strategies Unlimited estimates that fiber laser sales revenue grew 22% in 2015. Automotive manufacturers in particular have become comfortable with fiber lasers and willing to embrace advanced processes that improve productivity, as engineers from IPG Photonics explain in our cover story about using multiple laser beams in a single process for applications such as brazing, welding, and surface texturing (see page 27).

One product area where fiber lasers have not had an impact is handheld spectrometers, where the light source is more likely a laser diode or quantum cascade laser. As Senior Editor Gail Overton writes in this month's Photonics Products article, handheld spectrometer designs have continued to shrink in size and/or weight, while increasing in variety and performance (see page 35). The competition and choices have significantly grown in recent years, but the advantages this new generation of spectrometers provides are significant for research, process control, and security.

The light-emitting diode (LED), often thought of as little more than a light source for displays or illumination, is also penetrating important new markets. Ultraviolet LEDs can monitor water and cure adhesives and inks, micro-LEDs can be used in optogenetics, and GeSn LEDs, fabricated on silicon, could make their way into silicon photonic devices—all new applications that contributing editor Jeff Hecht describes in his Photonic Frontiers feature (see page 22).

Two other new applications described in this issue rely on innovations in lasers for biophotonics—mid-infrared optical biopsy and photoacoustic imaging. The great thing about covering photonics is that I can use the word "new" frequently, and still be very accurate.

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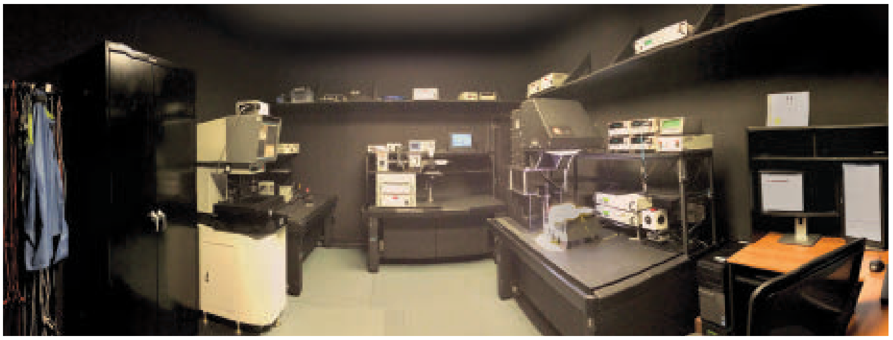
newsbreaks

Newport's PV Lab provides NREL-supported solar cell testing



Newport Corporation's (Irvine, CA) Photovoltaic Testing and Calibration Laboratory (PV Lab), administered out of the ILX Lightwave (a Newport company) facility in Bozeman, MT, provides an independent verification of solar-cell device performance and is the only commercial laboratory whose results are published in the *Solar Cell Efficiency Tables*, which are in turn published by the journal *Progress in Photovoltaics*.

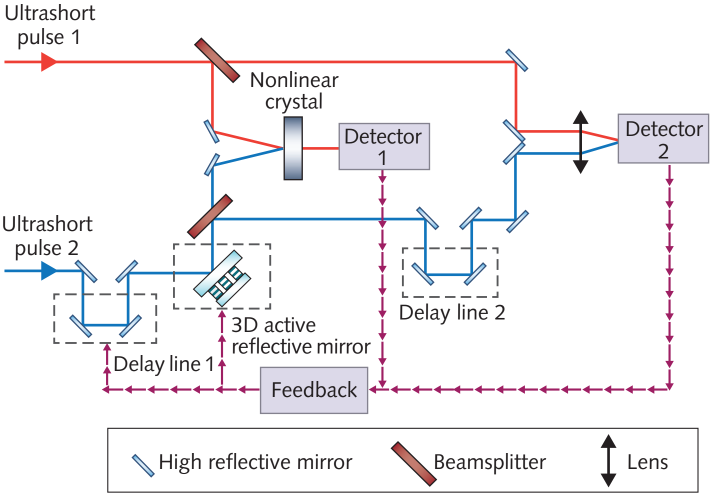
The Newport PV Lab works closely with the U.S. National Renewable Energy Laboratory (NREL; Golden, CO) to ensure that its calibration and certification results are accurate and consistent. The performance of PV devices is certified in accordance with ISO/IEC 17025:2005—an international standard describing the conditions under which an "ideal" calibration laboratory should operate, requiring meticulous documentation of procedures and continuous maintenance of measurement, training records, and equipment calibrations. All measurements are traceable to the International System of Units (SI) through a documented, unbroken chain of calibrations, each of which contributes to the overall uncertainty in the final measurement.

Currently, the Newport PV Lab can provide results on new material systems four times faster than some government labs—a critical capability considering that novel prototype materials may only have a physical lifetime of a few days if not yet engineered for environmental stability. And in the case of split-cell irradiance sensors, which are necessary for monitoring incident sunlight on utility-scale solar arrays, a rapid return of the calibrated sensors also maximizes the profitability of the array by minimizing measurement downtime. *Contact Geoffrey Wicks, PV Lab manager & application scientist, at gwicks@ilxlightwave.com.*

Two ultrafast beams with 29.8 fs pulses are coherently combined

Coherent combination of beams from separate lasers is an important and ongoing topic, as it can potentially achieve higher beam powers than any other technical approach. What may be surprising to some is that coherent combination of ultrafast laser beams is being pursued as well. Particularly interesting is a parallel configuration for ultrafast beam combining. In this case, an example system consists of an ultrafast oscillator whose beam is split into multiple beams, with each beam then sent through an ultrafast amplifier. The hard part comes last, when multiple ultrafast pulses must be precisely aligned in relative phase so that they can be combined into one very high energy pulse.

Researchers at the China Academy of Engineering Physics and the Science and Technology on Plasma Physics Laboratory (both in Mianyang), Shanghai Jiao Tong University (Shanghai), and Xi'an Jiaotong University (Xi'an) have developed and experimentally demonstrated a method for coherently combining ultrafast laser pulses. The method, which in its prototype form combines two pulses, relies on controlling phase (relative synchronization error), piston, and tilt of the two



pulses at two locations: first, at a point where the two pulses are overlaid noncollinearly (at an angle with respect to each other) and second in the far field. In the first region, a noncollinear cross-correlation allows the temporal characteristics of the pulses to be mapped to a spatial distribution of the cross-correlation signal, making the synchronization error clear. The researchers built a two-beam setup in which pulses seeded by a mode-locked oscillator were amplified to a 1 mJ pulse energy with a 29.8 fs duration and a 1 kHz repetition rate. The two beams were combined coherently with an efficiency of 99%. *Reference: J. Mu et al., Opt. Lett. (Dec. 3, 2015); http://dx.doi.org/10.1364/ol.41.000234.*

UV cavity-enhanced absorption spectroscopy detects 2 ps transients

In cavity-enhanced absorption spectroscopy (CEAS), the many round trips of a probe beam in a specimen-filled optical cavity increase the sensitivity to measurements of optical absorption. But the higher the finesse of the optical cavity and thus the number of round trips for the light beam, the less able the setup is to measure fast, transient events. A group at Stanford University (Palo Alto, CA) is creating CEAS setups that reduce the cavity's finesse while maintaining sensitivity, thus enabling the ability to measure transients. Now, the researchers have extended their work to the UV region using a picosecond-pulsed laser with quasi-continuous-wave (QCW) detection, and tested the setup in a shock tube (which produces highly transient events).

In the technique, picosecond pulses from a wavelength-tunable Ti:sapphire mode-locked laser are frequency-quadrupled to a wavelength adjustable from 206 to 245 nm and coupled into a low-finesse CEAS cavity without sweeping the laser wavelength or trying to match the laser mode to the cavity. A 15.24 cm cavity was used with 2 ps pulses in an on-axis configuration. The pulses, which arrived at intervals of 12.8 ns, do not interact with each other in the cavity. The system's photodetector has a 150 kHz bandwidth, meaning that the detector time-averages about 500 pulses at a time. Measurements of ethyl formate were compared with a single-pass and a CEAS setup—the minimum detectable absorbance and noise-equivalent absorption sensitivity of the CEAS setup were improved by a factor of 20 over those for the single-pass setup. Time resolution of the shock-tube measurements was 2 ps. Reference: S. Wang et al., *Opt. Express* (Jan. 11, 2016); doi:10.1364/oe.24.000308.

Bubble-pen lithography
See page 14

LIQUID-CRYSTAL DISPLAYS

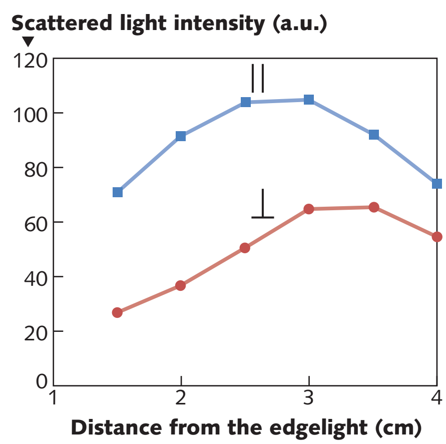
Backlight plate for LCDs produces polarized light, boosting efficiency

In a liquid-crystal display (LCD) for a smartphone or other handheld device, the light for the display is usually provided by an edge-lit transparent waveguide plate that contains scattering particles. The light enters the plate and is totally internally reflected across the plate, scattering out of plane toward the viewer (and through the LCD matrix) at a relatively uniform rate across the screen. Because the light source is unpolarized and a conventional waveguide plate is not in itself polarizing, a separate polarizer is placed between the waveguide plate and the viewer to provide the linearly polarized light required for the LCD to operate.

The problem with this approach is that the efficiency of the LCD is cut in half because the polarizing sheet must absorb the other polarization orthogonal to the polarization it passes.

Researchers at the Liquid Crystal Institute, Kent State University (Kent, OH), and BOE Technology Group (Beijing, China) have developed and experimentally tested a waveguide plate that intrinsically produces polarized light by scattering only (or mostly) one polarization towards the viewer. In addition, the unscattered light, which travels to the opposite side of the waveplate because of total internal reflection, could be made to bounce off a reflective quarter-wave plate that rotates the light's polarization by 90° to the orientation that is preferably scattered toward the viewer. In essence, it converts the "wrong" polarization to the "right" polarization, thus boosting the LCD's efficiency beyond what is possible using the conventional approach.

Because the new method does not produce perfectly linearly polarized light (the experimental ratio of orthogonal polarizations is about 2.6 to 1), a conventional polarizing sheet must still also be used. However, in this case, the polarizing sheet absorbs far less light than in a conventional LCD.



An edge-lit transparent waveguide plate scatters light of mostly one polarization toward the viewer. Scattered light was measured as a function of the distance from the edge light for polarizations both parallel and perpendicular to the liquid-crystal rubbing direction.

Stabilized liquid-crystal

The waveguide plate is in itself a liquid-crystal matrix, but stabilized by a polymer network. It consists of two rubbed glass plates spaced apart by 10 μm, with one of the plates containing an indium tin oxide electrode. The space is filled by a mixture of 92.9% nematic liquid crystal, 6.9% bifunctional monomer, and 0.2% photoinitiator.

In the fabrication process, the setup is first partially polymerized under UV light without a voltage across it, and then completely polymerized while 20 V is placed across it. The first step aligns the molecules in the proper polarization direction (along the rub direction of the plate), while the second step introduces an out-of-plane orientation to the molecules, allowing them to scatter light toward the viewing direction.

Light of the polarization that is not scattered sees a uniform refractive index across the plate, while light having the other polarization sees different refractive indices in different domains and is thus scattered.

The researchers fabricated a 4 x 4 cm polarized light waveguide plate and characterized it first using an unpolarized laser beam as a light source. As a check to see if the plate had fully polymerized, they applied a voltage of 20 V across the thickness of the plate and compared the optical results with those for no voltage (the normal operating state of the plate). The scattering of the plate was mostly the same in both instances, showing full polymerization. Placing a polarizing sheet over the waveguide plate at either parallel or perpendicular polarization allowed the researchers to characterize the plate's polarization properties as a function of distance from the edge light (see figure).

Next, three white LEDs were installed along one edge and their light coupled into the plate. As before, a polarizing sheet was used to characterized the plate's properties. Rotating the sheet from parallel to perpendicular polarization resulted in a change in intensity (in arbitrary units) from 71 to 27, or a ratio of 2.6 to 1.

In both the laser and LED characterization, the intensity of the light emitted by the plate (which was the first prototype) peaked approximately at the middle of the plate. For future iterations, this nonuniformity can be straightforwardly corrected by a better LED arrangement, tailoring of the polymerization process, or both.—*John Wallace*

REFERENCE

1. A. Moheghi et al., *Opt. Mater. Express* (2016); doi:10.1364/ome.6.000429.

NANOLITHOGRAPHY

Laser bubble-pen lithography patterns colloidal nanoparticles

Colloidal particles such as quantum dots and metallic nanoparticles are emerging as important devices for applications in microelectronics, renewable energy, and sensing/drug delivery in the medical field. Unfortunately, standard lithography methods using photons, focused ion beams, or electron beams cannot pattern these particles on a solid substrate. Optical tweezers offer powerful capability for versatile manipulation of particles, but it is still challenging to immobilize the particles onto the substrate. Also, the high-power operation (up to 100 mW/μm^2) limits its applications.

A unique method developed by researchers at the University of Texas at Austin uses a much-lower-power laser to create a microbubble at the interface between a plasmonic substrate and the liquid solution containing colloidal nanoparticles. This "bubble pen" uses convection, surface tension, and gas pressure to draw particles towards the bubble. Arbitrary patterns with different resolutions and architectures can be optically written on the substrate through this bubble-pen lithography (BPL) technique.

Plasmon-enhanced photothermal effects

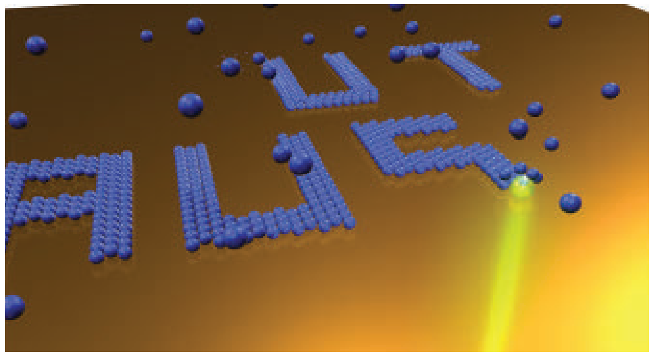
Nanoparticles with sizes on the order of tens of nanometers with single-digit nanometer spacings on a glass slide are used as the plasmonic substrate. Low-power lasers with single-digit milliwatts per square micrometer levels and with wavelengths tuned to match the plasmon resonance wavelength of the nanoparticles are adequate for patterning.

To form the bubbles, a 2-µm-diameter laser beam is focused from the underside of a plasmonic substrate onto which a solution of colloidal particles is sandwiched between the substrate and a cover slip with a 120 µm spacer. Because of water vaporization from plasmon-enhanced photothermal effects, a bubble with a diameter down to 1 µm is formed on top of the plasmonic substrate.

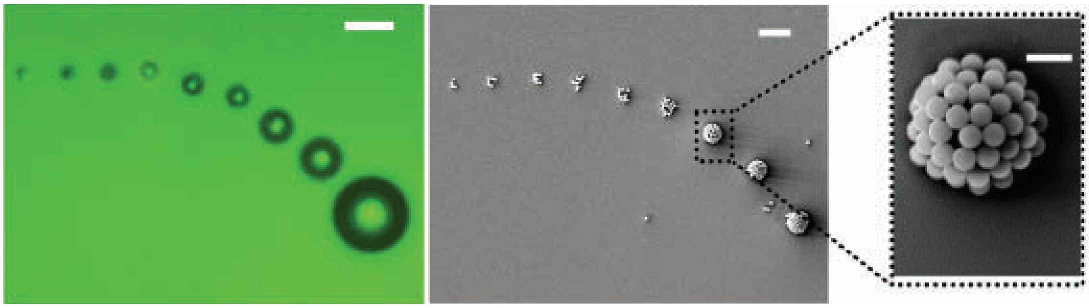
The colloidal particles are then dragged towards the microbubble, trapped on the bubble/solution interface, and immobilized on the substrate (see video). When the laser power is off, the particles remain at the location they were patterned because of the enhanced substrate adhesion by the thermal effect. These particle patterns remain even after the substrate is rinsed and dried, making the method applicable to the fabrication of functional devices. Using the laser beam as a pen, a pattern of nanoparticles is formed by moving the bubble as the laser beam is scanned (see figure).

Researchers at the University of Texas at Austin demonstrate writing with laser bubble-pen lithography.

Particle trapping at the microbubbles is because of a combination of natural convection caused by the temperature gradient on the substrate and Marangoni convection induced by the surface-tension gradient along the microbubble surface. The in-plane drag force of the bubble attracts the particle, trapping it when it touches the microbubble surface—a phenomenon quantified and predicted by force equations. In fact, the temperature distribution of the bubble can also be predicted by computational fluid dynamics (CFD) simulations.



In further experiments, lasers with different power densities can be used to create different-sized bubbles that can actually incorporate nanoparticles such as polystyrene beads onto the bubble in a sort of three-dimensional (3D) shell configuration at laser power levels around 1 mW/μm^2—100X less power than typical optical tweezers.



Bubble-pen lithography (BPL) is a way to pattern colloidal particles such as quantum dots, polystyrene beads, or other nanoparticles on plasmon substrates by using a laser to create optically controlled microbubbles that trap and immobilize the particles at the bubble (upper). Different laser power densities create bubbles of different sizes (lower left) that can trap particles in a three-dimensional shape on the spherical shell of the bubble itself (lower right).

"The patterned particles have a variety of applications depending on the types of the particles. For example, metal nanoparticles can lead to metasurfaces and metamaterials that can manipulate light in a way that natural materials cannot afford, and patterned biological cells will find important applications in tissue engineering and high-throughput drug screening," says Yuebing Zheng, assistant professor at the University of Texas at Austin. "Our future work will further improve the throughput and automation of the technique for high-volume manufacturing of functional materials and devices with colloidal particles and biological cells. One of the approaches will be to develop multiple-beam processing."—*Gail Overton*

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1. L. Lin et al., *Nano Lett.*, 16, 1, 701–708 (2016); doi:10.1021/acs.nanolett.5b04524.

OPTICAL SENSING

Absorption/fluorescence could enable gold nanoparticle detection at drill sites

With global demand reaching more than 4000 tons in 2013, gold is used worldwide not only for jewelry, but for electronics, drug delivery, sensing, and deep-space applications. Incredibly, gold in solution is taken up by the roots of trees and by some ground-dwelling bacteria, and converted to low-concentration-level gold nanoparticles whose detection could signal larger deposits underneath. With the average crustal abundance of gold at 1.3 parts per billion (ppb), detecting anomalous concentration levels up to 8 parts per million (ppm) is critical for finding new gold sources.

While easy to detect in parts-per-million concentrations using x-ray fluorescence (XRF) techniques, parts-per-million-level gold detection is more elusive. Unfortunately, parts-per-billion detection through inductively coupled plasma mass spectroscopy (ICP-MS) and inductively coupled plasma atomic-emission spectroscopy (ICP-AES) requires the ore sample to be transported to the lab and processed, adding significant time to the exploration workflow.

Recognizing that gold has unique optical properties such as localized surface plasmon resonance (SPR) and a catalytic effect on fluorophores that can be used for sensing methods, researchers at the University of Adelaide (Adelaide, SA, Australia) are exploring the utility of the optical absorbance and fluorescence in detection of low concentrations of gold in the field at the drilling site without arduous sample preparation.[1]

Comparing measurements

To determine the optimal means of detecting parts-per-billion traces of gold nanoparticles, the researchers used various concentrations of gold nanoparticles in solution with diameters of 5, 20, and 50 nm. Then, they compared the detection limit achievable with SPR and fluorescence using both laboratory and handheld or portable spectroscopy instruments.

Data was analyzed for different gold solutions within a cuvette and also within a suspended-core optical fiber (SCF) with a central solid core surrounded by three air holes. Optical fibers have the advantage of requiring small sample volumes, and can analyze samples at remotely distributed locations such as downhole environments.

By defining the limit of quantification (LOQ) as the measurement of the minimum quantifiable concentration of gold nanoparticles, experiments determined that the absorption LOQ in a cuvette measured with a laboratory spectrometer was 7X lower (dependent on nanoparticle size) than for a portable spectrometer. But for the fluorescence method, the LOQ was approximately the same for both. Comparing cuvette and SCF, the LOQ was nearly 2X lower in the SCF for 50 nm nanoparticles, but comparable for 5 and 20 nm nanoparticles.

"We have determined the LOQ of gold nanoparticles that can be achieved using optical methods. The methods are easy to use and are quite versatile, and could also be used for detection of gold in biological samples," says Agnieszka Zuber, researcher at the University of Adelaide. "Apart from a low detection limit, the most important advantage of these methods is their portability, which allows analysis time to be reduced from a few days to just hours, including sample preparation." The authors would like to note that their work has been supported by the Deep Exploration Technologies Cooperative Research Centre in Adelaide.— *Gail Overton*

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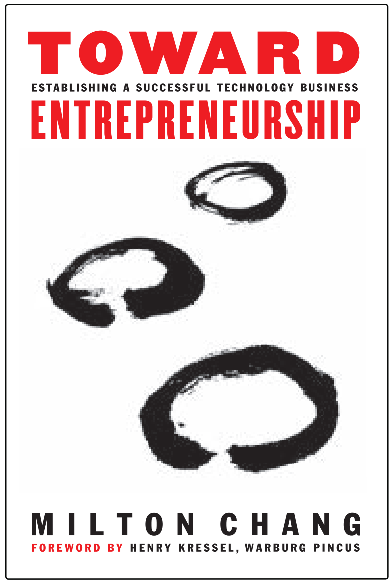

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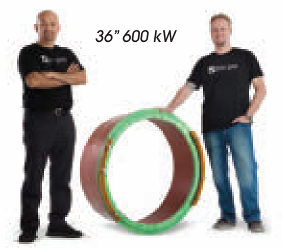

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Optical design and testing trends—better, faster, cheaper

OSA: *How have computers changed optical design?*

Daniel Malacara-Hernández: Early ray tracing calculations in the day of Eugen Conrady were done by hand with logarithmic tables. Even when mechanical calculators replaced them, tracing just one ray took many hours and a lot of patience. I designed a few lenses that way as a student at the University of Mexico starting in 1957, and I was tired after tracing just one ray.

When James G. Baker first used the Mark 1 computer for ray tracing at Harvard in 1944, it took two minutes to trace one skew ray through just one surface. In 1953, Robert E. Hopkins and Donald P. Feder started using a more powerful IBM 650 computer at the University of Rochester, which could trace rays much faster. The University of Mexico got an IBM 650 while I was a student, and I tried tracing rays on it.

When I came to Rochester in September 1961, they were doing wonderful things with computers. Rochester and Eastman Kodak were developing optimization techniques that greatly improved the design process.

The later advent of the personal computer led to development of several commercial programs that in less than a second could trace a complete bundle of rays through an optical system for one step in the optimization process. At the beginning, we traced only three or four rays to evaluate a lens—now, we can trace 12–15 rays for each of three colors.

DANIEL MALACARA-HERNÁNDEZ *is a professor at the Centro de Investigaciones en Optica (Center for Research in Optics) in Leon, Guanajuato, Mexico. He is a fellow of The Optical Society, the editor of* Optical Shop Testing, *and co-author of the* Handbook of Optical Design.

OSA: *How will optical design change in the future?*

DMH: When I teach optical design, my students always ask, "Why do we have to learn all the processes and theory for the rays when we have a commercial program?" I tell them it wouldn't work if they didn't know aberration theory.

Contemporary programs are quite powerful, but they need human intervention. The designer must pick a starting lens design before beginning optimization. After that optimization, the designer must make changes for a series of several iterations. The user of design software has to know the fundamentals of lens design to make these choices.

Future software will become so powerful that the designer will not have to intervene. That would be wonderful, but that may be 20 or 25 years away, so my students can dream of it. Then, they can concentrate on being creative and discovering new things.

The future will bring new design options and challenges. Free-form surfaces lacking rotational symmetry are quite useful in many off-axis optical systems, including the progressive eyeglass lenses used to correct presbyopia. Yet they have been hard to describe mathematically. Now, Greg Forbes of QED Optics has developed new mathematical descriptions that can use orthogonal polynomials to specify any surface shape. That will allow designers to use free-form surfaces in a wider range of applications.

OSA: *What changes do you expect in optical testing?*

DMH: My PhD thesis in 1965 was on testing aspherical surfaces, and I have worked on them most of my life. They attracted me because they are difficult to test and to make, and the problems are interesting.

The development of new instrumentation and tools has brought large advances in optical testing. We will continue seeking more dynamic range to test strongly aspheric surfaces, more sensitivity to increase accuracy, and less sensitivity to external noise.

Currently, more than 100 types of tests are used for aspheric lenses. My students ask me why they should have to learn them all, and want to know which test is "the best." But I tell them there is no such test—you need all those methods to test differently shaped lenses. So, another of my dreams is to have "the test" so powerful that it can be used to examine all aspheric surfaces, I think. It will not be in my lifetime, but I hope my sons may see it.

OSA: *How will these improvements in design and testing change what we can do with optics?*

DMH: The small cameras used in iPhones are built around tiny aspheric lenses. They are quite impressive and produce wonderful images, but it was impossible to dream of such a camera only 10 years ago.

Aspheric surfaces will become even more common as we continue making great advances in fabricating and testing them. The use of aspheric surfaces can improve the quality and reduce the cost of lenses and optical systems. Aspheric surfaces also will help reduce the number of elements in the lenses.

Another exciting area is the use of adaptive optics in areas such as medical examination of the human eye. Ophthalmologists now use an instrument called an ophthalmoscope to look into the retina, which can detect many health problems. It can show blood vessels, but it lacks the resolution to see the rods and cones in the eye, which could yield useful information.

The problem is that the fluid in the eye is moving all the time, causing turbulence that limits the resolution of the ophthalmoscope like air turbulence limits the resolution of a telescope. Adaptive optics has been very successful in improving astronomical resolution, and it can do the same thing for instruments examining the eye.

David Williams at the University of Rochester and several other researchers around the world use adaptive optics to image the eye with resolution so sharp that it can show the rods and cones. Three of my students have been working with him, and I am having this instrument assembled in my lab as we speak. Now, the optics are expensive and and must be assembled on a very heavy 2 × 1.5 m optical table.

My dream is to have a portable instrument for use in the office of an ophthalmologist. You will have to work hard to reach this goal because it is not easy to produce this kind of equipment. But I am sure it will be done in the future. Another dream that I have is that future eyeglasses could use adaptive optics. They might compensate for aberrations in the eyes, or they could change their shape to focus the eye at different distance. That would require an even smaller optical system, but with time it could be done.

I just ordered a flexible mirror that is only 1.5 in. across, but is very expensive. To comply with government regulations, I had to write a letter explaining what I was going to do with it. I hope that in the future you will be able to buy those flexible mirrors anywhere at a cheap price. ◄

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LEDs are workhorses with applications far beyond lighting

JEFF HECHT, Contributing Editor

Deep-UV LEDs could power new water-quality monitoring networks, near-UV LEDs cure adhesives and inks, micro-LEDs open doors for optogenetic research, and direct-bandgap GeSn LEDs can be fabricated on silicon.

Light-emitting diodes (LEDs) have come a long way from the arrays of red dots that served as numbers on the first pocket calculators. Today's glaring spotlight is on LED lighting, but LEDs are exploring a broad range of other frontiers. Advances in nitride semiconductors have pushed commercial LEDs well into the 200–280 nm ultraviolet-C (UV-C) band. Near-UV LEDs can deliver watt-scale output for applications ranging from sensing and adhesive curing to phototherapy. On the research frontier, micron-scale LEDs are powering investigations in optogenetics, and developers are exploring prospects for germanium-tin (GeSn) LEDs in silicon photonics.

The UV LED boom

Nitride semiconductors have spawned a boom in UV as well as blue light sources. The bandgap of pure gallium nitride (GaN) corresponds to 365 nm in the UV. Adding indium increases the wavelength to produce violet and blue LEDs. Adding aluminum decreases the wavelength, pushing LEDs deeper into the UV. As shown in Fig. 1, pure aluminum nitride (AlN) has a bandgap wavelength of 210 nm, which NTT Basic Research Laboratories (Atsugi-shi, Japan) reached a decade ago, and which remains the shortest LED wavelength.[1] Since then, the big improvements have been in power and performance.

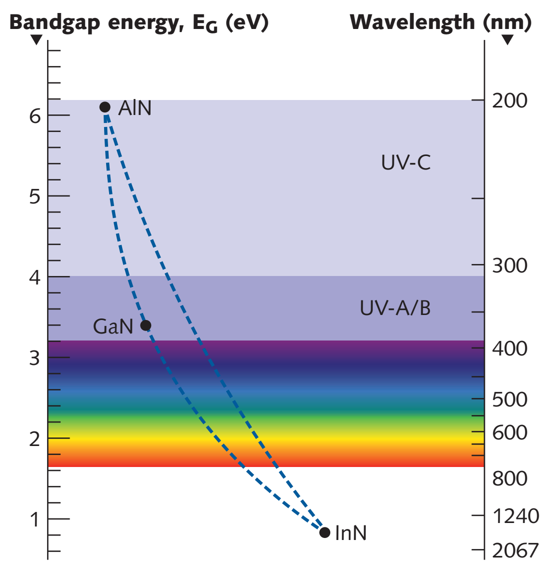

FIGURE 1. Bandgap energy, wavelength, and lattice constant of nitride semiconductors. *(Courtesy of Crystal IS)*

UV LED power and efficiency are highest at 360–400 nm, where the active layer is largely GaN. These devices typically are grown on sapphire (Al_2O_3) substrates, although GaN and silicon carbide also are used. Maximum outputs of commercial single-emitter LEDs are in the watt range.

Power and efficiency drop sharply at wavelengths shorter than about 350 nm. Some LEDs are available in the UV-B band from 280 to 315 nm, but there is more interest in the UV-C band at 200–280 nm, which has stronger bioeffects and is more attractive for important types of sensing. DARPA's Compact Mid-UltraViolet Technology (CMUVT) program, completed two years ago, sought better LEDs in this range for applications including sensing and water purification. Milliwatt-class commercial LEDs now are available from 240 to 280 nm.

The choice of substrate is a crucial for deep-UV performance. As the aluminum concentration increases, reducing the LED wavelength, the lattice mismatch with sapphire grows larger. Aluminum nitride is harder to grow, but provides better lattice matching for UV-C LEDs, says Hari Venugopalan, director of global product management at Crystal IS (Green Island, NY). He says AlN substrates are a key factor in the company's ability to offer LEDs with output above 10 mW at 250–280 nm. They are now sampling 230 nm LEDs, which will be a commercial first.

UV-C LED applications

The new generation of UV-C LEDs is attractive for environmental quality measurements long performed by deuterium, xenon, or mercury discharge lamps. LEDs have longer lifetimes and lower replacement costs. They don't yet meet the power requirements for disinfection in drinking-water plants, which largely have shifted from chlorine chemical treatment to UV treatment with intense 254 nm mercury lamps. But LEDs are well suited to monitoring absorption in the 255 nm band to ensure proper irradiation levels.

LEDs also can monitor treatment of wastewater, a problem in India where 40% of the treated water does not meet national standards. Ensuring compliance requires a network of UV-C-based sensors to measure and report BOD and UV absorption levels every 15 minutes. UV-C LEDs can meet those requirements more reliably and less expensively than deuterium lamps or chemical measurements systems, says Venugopalan.

High nitrate levels become a major issue for U.S. water systems because they can cause algal blooms that generate toxins and contaminate drinking water. This has led the Alliance for Coastal Technologies, the Environmental Protection Agency, and other organizations to sponsor a challenge program seeking new nitrate and phosphate sensors that can collect real-time data unattended for at least three months, and cost less than $5000. Nitrates absorb strongly at 230 nm, says Venugopalan, "so LEDs would be ideal candidates."

UV-C LEDs also can protect optical and acoustic sensors used in coastal or marine environments from fouling by biofilms that grow on hard surfaces. As little as 2–3 mW of light at 260–275 nm can deactivate DNA in the bacteria that that form the layers, keeping surfaces clean. As available powers increase, UV-C LEDs could be used for larger-scale treatments such as water purification or germicidal treatment.

LEDs emitting at 280 nm can measure absorption by uric acid to monitor the progress of kidney dialysis in real time, which previously required time-consuming blood tests. Another use of 280 nm LEDs is exciting fluorescence in oil that has leaked into water. The emitted wavelength can identify the type of oil, which is important for determining what dispersants to use to clean up the spill.

FIGURE 2. Wrapping a baby with jaundice in a fiber-optic "biliblanket" illuminates its skin with blue light, helping the child's body break down harmful bilirubin. *(Courtesy of AAP Gateway)*

Near-UV LED applications

More powerful LEDs emitting in the near-UV are replacing lamps for curing adhesives and inks. LEDs last over 40,000 hrs. compared to 1000–8000 hrs. for mercury lamps and consume much less electricity, lowering operating costs.

Typically, adhesives are cured with 365 nm LEDs to take advantage of photoinitiators originally developed for mercury lamps. The deep penetration of that wavelength eases full-depth curing. The ability of LEDs to focus light onto small areas is a big advantage for electronics manufacturing because it can avoid stray light damaging sensitive components, increasing production yields of products such as touch-screen panels, says Mark Gaston of Excelitas Technologies (Waltham, MA).

Printers prefer 395 nm for ink curing because they have developed special inks to take advantage of the higher LED powers available at that wavelength, says Mike Kay of Excelitas. The high powers available from 365 to 395 nm make LEDs at those wavelengths attractive for exciting fluorescence spectroscopy in a wide range of materials.

Phototherapy

Near-UV LEDs are promising for destroying pathogens in blood used for transfusion, says Gaston. Now used mainly in Europe, the process is based on adding a compound called amotosalen to the blood and activating it with a near-UV source.[2] This kills pathogens, but does not damage blood plasma and platelets as long as they are not illuminated by shorter UV wavelengths. Shifting from the fluorescent lamps now used to 350 nm LEDs would kill the pathogens, control the process better, and reduce heating of the blood, he says.

Phototherapy also extends into the visible, with blue LEDs now being used to treat jaundice in infants by breaking down a yellowish compound called bilirubin, which can accumulate to dangerous concentrations without treatment. Babies had been exposed to fluorescent lamps. Blue LEDs are more efficient, can be matched to the 458 nm peak absorption of bilirubin, and also can be connected to fiber-optic blankets, so the baby can be wrapped in the "biliblanket" and illuminated by blue light delivered through the fibers (see Fig. 2).

Micro-LEDs on the research frontier

Micro-scale LEDs are playing important roles on research frontiers such as optogenetics, the use of light to control neurons or other cells in living tissue. The cells are genetically modified to express light-sensitive "opsin" proteins, and to

allow monitoring of their response. The technique allows probing neural activity in living animals, and was listed as one of the breakthroughs of the decade in *Science*.[3]

Delivering light precisely to individual neurons has been a challenge. Fiber-optic probes are large compared with neurons, and can limit movement of mice used in experiments. Planar waveguide probes required fiber tethering or diode laser sources. Now, György Buzsáki of the New York University Neuroscience Center (New York, NY) and Euisik Yoon

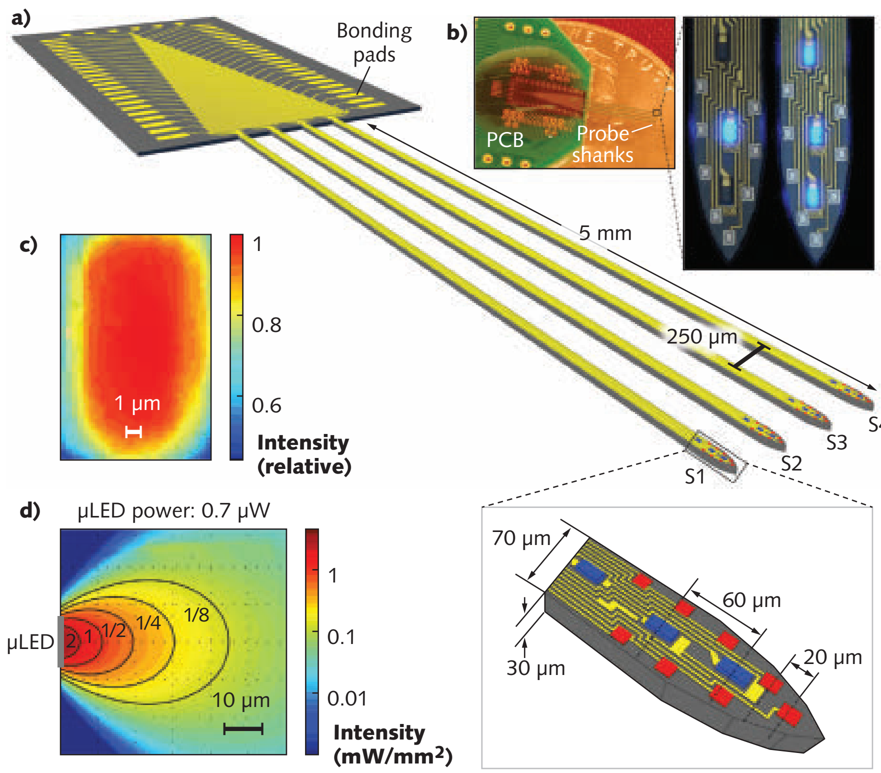

FIGURE 3. Structure of micro-LEDs used as optogenetic probes. The overall schematic (a) shows the shape of the silicon wafer, with bonding connections at top and the long "shanks" with the LEDs at the tips. Note the expanded version of the drawing at lower right, which shows the details of the LEDs (blue) and conductors (yellow). Photos of the devices are at upper right (b). (c) and (d) show the profile of emission from top and from above the LEDs. (*Adapted from F. Wu et al.4*)

of the University of Michigan (Ann Arbor, MI) have shown that a micro-LEDs can deliver a broader range of wavelengths and couple more directly to neurons (see Fig. 3).[4]

Germanium-tin LEDs

Another emerging technology is compound GeSn LEDs fabricated on silicon. Their allure is that blending about 10% tin into germanium can produce a semiconductor with a direct bandgap, offering far more efficient light emission than possible in other indirect-bandgap Group IV materials. Output is around 2 μm.

The field is young and demonstrations are hard. So far, a few groups have made LEDs and the only lasers made were optically pumped and operated well below room temperature. But in a review paper, Erich Kasper and Michael Oehme of the University of Stuttgart (Stuttgart, Germany) concluded that further work should lead to development of efficient LEDs.[5]

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Multiple laser beam materials processing

TOBY STRITE, ANDREAS GUSENKO, MICHAEL GRUPP, and TONY HOULT

Fiber lasers producing different spot sizes, pulse durations, or wavelengths can be combined into a single process for applications such as brazing, welding, and surface texturing.

Manufacturers view laser material processing as a mature, well-understood productivity enhancement, which they constantly seek to extend to new segments of their business. Lately, that search has produced a trend toward the deployment of multiple laser beams on a single workpiece, each optimized to perform a facet of the overall process. This trend is already undergoing rapid adoption in automotive manufacturing, and we believe it will soon impact other fields.

This article highlights three examples of multiple laser beam processing. To begin, we show how trifocal brazing utilizes coordinated beams to join automotive materials with high strength and superior cosmetics. Next, we examine the benefits of a two-step welding process for high-strength steel, in which a laser cleaning step enables laser welds of outstanding strength and integrity. Our final example highlights how laser surface texturing of a metal enables high-strength, hermetic polymer-to-metal bonding. These examples highlight the possibilities available when multiple laser beams of differing diameter, pulse durations, or even wavelength are coordinated to produce previously unobtainable results.

Trifocal brazing

The automobile industry relies of the unique ability of lasers to provide high joint strength with minimum material usage, at the same time promoting safety and fuel economy. While laser welding is entrenched within the automobile, a more cosmetic process is preferred in visible joints along the roofline and car sides. In contrast to welding, brazing is a technique that does not melt the surfaces to be joined. Rather, for automotive applications, laser energy melts a wire to form a cohesive joint between two steel or aluminum surfaces. Automakers desire a brazing process that requires just a light brushing prior to the application of paint to realize a truly seamless joint.

Brazing studies on electro-galvanized low-carbon steel link joint quality and aesthetics to edge variability. In particular, oxides and contaminants residing on the thin zinc (Zn) anti-scaling layer are the main causes of spatter and edge roughness. This knowledge inspired the development of a novel three-beam brazing system in which two lead beams travel along the steel edges ablate contaminants and pre-heat the Zn surface layer to promote wetting. The powerful trailing beam supplies energy to melt the Cu/Si wire to seamlessly join the newly cleaned steel surfaces (see Fig. 1).

The trifocal brazing system relies on the flexibility of fiber technology (see Fig. 2). Fiber lasers are coupled into three optical fibers of different diameter, which are delivered through a single cable. Near the workpiece, the delivery optic creates the desired three-beam profile, allowing the narrow lead beams to pre-clean before the trailing beam completes the spatter-free brazed seam.

To directly assess the benefits of trifocal brazing, a near-infrared (NIR) fiber laser was used to join a series of 0.8 mm hot-dipped steel samples using

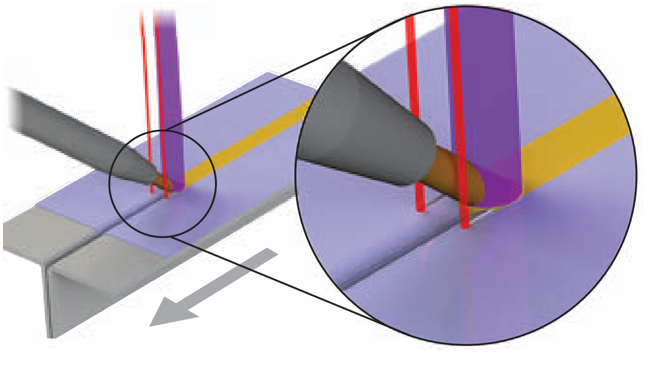

FIGURE 1. In trifocal brazing, two lead beams (red) clean and pre-heat the steel edge surfaces to promote wetting. The trailing beam (purple) melts the Cu/Si wire to form a seamless brazed joint which, after painting, can be invisible to the naked eye.

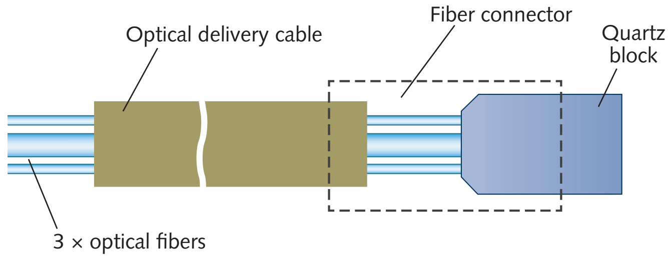

FIGURE 2. Three fiber core trifocal brazing optics enable different diameter fibers to pass through a single process cable to deliver spatially offset spots of different size to the brazing area.

1.6 mm $CuSi_3$ alloy wire with a 3.5 kW infrared brazing beam at a process rate of 4.5 meters per minute. When 350 W lead beams are added to pre-clean the steel edges prior to melting the copper silicon (CuSi) wire, greater edge uniformity and a better surface finish are readily observable (see Fig. 3).

Trifocal brazing combines cleaning and joining in a single process, greatly reducing post-processing requirements before painting. The brazing can be fully automated at high speed with excellent joint strength and reproducibility along straight and curved borders. Automakers are increasingly adopting trifocal brazing as their preferred solution for cosmetic steel joints to optimize both productivity and aesthetics.

Two-step laser welding of high-strength steel

Automakers constantly seek materials and joining methods that enable safer and more efficient vehicles. High-strength steels (HSS) bolstered by the element boron have moved to the forefront of automotive innovation, offering strength levels so great that the Jaws of Life auto rescue tool had to be re-specified in North America. Higher strength presents the opportunity to use less material for reduced vehicle weight, assuming joining technology can keep pace. Laser welding is automakers' preferred method for joining HSS. Early efforts were hampered by the aluminum silicon (AlSi) protective coatings added to avoid scaling during the hot stamping process. Brittle iron aluminum (FeAl) inter-metallic layers may result when AlSi-coated HSS is laser-welded.

Outstanding HSS weld quality is achievable when the anti-scaling coating on either side of the weld region is laser-ablated, enabling a weld between identical, clean steel surfaces free of FeAl inter-metallics. Figure 4 illustrates a clean steel surface prepared by laser ablation on which the AlSi coating is fully removed by a 1 kW, 70 ns NIR pulsed fiber laser. The ablation laser provides up to 100 mJ pulse energy (7–10 J/cm^2 fluence over a 1 mm^2 spot) delivered through a novel square process fiber to perform a precise and economical 10 m/min ablation of a 30 µm AlSi coating. Subsequent high speed welding using a multi-kilowatt continuous-wave (CW) NIR fiber laser completes the joining process, allowing strong but lightweight tailor-welded blanks to be supplied to the auto industry.

In contrast to trifocal brazing, which employs two CW laser beams of different diameter, two-step welding of HSS is

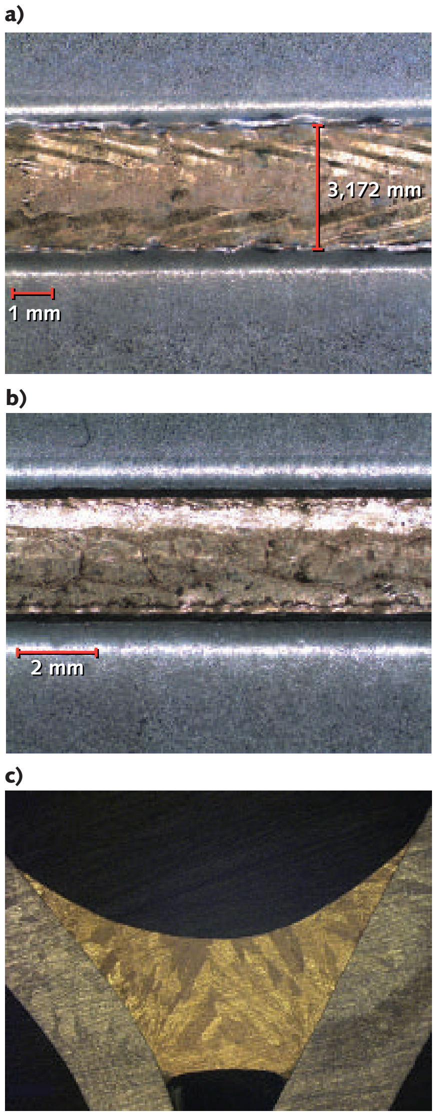

FIGURE 3. A comparison of single-spot (a) and trifocal (b) brazed seams that join steel with CuSi wire. An improved finish and suppression of edge roughness is evident in the trifocal brazing example. A cross-section (c) highlights the joint uniformity and quality obtainable with trifocal brazing.

optimized by first applying a high-energy pulsed nanosecond ablation laser, followed by a high-power CW welding laser. Our final example also utilizes a pulsed/CW laser one-two punch, but we extend into the sub-nanosecond pulsed regime and apply two different laser wavelengths.

Polymer-to-metal joining

Welding requires melting of opposing surfaces to fuse the materials into a robust joint. Welding is widely used to join metals to metals, or polymers to polymers. However, disparate melting temperatures largely rule out polymer-to-metal welding. Effective polymer-to-metal joining remains a highly sought technology for industries as diverse as consumer electronics and medical devices. A recently developed two-step process relying on new fiber laser technology provides a promising solution.

The first step relies on a 30 W NIR fiber laser capable of 400 kW peak power when pulsed at 150 ps to provide a novel metal surface texture (see Fig. 5a). Microscopic studies suggest the high laser fluence melts a nanometer-scale surface layer, which coalesces quickly into a fine, nodular structure, one whose large surface area is ideal for subsequent adhesive bonding.

What is remarkable about these textured surfaces is that they can be made perfectly black, even on highly reflective metals like Cu (see Fig. 5b). Experienced welders know that a uniformly dark surface provides the widest process window since reflectivity variations affect the threshold energy that a laser must supply to couple into a reflective metal.

Polymer-to-metal joining relies on the 1.9 µm lasing wavelength of thulium-doped CW fiber lasers. The mid-infrared wavelength is more strongly absorbed by common transparent polymers than NIR fiber laser or laser diode sources. Conventional 1 µm lasers pass through the polymer, heating only the opposing metal surface. This conducts heat into the polymer, eventually melting it into the metal to form a weak bond.

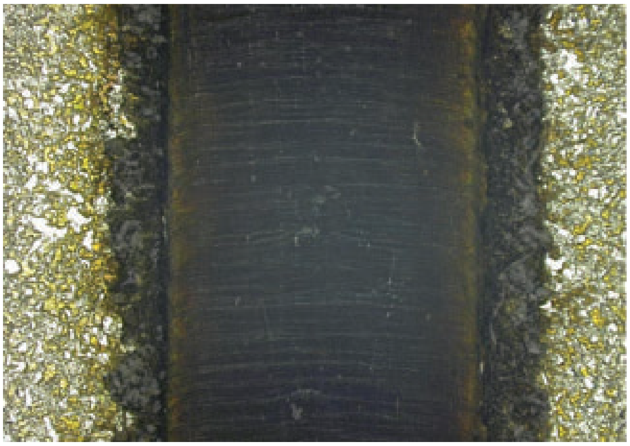

FIGURE 4. High pulse energy fiber laser technology delivered through a novel square fiber efficiently ablates the AlSi coating to expose the native HSS surface for enhanced weld quality.

We find that polymer-to-metal bond strength is remarkably improved by first texturing and darkening the metal surface, then applying thermal energy using the 1.9 µm fiber laser. The longer wavelength transfers heat directly to the polymer as well as the polymer-to-metal interface. The direct heating of the polymer, combined with the dark nodular metal surface, provides ideal bonding conditions. We have formed polymer-to-titanium bonds that are hermetic and so strong that they fail in the polymer when subjected to shear force.

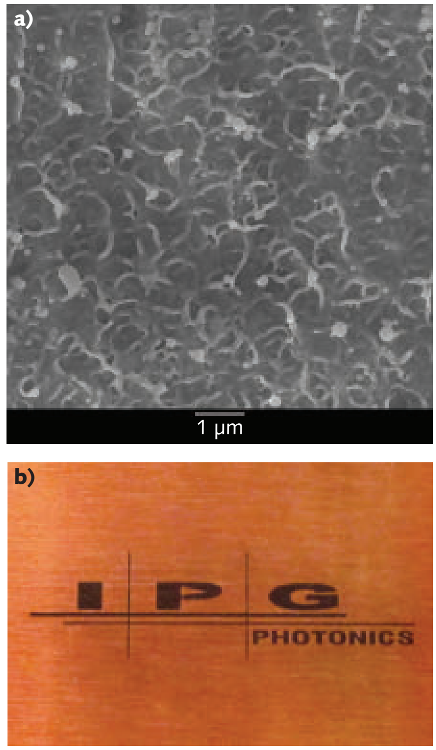

FIGURE 5. Example of the fine, nodular Cu surface structure (10,000X magnification) obtained using a sub-nanosecond NIR fiber laser (a). The textured Cu surface is perfectly black, making it an ideal absorber for subsequent laser processing (b).

In contrast, when the surface texturing step is omitted, lap shear tests fail at the polymer-to-metal interface, attesting to a weaker bond. Robust, hermetic joining of transparent polymers to metals opens a new degree of design and manufacturing freedom that has already generated interest among customers in fields as diverse as medical devices, consumer electronics, and low-cost consumer products.

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Fiber Bragg grating fabrication system is automated

RALPH DELMDAHL and KRISTIAN BUCHWALD

An interference lithography based production system enables pushbutton fabrication of fiber Bragg gratings (FBGs) for remote fiber sensing.

While fiber Bragg grating (FBG) technology has been available for decades, commercial use of these devices, especially in sensing applications, has been relatively limited for two reasons. The first is that, historically, interrogation systems for use with FBGs were quite expensive. However, prices on these have dropped substantially over the past two to three years. The second limitation has been the production methods for FBGs themselves.

Specifically, sensing FBGs are still often fabricated in research labs in small quantities. The result is long lead times and high unit costs. This situation makes their use particularly problematic for sensor manufacturers since the development of a new product may require dozens of design iterations, each with slight variations in FBG properties. And, after that, it is difficult to obtain production quantities of FBGs having consistent performance characteristics.

This situation is now being addressed with a new, automated system from Northlab Photonics (Nacka, Sweden) that enables essentially pushbutton FBG production. The benefits of this system are twofold. First, it substantially reduces the unit cost for FBG production, and second, it delivers FBGs with excellent unit-to-unit consistency and quality, which greatly simplifies the task of the system integrator. This article reviews the construction, operation, and use of this system.

FBG background

A FBG is formed by producing a periodic modulation in the refractive index of the core of an optical fiber along the direction of propagation. The periodic pattern creates a Bragg grating that acts as a filter, which because of interference reflects some of the incident optical field. Acting in a manner analogous to a high-reflection thin-film coating, the magnitude, center wavelength, and spectral bandwidth of the FBG reflectance can be precisely controlled by varying grating parameters. Specifically, these include the grating period, depth of refractive-index modulation, and FBG length.

The most obvious use for FBGs is as integrated mirrors or spectrally selective filters. They have been widely deployed for these tasks in telecommunications applications, where they can be fused directly onto the end of another fiber, eliminating the need for individual bulk components. For this same reason, they are also used extensively in fiber laser systems as resonator end mirrors.

Any change in grating period or effective refractive index, which can be introduced by either ambient temperature changes or mechanical strain, will shift the center wavelength of the FBG reflectance band. This leads to their utility as temperature and pressure (or mechanical movement) sensors.

In this role, FBGs offer several advantages over other sensor types. In particular, they are insensitive to magnetic and electromagnetic fields, and can operate without difficulty in high temperature and high pressure environments. They are largely immune to corrosive chemicals, and even nuclear radiation. In addition, they do not require electrical power and can be easily physically

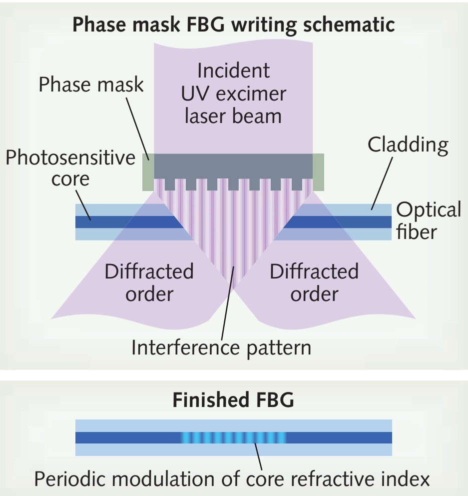

FIGURE 1. As seen in this schematic, the phase-mask method of FBG writing produces an interference pattern that projects downward through space onto an optical fiber (top), resulting in evenly spaced FBG pattern in to fiber (bottom).

embedded within other structures without significantly compromising the mechanical characteristics of the material. This makes them ideal for use in a variety of extreme settings, such as nuclear plants, downhole in the oil and gas industry, and in proximity to magnetic resonance imaging (MRI) scanners, as well as being built directly into buildings and bridges.

Manufacturing FBGs

Fabrication of FBGs benefits from the fact that the core of most optical fibers is doped with germanium (to increase the refractive index), which makes it photosensitive in the ultraviolet (UV). Specifically, photosensitivity means that exposure to UV light will induce a permanent refractive-index change. In some cases, photosensitivity is created or further increased by hydrogen loading.

The most common method for FBG fabrication is to expose a photosensitive fiber to an interference fringe pattern in UV light. This is usually accomplished by directing the output of an excimer laser through a phase mask (essentially a diffraction grating; see Fig. 1). The phase mask diffracts the incident laser light into various orders, which overlap and optically interfere with each other in the mask vicinity. This interference creates stationary, alternating zones of high and low laser intensity whose spacing is either equal to the phase-mask period or half of this value, depending upon the exact exposure geometry.

While this process is conceptually straightforward, in the real world there are several significant barriers to overcome when producing FBGs. The first is cost, specifically of the excimer laser as well as the phase mask. Next is holding and positioning all the components such that a grating having precisely the right spacing and index variation characteristics can be produced at exactly the correct place along the fiber. And, if the goal is to produce a large number of FBGs with each having consistent characteristics, the system must have some way to accommodate the batch-to-batch variations in the index of the optical fiber used.

The automated system by Northlab Photonics was developed to meet the need for cost-effective, flexible manufacturing of high-quality, consistent FBGs on a production basis (see Fig. 2). Their NORIA tool integrates a Coherent ExciStar XS excimer laser operating at 193 nm, beam-conditioning optics, up to 16 Ibsen Photonics phase masks (uniform or

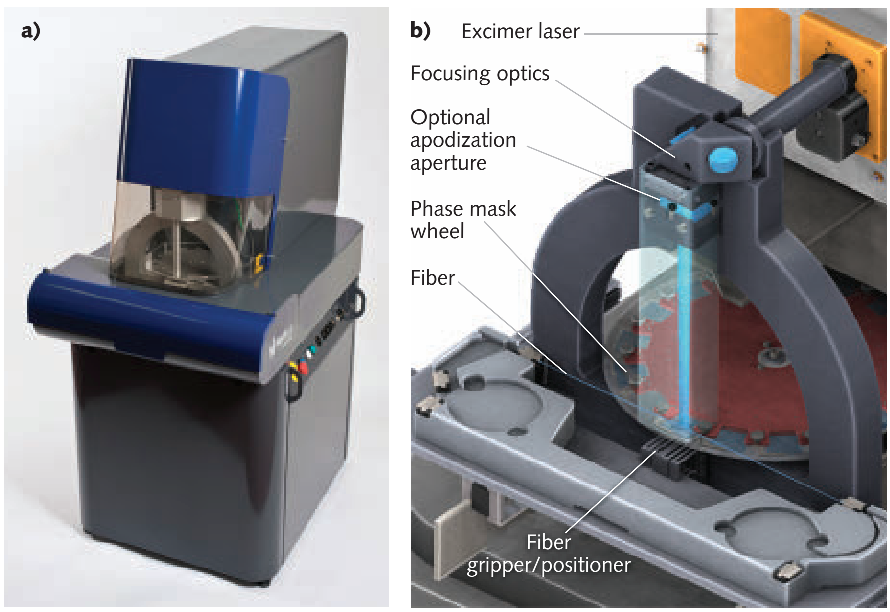

FIGURE 2. The NORIA automated FBG writing tool (a) writes FBGs into an optical fiber using an excimer laser and one of a number of wheel-mounted phase masks (b). *(Courtesy of Ibsen Photonics)*

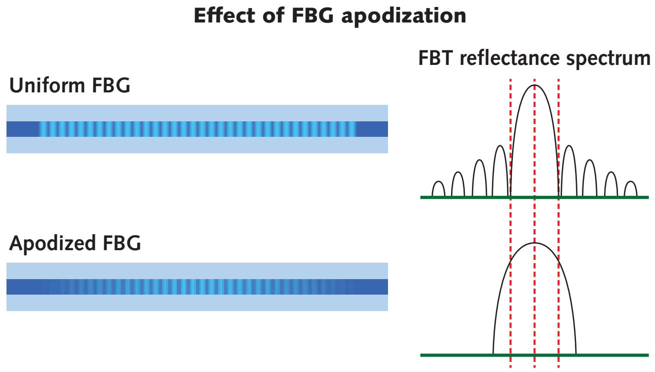

FIGURE 3. FBG apodization suppresses side lobes, but increases reflectance bandwidth.

chirped), automated mechanics, and control software to deliver pushbutton FBG manufacture.

For example, the phase masks are all held on a rotating disc to enable switching between fabrication of different FBG types without operator handling. The optical fiber is mounted in a modular fixture and is positioned on a linear stage that allows FBGs to be written along the fiber in a precise position in an automated fashion. Moreover, the total system cost is less than what would be spent to procure all the components individually. Several aspects of how this system delivers operational flexibility and a consistent product merit examination.

Center wavelength accuracy

Probably the single most critical parameter for an FBG is the center wavelength of its reflectance band. This quantity is determined by two parameters: the FBG period (set by the phase mask used), and the effective refractive index of the fiber (which depends upon both the core and cladding index). The effective fiber index can be derived from the fiber numerical aperture (NA), the value of which is specified by the manufacturer for every fiber. Unfortunately, fiber manufacturers don't control core refractive index that tightly, resulting in significant batch-to-batch variations from their specified values, and sometimes even variations within a batch.

Because phase masks are expensive, the goal is to be able to consistently write production FBGs having a fixed target center-wavelength value using just a single phase mask, despite variations in the refractive index of the supplied fiber. The NORIA system accomplishes this by applying a force to physically stretch the fiber during the writing process (called "pretensioning"). When the fiber is subsequently released from this force, it springs back to its original length, thus changing the FBG period. Therefore, adjusting the pretensioning force enables FBGs over a range of periods to be written using the same phase mask.

In practice, the NORIA tool can shift FBG center wavelength as much as 4 nm (for a phase mask nominally centered at 1550 nm) using pretensioning, which is more than twice what is necessary to correct for the typical batch-to-batch variations in fiber NA. Control of the pretensioning force is precise enough to deliver a FBG center wavelength accuracy of 0.1 nm and a repeatability of ±50 pm in production.

Reflectance bandwidth

After center wavelength, the next critical FBG properties are typically reflectance bandwidth and the presence of any reflectance peaks outside of the nominal reflectance band (side lobes). The parameters that control reflectance bandwidth are FBG length and the modulation depth of the index changes.

For a grating with a uniform index modulation along its length, reflectance bandwidth narrows as the grating length increases. Unfortunately, the sharper the reflectance peak, the more energy is shunted into side lobes. This effect can be countered by varying the depth of index modulation along the FBG, which is called apodization. However, this does produce some increase in the center reflectance peak bandwidth because it decreases the effective grating length (see Fig. 3).

The Coherent Excistar laser outputs a 3 × 6 mm beam that has a uniform (top hat) intensity distribution in the long direction and a Gaussian profile in the shorter dimension. Optics reshape the beam in the NORIA system such that it can write FBGs from 1 to 10 mm in length. The capability for beam apodization is directly built into the NORIA system. This is accomplished by using a shaped aperture in the beam path to convert the uniform distribution of the laser into a Gaussian (or other) profile. Currently, the system is configured with a Gaussian apodization mask that delivers a sidelobe-suppression ratio of at least 15 dB for a 10-mm-long FBG. The company can create custom masks for other configurations on request.

Mechanical stability and positional accuracy

Writing a uniform FBG with a center-wavelength transmission reduction of 20–50 dB might require as many as 1000 of the 5 mJ pulses from the laser. As this laser operates at 500 Hz, this means an exposure time of 2 s. Chirped FBGs (in which the grating period changes along the length of the grating) require much higher refractive-index contrast to reach the same level of reflectance, meaning even longer exposure times. Any relative motion between the phase mask and fiber over this period, even at the nanometer level, is enough to degrade FBG performance. To eliminate any relative vibrational motion in the NORIA system, the fiber is clamped securely during exposure against the phase mask, which is in turn attached to a relatively massive mechanical structure (the "U"-shaped piece seen in Fig. 2).

However, the fiber holding and clamping system must meet another important requirement. For sensing applications in particular, it's not uncommon to write multiple FBGs on a single fiber. Furthermore, the spacing between these individual FBGs must usually be controlled very precisely. But because each FBG is created serially, it is normally difficult to locate it again within 1 mm after it has been written.

The NORIA system utilizes its own clamping and positioning technology to position the fiber relative to phase mask with submicron accuracy. The system also integrates a translation stage that enables multiple FBGs to be written over a total fiber length of 250 mm with a positional accuracy of 0.1 mm. It has not been previously possible to accomplish this task with this level of accuracy and repeatability.

Widespread deployment of FBGs has been limited up until now partially because of the expense and difficulty of device fabrication. The new excimer-laser-based tool can write a single FBG in under 30 s, including fiber positioning, automatic phase-mask selection, exposure, and undocking of the fiber. This should dramatically reduce the unit cost of production FBGs while also delivering the unit-to-unit consistency critical to their successful use in sensing and other applications.

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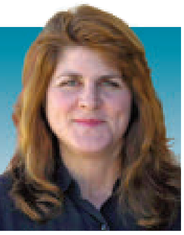

How spectrometers have shrunk and grown since 2010

GAIL OVERTON, Senior Editor

In 2010, *Laser Focus World* profiled a number of handheld spectrometer designs and their myriad applications. More than five years later, they continue to shrink in size and/or weight, yet grow in variety and performance to expand the sphere of applications served.

Handheld spectrometers, representing a middle-range spectroscopy capability compared to larger benchtop systems and tiny, narrowband chip-scale spectral engines such as ring resonator designs, continue to shrink in size and/or weight and yet grow in terms of measurement capability as trends in optics and sensor miniaturization continue within the photonics industry.

Whether an application requires a visible-light spectrometer, a Fourier-transform infrared (FTIR) instrument that does not experience the autofluorescence that can hinder Raman detection, or a Raman spectrometer to see through the spectral water peak of liquid samples, there is an abundance of handheld spectrometer manufacturers competing for the business of a seemingly endless list of customers that grows even longer with each performance improvement and price reduction.

Smaller, faster, better

"Our customers have inspired us to make ever-smaller spectroscopy instrumentation. They appreciate how miniaturization makes it easier to take the spectrometer to the sample, and to integrate the spectrometer into other devices," says Rob Morris, marketing operations manager at Ocean Optics (Dunedin, FL). "Since 2010, customer expectations are no longer about whether the device will work, but whether it will work as well as a laboratory-grade integrated benchtop spectrometer. 'Smaller, faster, better' are now basic assumptions with customers on how instruments evolve."

Morris says that the Ocean Optics Spark is a small spectral sensor operating from 380 to 700 nm that bridges the spectral measurement gap between filter-based devices such as RGB color sensors and CCD-array instruments such as miniature spectrometers by producing a digitized spectrum from a 1024-pixel array. Thermally stable over a -10°–60°C operating range and with signal-to-noise ratio (SNR) of 1500:1 and 4.5–9.0 nm full-width half-maximum (FWHM) resolution, Spark—as its customers expect—can be used for all types of spectral measurements,

FIGURE 1. Unmanned aerial vehicles (UAVs) are a logical platform for smaller, faster, and better handheld spectrometers. *(Courtesy of Ocean Optics)*

including absorbance, emission, and fluorescence.

At less than 40 × 42 mm and 24 mm high, the Ocean Optics STS microspectrometer also has a 1500:1 SNR, but with optical resolution as high as 1.0 nm FWHM. Available in ultraviolet (UV; 190–650 nm), visible (VIS; 350–800 nm), and near-infrared (NIR; 650–1100 nm) versions, the STS accommodates absorbance and emission measurements for point-of-care diagnostics and laser characterization while functioning as a handheld device for light metrology, color measurement, and remote monitoring applications such as volcano emission studies when mounted onto an unmanned aerial vehicle (UAV; see Fig. 1).

Beyond smaller, faster, and better, Morris says, the other exciting development for handheld spectrometers is how computing power and flexibility have advanced, making it simpler to acquire and process scientific data across many

FIGURE 2. The OreXpress spectrometer identifies minerals by comparing spectral traces against a library of 1500 known mineral spectra. *(Courtesy of Spectral Evolution)*

areas. "Today's computing capabilities did not exist when miniature spectrometers were first developed," adds Morris. "Now, computing and connectivity are driving spectroscopy into new applications."

Too much information?

As spectral resolution and data acquisition rates increase over time, so too does the amount of data needing to be processed by a handheld spectrometer. For example, the Spectral Evolution (Lawrence, MA) oreXpress spectrometer for mining exploration has an optional contact probe and EZ-ID software that allows geologists to identify minerals by matching up to 1500 known spectra in two mineral libraries (see Fig. 2).

OreXpress operates over a full UV/VIS/IR 350–2500 nm spectral range with 3/8/6 nm accuracy, respectively, and the ability to store up to 1000 data scans (acquired in as little as 100 ms) and save them in ASCII format—no post-processing necessary—for compatibility with SpecMIN, GRAMS, The Spectral Geologist (TSG), and other third-party software.

"Six years ago, there was no oreXpress," says Maurice Kashdan, VP of sales and marketing for Spectral Evolution. "Field spectrometers for mining were bulky, heavy, slow, not as accurate, and didn't have a full UV/VIS/NIR range. That said, creating bigger and better libraries of known 'fingerprints' for geology, mining, and vegetation and soil characteristics, for example, is the key for future development."

Next-generation FTIR

"Our design philosophy has always been that the needs of the application define the specifications of the instrument," says John Seelenbinder, FTIR market manager for Agilent Technologies (Santa Clara, CA). "Eight years ago, when A2 Technologies introduced the Exoscan handheld FTIR spectrometer, it was developed to measure thermal damage in epoxy composite used in aerospace applications, requiring a significant performance envelope in a 3.2 kg handheld configuration." Seelenbinder continues, "After Agilent acquired A2 in 2011, we redesigned the handheld FTIR instrument to not only have the performance to meet the growing body of applications, but to reduce the weight to 2.2 kg and improve its ergonomics, resulting in our easier-to-use recently introduced model 4300 Handheld FTIR."

Currently, Agilent's handheld FTIR spectrometers are used for a variety of material science applications, such as ensuring that surfaces are free of contaminants so that proper bonding of parts can be accomplished, tracking cleaning processes for a variety of surfaces, aiding in the maintenance of art and historical objects, determining that multi-part coating systems are properly formulated and applied, measuring weathering processes

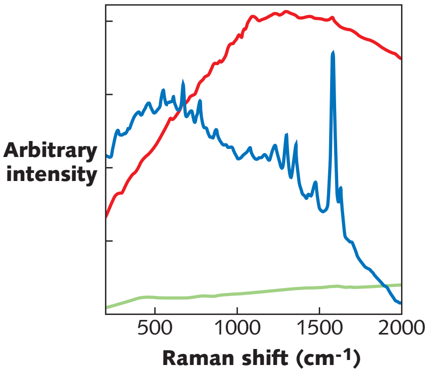

FIGURE 3. FD&C Blue #2 measured using 532 nm (green), 785 nm (red), and 1064 nm (blue) handheld Raman systems. The material is identifiable at the 1064 nm excitation wavelength but impossible to identify at shorter-wavelength excitation because of fluorescence background interference. *(Courtesy of Rigaku Analytical Devices)*

in polymers and paints, and verifying the identity of polymeric parts. They are even specified in the Boeing 787 Service Repair Manual for measuring thermal damage in composite airframe materials.

Next-generation Raman

In 2010, BaySpec (Fremont, CA) VP of sales and marketing Eric Bergles said that the spectrometers of old on bulky optical benches with expensive prisms, complicated alignment routines, and liquid-nitrogen cooling systems had been replaced by smartphone-sized handheld spectrometers with volumetric phase gratings, self-alignment /automatic calibration, and thermoelectric coolers.

In 2011, the BaySpec 2.3 kg FirstGuard Raman spectrometer technology with a 400–1750 nm wavelength range and a 500 mW, 785 or 532 nm source was sold to Rigaku Analytical Devices (Wilmington, MA). And in 2016, it has morphed into the even-smaller 1.5 kg Progeny family of Raman spectrometers with comparable wavelength range, but an adjustable power (30–490 mW) 1064 nm fluorescence-interference-minimizing source (see Fig. 3).[1]

Able to analyze 30% more materials than its predecessor designs, Progeny received the Bronze Award for the Portable Analytical Instrument Industrial Design category in the 2014 Instrument Business Outlook (IBO) design awards for its ability to provide comprehensive material identification and analysis across applications, including raw material identification in the pharmaceutical industry and chemical detection for first responders.

In 2013, instrumentation company SciAps (Woburn, MA) acquired then-Raman analyzer manufacturer DeltaNu and its one-handed ReporteR spectrometer for immediate identification of illicit drugs and explosives as well as other suspicious materials in liquid and solid form. Basically the size of a TV remote control and weighing just 400 g with a spectral library of 1500 signatures in 2010, ReporteR now weighs just 312 g and can easily store thousands of signatures.

FIGURE 4. The TruNarc Raman spectrometer provides noncontact, nondestructive testing for controlled substances for law enforcement. *(Courtesy of Thermo Fisher Scientific)*

With a built-in library of more than 60 controlled substances that can be updated regularly to account for emerging drug threats such as new synthetic cannabinoids, the 570 g handheld TruNarc—branded as the Thermo Scientific TruNarc analyzer—from Thermo Fisher Scientific (Waltham, MA) uses lab-proven Raman spectroscopy for a noncontact, nondestructive test for multiple controlled substances (see Fig. 4). TruNarc provides law enforcement personnel with clear, definitive results for presumptive identification of narcotics.

Thermo Fisher Scientific also combines FTIR and Raman spectroscopy in its Gemini analyzer, a two-in-one instrument that integrates these complementary and confirmatory chemical identification techniques in a rugged, handheld instrument that is smaller and lighter (1.9 kg) than carrying two individual instruments. And to keep individuals safe from radiological threats, the RadEye SPRD is a < 200 g personal radiation detector that adds nuclide identification capabilities. Advances in handheld Raman spectroscopy have also come to the pharmaceutical industry with the 900 g, 785 nm, 250 mW TruScan RM analyzer—smaller and lighter than the previous-generation TruScan—used by manufacturers for raw material identification and finished product inspection as part of the fight against substandard medicine.

Mid-IR miniaturization

Pyreos (Edinburgh, Scotland) advertises its handheld mid-IR spectrometer to be 10X lower in cost, 50X smaller and lighter, and 100X more robust than competitive portable mid-IR spectrometer designs, calling it the "world's smallest application specific spectrometer" at 4.5 × 2.5 × 1 cm and using "pioneering Mid IR sensor technology offering extremely low power array sensors solutions."[2]

The core technology is an IR sensor layer consisting of a thin-film of pyroelectric lead zirconate titanate (PZT) with a crystalline orientation that provides a spontaneous permanent polarization and high Curie point (>500°C). The IR sensor is deposited on a thermally insulating membrane layer suspended on top of a robust silicon frame, making a simple, uncooled microelectromechanical sensor (MEMS) device with a tunable response such that frequency and peak wavelength absorption can be custom-designed for wide applicability for liquid and solid analysis in the 5.5–11 μm fingerprint region and 2.5–5.0 μm window.

The Pyreos handheld spectrometer can be pre-loaded with chemometric calibration data and its simple software guides the user to application-specific analysis for oil, oil in water, wastewater, biodiesel, soil, food, pharmaceuticals, and medical analysis of urine, saliva, and multi-component liquids.

Application-specific trend

Joining Pyreos is a host of companies offering application-specific handheld spectrometers that address unique markets and a subset of materials applicable to those markets.

Sentronic (Dresden, Germany) offers the SentroID NIR laser-diode-array analyzer for fast identification and composition analysis of plastics and polymers, using classic methods of wavelength correlation, principal component analysis, and cluster-based methods to compare a NIR spectrum for an unknown material to its stored spectra. Weighing only 1.1 kg, SentroID spans a wavelength range from 900 to 1700 nm with 7 nm FWHM spectral resolution.

"Spectrometer system development combines hardware, software, and application knowledge to solve problems that would otherwise cost customers huge amounts in custom solutions," says Jason Pierce, director of business development for StellarNet (Tampa, FL), a manufacturer of low-cost, compact spectrometer instrumentation for more than 20 years.

"We have recently released a line of portable analyzer systems that utilize Raman, LIBS [laser-induced breakdown spectroscopy], and NIR spectroscopy techniques that can be used for raw material identification and elemental and composition analysis," adds Pierce. "These targeted systems can calculate percent moisture, fat, and protein in ground meat, for example, and are only a fraction of the cost of a more general analyzer." Pierce says that prices have been reduced 15–20% in the past few years and spectrometers have become more accessible to a broader customer base.

"In 2010, many compromises were made for handheld and portable instrumentation. For example, for portable Raman, it used to be that no available devices could meet all the desired specifications at the same time, including higher than 5 cm^{-1} [about 0.3 nm at 785 nm excitation] resolution, wider than 175–3300 cm^{-1} [796–1059 nm at 785 nm] coverage, smaller than 7 × 14 × 9 in., and better than below 5°C in detector array cooling," says Jack Zhou, CEO at B&W Tek (Newark, DE). "However, over the past six years, we have gone through two generations of portable Raman already and our B&W Tek i-Raman Pro can now offer resolution down to 3.5 cm^{-1} (about 0.2 nm at 785 nm excitation), 65–3300 cm^{-1} (789–1059 nm at 785 nm), and cooling down to -25°C while still maintaining the compact size. Indeed, we have witnessed the delivery of lab analytical capabilities to the field in portable and handheld format for onsite applications."

Software has also improved dramatically since 2010, says Zhou, with easy-to-use qualitative and analysis power, and data collected using portable Raman instrumentation is finally accepted for the most critical scientific research.

"The difference in LIBS is even more pronounced than for basic spectrometers," Zhou observes. "Six years ago, there were only benchtop LIBS available, with operator interpretation of results required for most of the spectra obtained. Yet now, B&W Tek and other vendors have been able to shrink the technology down to a handheld device while integrating with easy-to-use and powerful quantitative and qualitative models, targeting real-world applications."

As is happening with LIBS, cameras, optical communications components, light detection and ranging (lidar) instrumentation, and most all optoelectronic devices, the trend in miniaturization, improved performance, cost reduction, and the addition of added functionality for spectrometers will continue as long as the application list expands.

"Ancillary technologies are being incorporated in a number of handheld spectrometers to give the user more information or enable integration with other devices," says Richard Crocombe, senior director at PerkinElmer (Waltham, MA). "For instance, GPS is available with handheld XRF instruments, enabling field geologists to tag spectra with coordinates and feed the analytical results into maps; cameras and barcode readers are used in instruments designed for incoming raw material confirmation; and instruments used in hazardous material analysis can have built-in communications capabilities so that an operator in a 'hotzone' can communicate results to a field commander."

Alluding to the future of handheld spectrometers, Crocombe describes a fascinating study performed in the Netherlands where 8000 people were equipped with an add-on spectropolarimetric accessory to study atmospheric aerosols.[3] On one cloud-free day, 6007 measurements were made and correlated with both satellite and scientific ground station measurements. It was found that this "citizen science" could deliver, in real time, crucial data complementary to that from professional instrumentation.

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For More Information

Conference tracks related to handheld spectroscopy:

Pittcon 2016
Society for Applied Spectroscopy (SAS) Handheld Spectrometers Symposium (session 2110); Atlanta, GA; March 10, 2016; http://pittcon.org/plan-your-pittcon/#program.

SPIE Defense + Commercial Sensing
Next-Generation Spectroscopic Technologies IX (conference 9855); Baltimore, MD; April 18-19, 2016; http://spie.org/SIC/conferencedetails/next-generation-spectroscopic-technologies.

Companies mentioned in this article include:

Agilent Technologies
Santa Clara, CA
www.agilent.com

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

BaySpec
Fremont, CA
www.bayspec.com

Ocean Optics
Dunedin, FL
www.oceanoptics.com

PerkinElmer
Waltham, MA
www.perkinelmer.com

Pyreos
Edinburgh, Scotland
www.pyreos.com

Rigaku Analytical Devices
Wilmington, MA
www.rigakuraman.com

SciAps
Woburn, MA
www.sciaps.com

Sentronic
Dresden, Germany
www.sentronic.de

Spectral Evolution
Lawrence, MA
www.spectralevolution.com

StellarNet
Tampa, FL
www.stellarnet.us

Thermo Fisher Scientific
Waltham, MA
www.thermofisher.com

FOR A COMPLETE LISTING OF COMPANIES *making handheld spectrometers, visit the* Laser Focus World *Buyers Guide (http://buyersguide.laserfocusworld.com/index.html).*

Computational photonics models waveguide-based optics

MAREK S. WARTAK

This overview of available options for the numerical modeling of light propagation in integrated photonic structures aims at matching the user with the proper software for the job.

Computational photonics is a branch of physics in which numerical methods are used to study properties and propagation of light in waveguiding structures (here, "light" is used in a broad sense as a replacement term for electromagnetic waves). Within this field, an important part is played by studies of the behavior of light and light-matter interactions using analytical and computational models. This emerging field of computational science is playing a critically important role in designing new generations of integrated-optics modules and long-haul transmission and telecommunication systems.

Generally, computational photonics is understood as a replacement of the experimental method in which one is performing all the relevant "experiments" on a computer. Clearly, such an approach reduces development costs and speeds up development of new products.

An important subtopic in photonics is integrated photonics, where the concentration is on waveguides, simulations of waveguide modes, and photonic structures.[1] A central role is played here by the beam-propagation method.

At present, there is a significant critical mass of commercial software as well as public-domain programs, both of which are aimed at simulations of various photonic devices.

Commercially available photonics software

The following list represents our personal selections:

Optiwave provides comprehensive engineering design tools that benefit photonic, biophotonic, and system-design engineers with a comprehensive design environment.[2] OptiBPM, which is based on the beam-propagation method (BPM), offers design of complex optical waveguides that perform guiding, coupling, switching, splitting, multiplexing, and demultiplexing of optical signals in photonic devices. OptiFDTD is based on the finite-difference time-domain (FDTD) algorithm with second-order numerical accuracy and the most advanced boundary condition, namely uniaxial, perfectly matched layers. Solutions for both electric and magnetic fields in temporal and spatial domain are obtained using the full-vector differential form of Maxwell's equations. OptiFiber uses numerical mode solvers and other models specialized to fibers for calculating dispersion, losses, birefringence, and polarization-mode dispersion (PMD). OptiGrating uses the coupled-mode theory to model light and enable analysis and synthesis of gratings.

The *RSoft product family* includes a component-design suite to allow analysis of complex photonic devices and components through computer-aided design; system simulation to determine the performance of optical telecom and datacom links through comprehensive simulation techniques and component models; and network modeling for cost-effective deployment

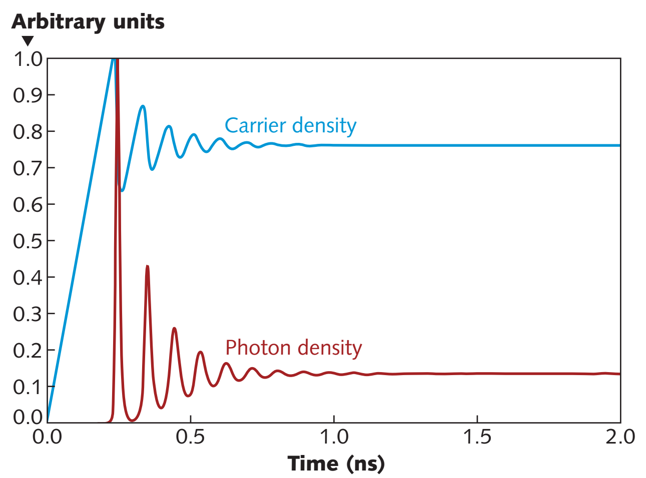

FIGURE 1. Shown are numerical solutions of large-signal rate equations for the active region of a semiconductor laser after applying a rectangular current pulse at t = 0. Results include the normalized values of electron density and photon density.

of dense wavelength-division multiplexing (DWDM) and synchronous optical network (SONET) technologies while designing and optimizing an optical network.[3]

Photon Design offers several products for both passive and active component design, including FIMMWAVE and CrystalWave.[4] FIMMWAVE is a generic, full-vectorial mode finder for waveguide structures that combines methods based on semianalytical techniques with other more-numerical methods such as finite difference or finite element. FIMMWAVE comes with a range of visual tools for designing waveguides, each optimized for a different geometry: rectangular geometries often encountered in epitaxially grown integrated-optics, circular geometries for the design of fiber waveguides, and more-general geometries to cover, for example, diffused waveguides or other unusual structures. CrystalWave is a design environment for the layout and design of integrated-optics components optimized for the design of photonic-crystal structures. It is based on both FDTD and finite-element frequency-domain (FEFD) simulators and includes a mask-file generator optimized for planar photonic crystal structures.

VPIphotonics provides simulation software supporting requirements of active/passive integrated photonics and fiber-optics applications, optical transmission system and network applications, and cost-optimized equipment configuration.[5]

Much other simulation software exists, mostly oriented towards the design of optical devices. A recent article reports on some relevant software packages.[6] Optical-design software is used by engineers and scientists to perform a variety of tasks, including illumination calculations, laser-beam propagation, stray-light analysis, and freeform optical design. Such software enables accurate and rapid virtual prototyping, allowing the performance of optical systems to be predicted and analyzed prior to fabrication. A number of websites are devoted to photonics software and numerical modeling in photonics. We mention the following website entitled Optical Waveguides: Numerical Modeling.[7]

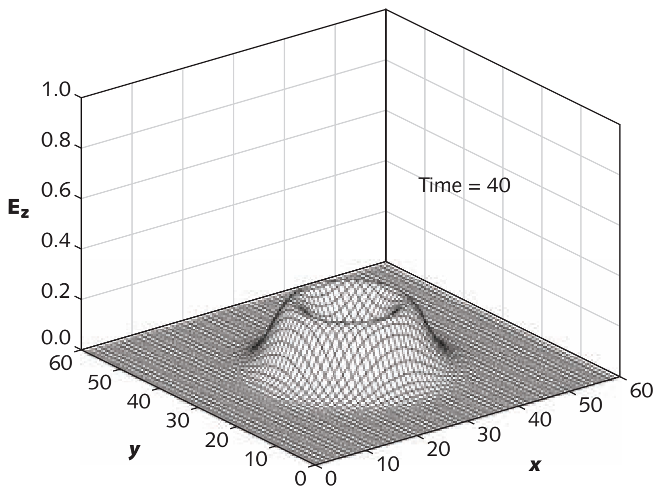

FIGURE 2. The propagation of a Gaussian pulse is modeled using the FDTD method. The pulse travels symmetrically outwards from the point at which it was initiated.

Two computational platforms: MATLAB and Octave

A special role in computational photonics in recent years has been played by the MATLAB and Octave computational platforms.

MATLAB (matrix laboratory) is a multi-paradigm numerical computing environment and fourth-generation programming language.[8] A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran, and Python.

GNU Octave is software based on a high-level programming language and is primarily intended for numerical computations.[9] It provides a command-line interface for solving linear and nonlinear problems numerically, and for performing other numerical experiments using a language that is mostly compatible with MATLAB. It may also be used as a batch-oriented language. It is part of the GNU Project, so it is free software under the terms of the GNU General Public License. Octave is the major open-source alternative to MATLAB and is almost 100% compatible with it.

MATLAB tools available for photonics simulations

The website MATLAB Central is an excellent resource for anyone looking for photonics-simulation software.[10] MATLAB toolboxes for optics and photonics simulations listed there include:

Interactive Simulation Toolbox for Optics. Based on the FDTD method, this software is aimed at simulations of two-dimensional optical systems. The Yee FDTD algorithm has been implemented—the user inputs parameters using a graphical user interface (GUI).

Optical Waveguide mode solver. This implementation, which is based on the semivectorial finite-difference method, was developed for finding the eigenmodes of various waveguides.

Semiconductor optical amplifier model. This simulates gain and spontaneous emission in semiconductor optical amplifiers (SOAs)—all details are also provided in a book.[11]

Optical Fiber Toolbox. This allows for fast automatic calculations of guided modes in optical fibers and finds solutions for weak and strong guiding.

Phase-based Optical Flow. This code implements a new technique for estimating the optical flow field starting from image sequences.[12]

Recent books devoted to photonics simulations

Salah Obayya, Computational Photonics, *Wiley (2011)*. "In this book, the author provides a comprehensive coverage of modern numerical modeling techniques for designing photonic devices for use in modern optical telecommunications systems. In addition, the book presents the state-of-the-art in computational photonics techniques, covering methods such as full-vectorial finite-element beam propagation, bidirectional beam propagation, complex-envelope alternative direction implicit finite difference time domain, multiresolution time domain, and finite volume time domain. The book guides the reader through the concepts of modeling, analyzing, designing, and optimizing the performance of a wide range of photonic devices by building their own numerical code using these methods."

Slawomir Sujecki, Photonics Modelling and Design, *CRC Press (2015)*. "The intention of this book is to introduce an engineer or applied physicist to the modeling and design of photonic devices. This book was written on the basis of both teaching and research carried out by the author. It is therefore written in such a way that it contains material suitable for both

undergraduate and master's students, but is also of benefit to PhD students and researchers interested in the modeling and design of photonic devices. The author has tried to avoid using specialized mathematical and quantum mechanical language to make this book approachable to a wider audience. Further, the book contains a strong 'hands-on' element that is backed up by several, relatively simple illustrative examples of software developed within the MATLAB environment."

Marek S. Wartak, Computational Photonics, *Cambridge University Press (2013)*. This book presents itself as a comprehensive manual on the efficient modeling and analysis of photonic devices. It is aimed at graduate students and researchers who are expected to have the theoretical background and MATLAB programs necessary for them to start their own numerical experiments. The author introduces the physics required to enable students to gain an understanding of photonics. The underlying philosophy is that conducting numerical experiments will deepen a student's understanding of the material. The amalgam of text and MATLAB programs provides the reader with a unique combination of photonics principles and simulation software. The book covers new topics like metamaterials, as well as staples such as optical waveguides and semiconductor lasers. The book's content has been "road-tested" at a number of universities in Europe and North America, and is the result of the author's 25 years of experience in the field. The book will be most useful to emerging photonics experts who have access to the necessary computer programs.

Two MATLAB examples

Examples of simulations using MATLAB are shown in the two figures. Phenomenological description of semiconductor lasers is often done based on the rate-equations approach.[13] The main role in those devices is played by two subsystems: carriers (electrons and holes) and photons. They interact in the so-called active region, defined as the part of the structure where recombining carriers contribute to useful gain and emission of photons. The dynamical processes there are described by rate equations that provide time evolution of photon and carrier densities. In Fig. 1, we show typical results of the numerical integration of large-signal analysis rate equations after applying a rectangular current pulse at time $t = 0$. Oscillations of both carrier and photon densities are observed. The frequency of these oscillations determines the rate at which energy is exchanged between photon system and carriers.

In Fig. 2, we show the propagation of a Gaussian pulse at some time value. The pulse was initiated at a central point and travels outwards symmetrically from there. The pulse propagation is governed by discretized Maxwell equations carried out using a widely used numerical FDTD scheme for an approximate description of electromagnetic-wave propagation—a two-dimensional implementation (the Yee algorithm) without dissipation. The details of numerical discretization and the relevant MATLAB codes are provided in Wartak's book, p. 275.

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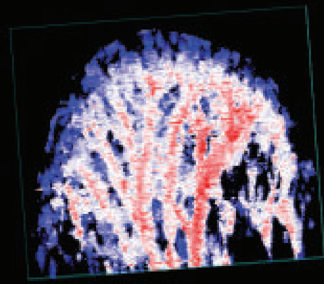

BioOptics News & Breakthroughs

BioOptics Features

Thanks, OSA!

The International Year of Light and Light-Based Technologies (IYL) may have concluded with the close of 2015, but there's still reason to celebrate: 2016 marks The Optical Society (OSA)'s centennial. OSA was launched to facilitate scientific collaboration, said society CEO Elizabeth Rogan: "Our founders saw the need to bring together the best scientific minds in industry and academia to share ideas in pursuit of technological breakthroughs." It's hard to say where the field would be without OSA's coalescing influence, but wouldn't Perley G. Nutting, the "applied optics" visionary who pursued its establishment for years and became founding president, be amazed to witness the fruits of optical scientists' collaboration? And to know that 270,000 folks are members today?

Barbara Gefvert
Editor in Chief
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Commenting on the centennial, 2016 OSA president Alan E. Willner emphasized life sciences. "In the years ahead," he said, "the field of optics has tremendous potential to address challenges such as supporting health and medicine as well as the continued exponential growth of the Internet."

A life scientist is chairing the society''s Centennial Advisory Panel: Chris Dainty, professorial research associate at Institute of Ophthalomolgy, University College London, has been working with staff and volunteers to develop a series of celebratory programs and products. Check out www.osa.org/en-us/100/osa100 and watch for activities throughout the year.

BioOptics World is grateful to OSA and all contributors. We think that, even considering its remarkable progress, Willner is correct to observe that, "We are only at the beginning of what optics technology can do."

online@biopticsworld.com

Optical fiber sensor could monitor IVF noninvasively
A new fiber-optic sensor can measure key parameters for IVF in a simpler manner and noninvasively. **http://bit.ly/1KI8a59**

Laser combo therapy for skin infection treatment
A laser therapy approach was shown to successfully treat cutaneous leishmaniasis, a skin infection. **http://bit.ly/1SIYAex**

Imaging cytometry technique optimizes cell cycle analysis
Imaging cytometry data could improve the identification of cell cycle phases. **http://bit.ly/1VurVD4**

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NEAR-INFRARED/NANOTECHNOLOGY

NIR, UV light combine for effective drug-delivery localization

Localized drug release hopes to improve cancer treatment and reduce the unhappy side effects of standard approaches. Now, researchers at McGill University (Montreal, QC, Canada) have developed an approach that combines the positives of two earlier proposals, and overcomes drawbacks of both.

They created nanoparticles able to convert near-infrared (NIR) light (which penetrates tissue, but has limited ability to trigger photosensitive drug carriers) into ultraviolet (UV) light (which effectively triggers drug release, but does not penetrate tissue well and is biotoxic).[1] The "secret sauce" is a UV-sensitive hydrogel coating infused with a fluorescent protein—which served as a stand-in for drug molecules in their experiments. When exposed to NIR light, the particles instantaneously converted the light to UV, which induced the shell to release the protein payload. The researchers note that the approach could also be used to target agents for imaging and diagnostics.

1. G. Jalani et al., *J. Am. Chem. Soc.*, 138, 3, 1078–1083 (2016).

LASER ARTERY DISEASE THERAPY

FDA approves next-gen laser atherectomy catheter

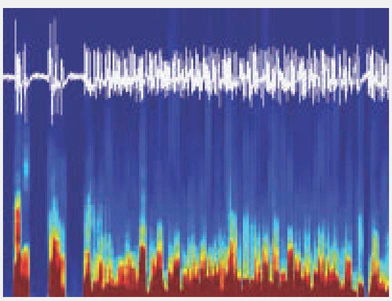
Spectranetics (Colorado Springs, CO) has received FDA 510(k) clearance for its Turbo-Power laser atherectomy catheter to treat in-stent restenosis (ISR). The company notes that laser atherectomy is driving a new standard of care for treatment of coronary artery disease, with improved clinical outcomes. The tool uses vaporizing technology to maximize luminal gain—it debulks the lesion in a single step and offers remote automatic rotation for precise directional control.

OPTOGENETICS/NEUROLOGY

Optogenetics-based discovery aims for sleep therapy, coma arousal

Recent studies show that subtle, chronic sleep problems are associated with such neurological disorders as Alzheimer's disease, Parkinson's disease, and schizophrenia, in addition to hormonal imbalance and high susceptibility to cardiac or metabolic disorders. Now, researchers from the University of Bern and Bern University Hospital (Germany) have used optogenetics to make a discovery that portends new strategies for medical treatment of sleep disorders—and even recovery of consciousness from vegetative states.[1]

The scientists identified a brain circuit in mice whose activation



EEG recordings from a mouse brain controlled with optogenetics show emergence from anesthesia. *(Image credit: Department of Clinical Research, University of Bern)*

causes rapid wakefulness, and whose inhibition deepens sleep. They engineered neurons taken from the hypothalamus to be controllable with millisecond-timescale light pulses. Then, they showed that activating these neurons produced wakefulness: Transient activation during light sleep quickly induced awakenings, while chronic activation maintained prolonged wakefulness. In contrast, optogenetic silencing of this circuit was shown to stabilize light sleep and increase its intensity. Thus, the circuit is a potential a new therapeutic target.

1. C. Gutierrez Herrera et al., *Nature Neurosci.*, doi:10.1038/nn.4209 (2015).

CELL IMAGING/CELL ANALYSIS

EUV-enabled spectrometry images cells in 3D at nanoscale

Researchers at Colorado State University (Fort Collins, CO) have developed a spectral imaging instrument that maps cellular composition in 3D at the nanoscale.[1] The system allows study of cells at approximately 100% greater detail than previously possible, enabling observation of cell response to drugs.

Precise positioning of cell samples allows laser drilling, which in turn enables chemical characterization and nanoscale anatomical charting in 3D.

The researchers explain that earlier laser-based mass-spectral imaging could identify the chemical composition of a cell and could map its surface in 2D at the microscale, but could not chart cellular anatomy in nanoscale or in 3D.

The instrument features a laser able to produce a hot, dense plasma stream that acts as a gain medium for generating extreme ultraviolet (EUV) pulses. When properly focused, the laser drills a tiny hole into a cell sample, enabling ions to evaporate from the cell surface. These ions can be separated and identified to determine chemical composition, and used to chart the anatomy of a cell.

1. I. Kuznetsov, *Nature Commun.*, 6, 6944, doi:10.1038/ncomms7944 (2015).

DENTAL LASERS

Biolase, IPG Photonics partner on dental lasers

Dental laser developer and manufacturer Biolase (Irvine, CA) has made a development and distribution agreement with fiber laser maker IPG Photonics' medical laser division, IPG Medical (Oxford, MA). The agreement covers several projects in various stages of development, with the expectation that these projects will yield commercial products, accessories, integral system components, and applications. Biolase will be responsible for U.S. and international registrations of all dental products resulting from the agreement, and will have exclusive worldwide commercial distribution rights for certain products over a multi-year initial term.

Moving toward MIR optical biopsy

ANGELA B. SEDDON, BRUCE NAPIER, IAN LINDSAY, SAMIR LAMRINI, PETER M. MOSELUND, NICK STONE, and **OLE BANG**

Advances in light source bandwidth, brightness, and portability are enabling the development of real-time in vivo *MIR imaging with the promise of early cancer detection, among other benefits.*

Limited availability of tests to diagnose cancer in its early stages has contributed to an unfortunate prevalence of late-stage diagnoses and metastatic spread. For this reason, emerging technologies that promise early diagnosis constitute a key focus of research. Mid-infrared imaging (MIR), with its ability to enable *in vivo* medical diagnosis, is particularly interesting. In fact, the European Commission provides support for a major effort to develop the technology through its Framework Seven (FP7) project called MINERVA (MId- to-NEaR- infrared spectroscopy for improVed medical diAgnostics).

Why MIR?

In 1800, Sir William Herschel used a thermometer to analyze sunlight passing through a prism, and detected "heat rays" beyond the red of the visible rainbow.[1] Discovering a "rainbow of colors" in the sunlight at shorter frequencies than those visible to the naked eye, he named the infrared (IR; Latin for "beneath red") region with far-reaching implications. Since then, we have come to divide the invisible IR rainbow into three light frequency regions: near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR) (see Fig. 1).

An interesting characteristic of the MIR is that oscillation frequencies of lightwaves in this region match the frequencies of characteristic vibrations of molecular bonds. Thus, bond vibration increases in amplitude when (resonantly) absorbing MIR light of the same frequency. Shining a bright MIR rainbow of light at a molecular sample and collecting the light after its interaction with a sample reveals that some MIR frequencies are diminished in brightness. That is, those frequencies have gone to stimulate particular molecular vibrations in the sample. This technique is called MIR spectroscopy and for any given sample, the complex pattern of

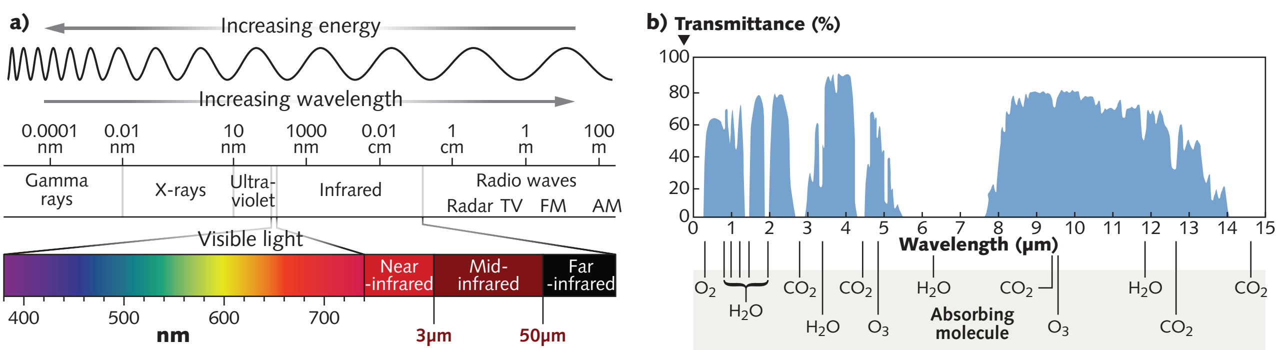


FIGURE 1. While there is discrepancy among scientific communities about boundary values on the electromagnetic spectrum, ISO standards define the mid-infrared (MIR) region as 3–50 µm (wavenumber: 3333–200 cm^{-1}) (a). The region covers the important atmospheric windows of 3–5 µm, referred to as the midwave (MWIR) range, and 8–12 µm, the longwave (LWIR) range. Wavelength limits of these atmospheric windows correspond with transmittance through a roughly one-mile sea-level path.[4] Note that only MIR light of certain frequencies will pass through Earth's atmosphere because molecules of carbon dioxide and water absorb MIR light at characteristic MIR frequencies (b).

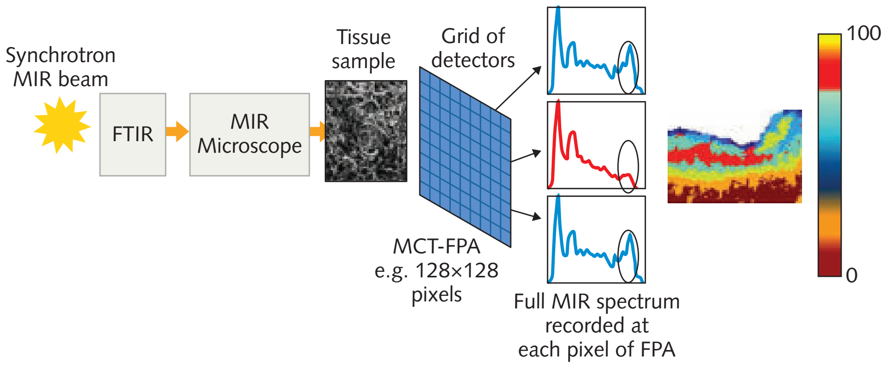


FIGURE 2. Traditional MIR spectral imaging of excised biological tissue involves a benchtop setup comprising a source (MIR blackbody or a synchrotron-generated MIR beam, as depicted here) passed through a FT-MIR spectrometer and onto the tissue sample in a MIR microscope. A MCT-FPA detector captures spectral images and records a full spectrum at each pixel. The acquired spectral sets are treated statistically to yield molecular discrimination across the MIR tissue image shown as a false color map. The false color map is obtained by establishing similarities in spectral patterns (mathematically), then grouping spectra accordingly, and finally assigning color codes to form an objective map—free from subjective assignment.

diminished and undiminished light frequencies is called the characteristic MIR spectrum of the material (see Fig. 2).

MIR molecular spectroscopy of cells and tissue

The MIR spectrum of a sample enables us to detect, identify, and even quantify its molecular makeup. Thus, we can sense numerous molecular gases, liquids, and solids, including biological tissues such as human cells, though the technique is also applicable to greenhouse gases; ground, water, and air pollutants; pharmaceuticals; toxic agents; narcotics and explosives; food and beverages; oil, oil products, and plastics; and more.

All living tissue is composed of cells, which comprise biomolecules[2]—DNA is one example. Biomedical MIR absorption spectroscopy on cells and tissue may be conducted either *in vitro* (in the laboratory) or *ex vivo* (in the laboratory, but with minimal alteration of natural conditions), as opposed to *in vivo* (in a live body). To understand the MIR spectroscopy of a collection of biomolecules as a living entity is a compelling notion!

Biomedical spectroscopist Max Diem, a professor at Northeastern University (Boston, MA), has been in the vanguard of *in vitro* and *ex vivo* MIR spectroscopy of human cells and tissue. His seminal paper[3] was critical of some prior work being too simplistic in using MIR absorption spectroscopy to detect malignant, as opposed to normal, cells and tissue. MIR spectral changes between diseased and normal tissue are subtle, and statistical analysis (principal component analysis or clustering techniques) of multiple MIR spectra are in fact required to confirm these differences.

Diem has highlighted that MIR spectroscopy of cells and tissue can potentially provide an immense amount of information on cellular composition, packing of cellular components, organ and cell architecture, metabolic processes, and the absence/presence of disease. Most importantly, he was the first to recognize that the spectroscopic information revealed by cells and tissue may revolutionize the way that pathology is performed in the 21st century. Pathology is the study and diagnosis of disease through examination of organs, tissue, cells, and bodily fluids.

Currently, *ex vivo* biomedical MIR molecular vibrational absorption spectroscopy is accruing evidence of the ability to distinguish excised diseased tissue from normal tissue.[4,5] MIR spectra are collected using a microspectrometer, a desktop instrument combining MIR microscopy with Fourier transform (FT) MIR spectroscopy (see Fig. 2). The MIR rainbow light source is usually either a

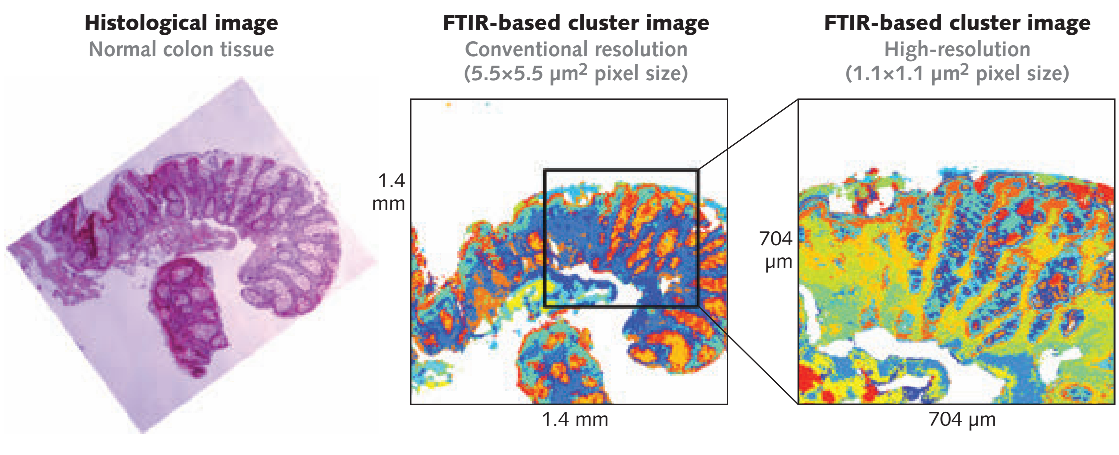


FIGURE 3. State-of-the-art MIR spectral images of excised normal colon tissue (right) provide more information than does a conventional histopathological micrograph of the H&E-stained colon tissue (left). *(Images courtesy N. Stone, University of Exeter, England[5])*

synchrotron MIR beam or conventional blackbody-type source (e.g., GloBar). MIR spectral collection across the lateral dimension of the tissue sample in imaging mode uses a focal-plane array (FPA)-type MIR mercury cadmium telluride (MCT) detector to collect directly a pixelated image based on the averaged MIR spectral absorption of tissue captured per pixel to obtain a visual representation of the molecular makeup of a tissue sample in terms of false color maps. MIR micro-spectroscopic imaging is widely recognized as nondestructive, label-free, and highly sensitive, and is applied particularly *ex vivo* in cancer research and diagnosis on excised tissue. State-of-the-art MIR MCT FPA imaging of excised tissue from the MINERVA Project is shown in Fig. 3.[5]

Today's gold standard for cancer diagnosis is histopathology, which involves microscopic study (using visible light) dye-stained cells and tissue. Most major hospitals are equipped with a "path lab," where excised tissue, taken from the patient, is frozen, microtomed into slices <10 μm thick, and then individually mounted in sequential order on microscope slides and stained with hematoxylin and eosin (H&E) dyes to reveal cell and tissue morphology (shapes). A pathologist's examination of the processed tissue informs diagnosis and treatment planning. Histopathology is time- and labor-intensive, highly dependent on the judgment of the pathologist, and involves patient discomfort and stress while awaiting the biopsy results.

In vivo imaging with MIR

The goal of the MINERVA project is, instead, to achieve *in vivo* MIR molecular vibrational spectroscopy. MIR optical biopsy *in situ* in the body aims to provide fast, real-time cancer diagnosis to reduce patient discomfort. For example, MIR endoscopic monitoring of cancer margins during surgery (including during MIR fiber laser surgery) would involve portable, inexpensive MIR photonic systems capable of being used in either a hospital/clinic setting or a primary-care practice. This new paradigm will be enabled through focused development of MIR photonic devices and systems that are robust, functionally designed, safe, compact, cost-effective, and based on active and passive MIR optical fiber.[7-9]

MIR cell and tissue studies have typically involved a benchtop FT MIR spectrometer designed to keep the weak blackbody-type MIR source, sample, and MIR detector in close enough proximity that MIR photons can complete the optical circuit. Alternatively, excised cell and tissue samples are taken to a non-portable, bright synchrotron MIR source. Key to development of *in vivo* systems are MIR light sources that are broadband, very bright, and portable.

Within the MINERVA project, the MIR Photonics Group at the University of Nottingham (England), in conjunction with researchers at Technical University of Denmark (DTU; Copenhagen, Denmark), has demonstrated extreme broadband supercontinuum (SC)-generated light 1.4–13.3 μm in a specially engineered, high-numerical-aperture MIR optical fiber (see Fig. 4).[9,10] These active MIR fibers, exhibiting broadband supercontinuum lasing, have the potential to rival the brightness of even synchrotron-produced MIR light—thus offering, for the first time, the possibility of a bright MIR wideband source in a portable package. The work has been corroborated by others.[11]

Narrowband MIR fiber lasers[12,13] are now required to pump the broadband SC fiber to provide a complete fiber solution for bright, MIR broadband sources as well as for stand-alone devices for coherent tissue imaging and new MIR laser surgery (see Fig. 5). In addition, MINERVA

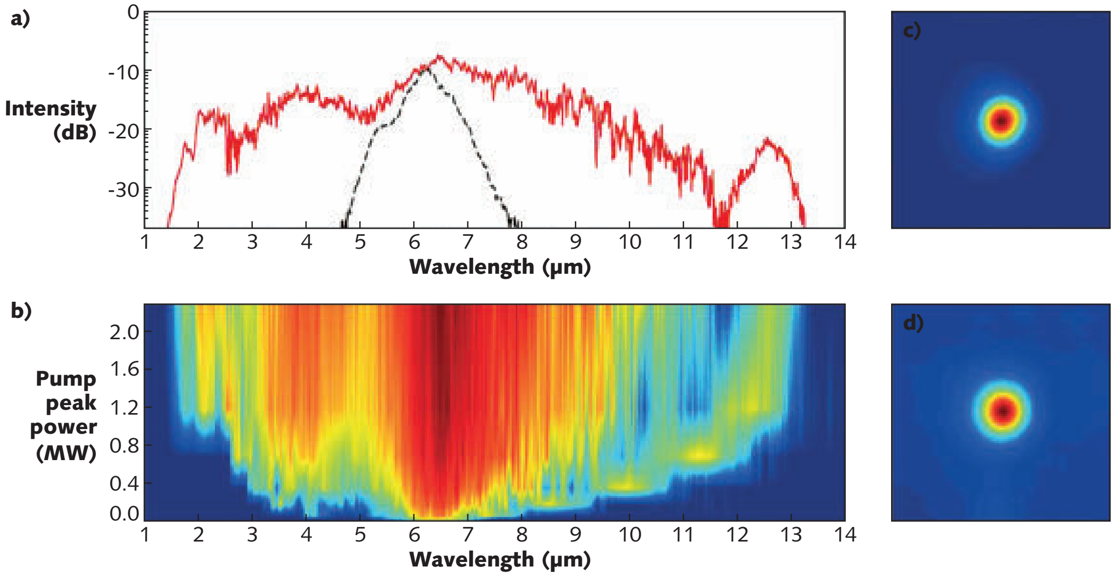


FIGURE 4. Achieving record extreme broadband supercontinuum-generated light in a specially engineered MIR optical fiber involves input pump spectrum (dashed line) and spectral profile at maximum pump power (solid line), showing broad, flat supercontinuum (1.64–11.38 μm at -20 dB) followed by a strong spectral peak extending the spectrum all the way to 13.3 μm (a).[9] Spectral evolution with increasing pump peak power shows a gradual redshift of a distinct spectral peak at the long-wavelength edge, plus corresponding formation and blueshift of dispersive waves (b). Fiber output near-field beam profiles—for all wavelengths of input pump spectrum (c) and beam profile for wavelengths >7.3 μm only (d)—show that long wavelengths are still confined to the core. This exceeds previous record values by factor of two.[10]

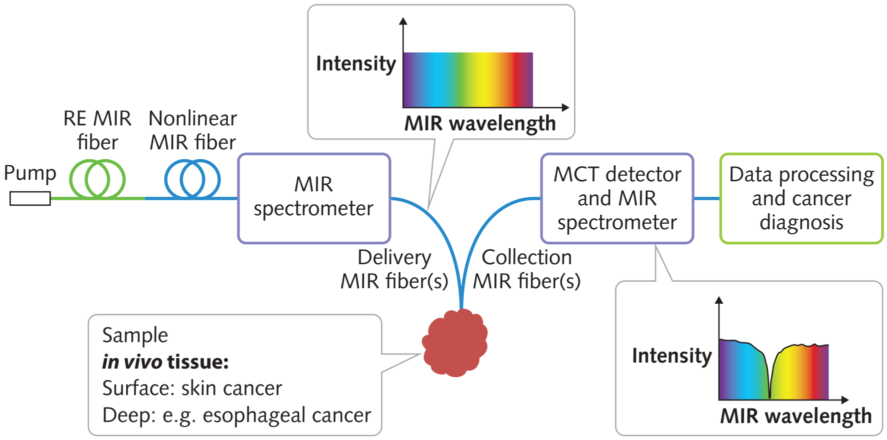


FIGURE 5. The proposed methodology for *in vivo* MIR spectral bioimaging (that is, MIR optical biopsy) involves a benchtop setup comprising a bright MIR supercontinuum source—a rare-earth (RE) MIR fiber laser pumping a nonlinear MIR fiber. The light is passed through a FT-MIR spectrometer and onto a patient's lesion. A passive MIR fiber collects the signal. The spectral sets acquired from the light-tissue interaction are treated statistically to yield molecular discrimination and early cancer diagnosis. *(Schematic adapted from original drawing by L. Sojka, MINERVA Fellow, University of Nottingham)*

participants have developed record-breaking low optical-loss fiber for routing MIR light.[14] Such low-loss routing is key to enabling *in vivo* and real-time MIR spectroscopic monitoring of malignant and normal tissues.

Availability of low optical-loss silica glass fiber has enabled the development of Raman scattering for *in vivo* MIR optical imaging, another emerging clinical technique. Raman and MIR absorption are both vibrational spectroscopies, governed by different quantum mechanical selection rules. Because the MIR approach is based on direct fundamental vibrational molecular absorption, it is potentially more sensitive, with excellent contrast for clinical application. While the Raman effect is intrinsically weak, its spectral output can complement that of MIR absorption, so together the approaches can work synergistically.

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The wide-ranging benefit of photoacoustic commercialization

KATHY KINCADE

Laser-induced acoustic imaging uniquely enables functional visualization deep into tissue. Advances in lasers are facilitating the commercial emergence of highly tunable, noninvasive tools that promise great benefit for a broad range of applications—and ultimately, for patients.

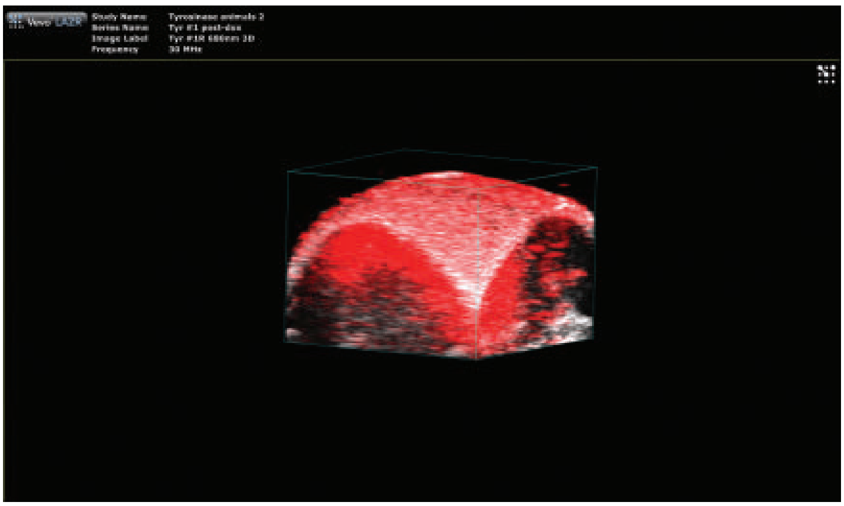

FIGURE 1. A photoacoustic image of melanin expressed under the tyrosinase reporter in a subcutaneous tumor. *(Courtesy of VisualSonics)*

Biomedical imaging has enabled many advances, thus feeding and sustaining a thirst for better ways to visualize what can't be seen with the naked eye. From x-ray and ultrasound to confocal microscopy and optical coherence tomography (OCT), each new modality offers some balance among resolution, scope, and functionality to yield helpful details about what makes our bodies tick.

A duo for depth

Of course every modality has some restictions. Optical techniques are impacted by light scattering, which limits the amount of information that can be captured and the quality of images produced. But photoacoustic imaging (a.k.a. optoacoustic imaging) combines the best of two worlds to overcome this limit, and provides unique benefit to boot. *Optical* stimulation of *acoustic* signals enables multi-scale, high-resolution, noninvasive imaging of both structure and function deep into tissue.

"When you are talking about going inside the body, you need infrared light, between 650 and 1000 nm. That will get you a few centimeters' penetration into the human body, which is quite a bit," said Eli Margalith, CEO of Opotek, which supplies Nd:YAG-pumped optical parametric oscillators (OPOs) to research labs and equipment manufacturers for their photoacoustic imaging systems. Thanks to the use of OPOs for acoustic signal creation, many photoacoustic imaging systems allow wavelength tunability, so a single device can serve multiple applications.

"Photoacoustic imaging is showing real promise as an alternative to MRI and CT scans," added Patrick Maine, president of Quantel Laser, which makes the Nd:YAG lasers used in Opotek's OPOs. "We are seeing strong research interest driven by the high resolution enabled by this technique. And it is encouraging to see this beginning to move out of the lab and into clinical applications."

The photoacoustic effect was discovered by Alexander Graham Bell in the 1800s, but it took another century for the technology to catch up.[1] In photoacoustic imaging, a short-pulsed laser is used to produce ultrasound in tissue. When the laser energy hits the target tissue, it heats and expands, generating an acoustic signal that can be reconstructed to show the distribution of optical absorption inside the target.

Because the ultrasonic scattering coefficient in tissue is two to three orders of magnitude less than its optical counterpart, photoacoustic imaging overcomes the optical diffusion limit (~1 mm in the skin) found in high-resolution optical-contrast imaging. And because either unscattered or scattered photons can trigger the photoacoustic signals, photoacoustic waves can be generated several centimeters deep into tissue—currently 1–7 cm.[2] As a result, light-absorbing structures inside these tissues can be detected and visualized with resolutions far superior to optical methods at those depths and without the need for biomarkers.

Uniquely reveals function

"The functionality you get from photoacoustic imaging is key," Margalith said. "When you do ultrasound, you get morphology, you get information about different organs and where they are, but you do not have any information about functionality. With the laser as the initiating mechanism for the ultrasound, functionality becomes the main reason. You can measure, for example, the oxygen level in the blood in real time. You cannot do that in any other imaging modality."

As a result, the biomedical research community has been excited about the possibilities of photoacoustic imaging for decades. Preclinical applications include the study of non-fluorescent pigments, angiogenesis, microcirculation physiology and pathology, drug response for screening, and brain functions. In addition, photoacoustic microscopy and photoacoustic tomography devices are being developed for a variety of clinical point-of-care applications, including cancer screening, brain imaging, intravascular catheter imaging, chemotherapy monitoring, and blood flow/oxygenation imaging (see Figs. 1-3).

For example, Lihong Wang, a professor of biomedical engineering at Washington University in St. Louis (Missouri) and a pioneer in the development of photoacoustic imaging techniques and technologies, has made major inroads in the study of the brain. His research has attracted nearly $50 million in grant funding, including a three-year, $2.7 million award as part of the BRAIN Initiative, and his lab (now relocating to Caltech in Pasadena, CA) is credited with being the first to report on functional photoacoustic tomography, 3D photoacoustic microscopy, and photoacoustic endoscopy, among many others. In spring 2015, they announced yet another photoacoustic breakthrough: the ability to visualize single capillaries and blood oxygenation in the brain through the intact skull of a mouse.

Market emergence

Slow to start, commercialization of photoacoustic imaging is at last gaining momentum. TomoWave (Houston, TX) a startup founded by optoacoustics pioneer Alexander Oraevsky, is commercializing

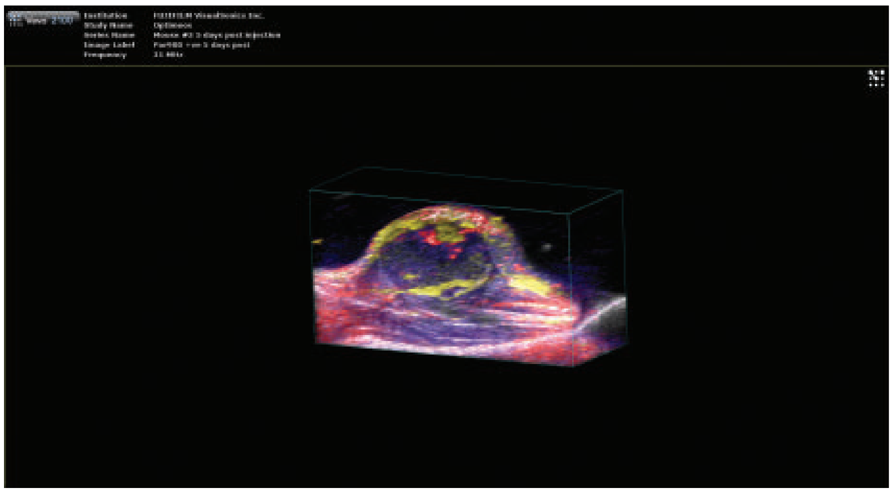

FIGURE 2. A D-coregistered ultrasound (grayscale) and photoacoustic image of a subcutaneous mouse hindlimb KB tumor showing nanoparticle microdistribution (yellow), deoxygenated hemoglobin (blue), and oxyhemoglobin (red). *(Courtesy of VisualSonics)*

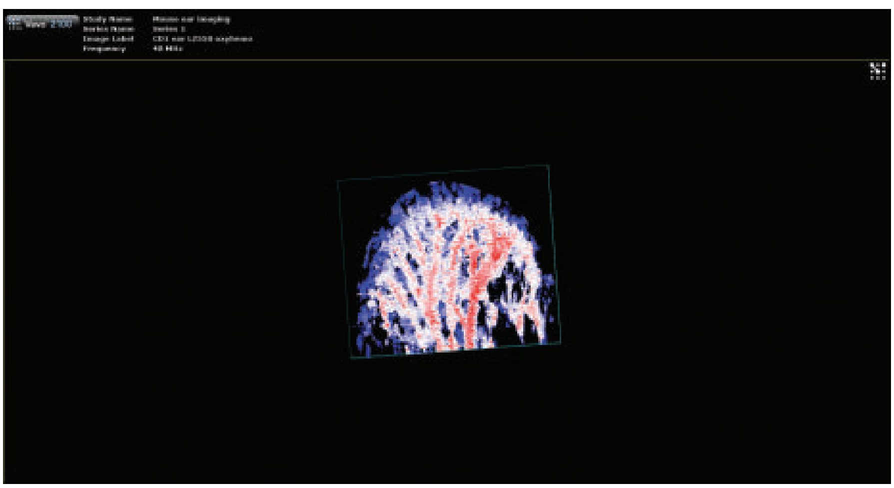

FIGURE 3. A photoacoustic image of vasculature in a mouse ear shows an oxygen saturation map of the vasculature (red = high oxygen saturation, blue = low oxygen saturation). *(Courtesy of VisualSonics)*

the Laser Optoacoustic Ultrasonic Imaging System Assembly (LOUISA) for breast imaging. The system provides 3D full-view optoacoustic tomography that works in conjunction with laser-generated ultrasound to produce functional and anatomical maps with high sensitivity, high resolution, and minimal artifacting or distortion.[3] And Seno Medical Instruments, which acquired the rights for the first core patent by Oraevsky, is leading the commercialization of a handheld two-dimensional optoacoustic and ultrasound device based on that patent.

Meanwhile, the European FULLPHASE project launched in October 2012 is making headway in its development of a portable, multiwavelength photoacoustic/ultrasound system for point-of-care disease detection and treatment monitoring in oncology, rheumatology, and cardiovascular disease (see Fig. 4). Among the project participants is Quantel, which was selected to provide the diode lasers for this program because of the company's unique ability to efficiently package high-power quasi-continuous-wave (QCW) diode stacks and arrays, according to Andreas Kohl, technical lead for Quantel's diode laser group.

"The diodes we provide are very short pulse, about 90 ns or less, so for penetration depth we also need high pulse energy," Kohl said. "We started with 1 mJ and are now going up to 4 mJ. And that is where it gets critical, because if you have high pulse energy and short pulses, you have very high electrical currents driving the diodes, and this is meant to be a handheld device. So you want to make sure the lasers are very efficient because you want to make sure that the generated heat does not burn the hand of the person using it."

Important endorsements

Another sign that photoacoustic imaging is "arriving" in medicine is that large companies are beginning to invest in it. For instance, Canon is commercializing a photoacoustic mammography system developed by the startup OptoSonics (Oriental, NC). And in 2010, Sonosite—a subsidiary of Fujifilm and a leading manufacturer of point-of-care ultrasound equipment—spent $71 million to acquire VisualSonics, a manufacturer of real-time, ultra-high-frequency micro-ultrasound technology. Now, VisualSonics is marketing the Vevo LAZR photoacoustic imaging system that offers a selection of modalities, from micro-ultrasound, Doppler, and microbubble contrast to photoacoustic. The system uses an OPO pumped by a doubled Nd:YAG laser that is tunable from 680 to 970 nm, and features a repetition rate of 20 Hz, pulse width of 5 ns, and pulse energy of 50 mJ.

"We are a preclinical ultrasound company that is using pulsed laser light to generate acoustic signals," said Drew Heinmiller, photoacoustics product manager at VisualSonics. "The OPO allows us to change the wavelength of the laser, which is key to being able to do just about anything in photoacoustic imaging."

In addition to its conventional cardiovascular market, VisualSonics is targeting applications in cancer research, where the ability to tune the laser to measure blood oxygenation levels in real time is a major advantage for tumor monitoring and analysis.

"We can tune the laser and do a calculation to show in an image, with very high resolution, what the oxygen saturation status of the blood is," Heinmiller said. "So now we measure how much oxygen the blood is carrying in real time, *in vivo*, in animal models."

Combining photoacoustic imaging with ultrasound offers additional insights into the disease process, he noted.

"One of the benefits of having ultrasound in this system is that you can use it to find the tumor, and then you can overlay the oxygen information on top of the ultrasound image and it gives you a physiologically relevant parameter (oxygen saturation) and allows you to place the tumor within the anatomy," Heinmiller said. "If you're using just photoacoustic imaging, you would be looking at blood vessels, vasculature, etc., but you wouldn't necessarily know exactly where it was located."

Also entering the commercial sector is another photoacoustic imaging pioneer, John Viator, who began his biomedical research career in 1995 in Steve Jacques' lab at Oregon Health and Science University (Portland, OR). Viator's company, Acousys Biodevices, is focused on using photoacoustic flow cytometry to detect circulating tumor cells, a technique he invented while at the University of Missouri. His company is initially targeting melanoma, the most aggressive type of skin cancer.

"We use the Opotek device in our laboratory since it is an outstanding tunable source," Viator said. "While the OPO was critical in our laser wavelength studies in device development and engineering, our commercialized device will probably be a single wavelength device, since it doesn't need the flexibility of the OPO."

Acousys' device emits laser light into enriched blood cell samples to determine whether cancer cells are lurking among millions of white blood cells. Melanin within the cancer cells uniquely absorbs the light, which generates high frequency acoustic responses detected by sensors in a photoacoustic flow meter. The device has been shown to detect and capture as little as a single melanoma cell from a sample of 10 mL of blood, and sample processing takes only 20–30 min. Captured cells can be further analyzed.

"Once you capture these individual cancer cells, you can do molecular tests, genetic tests, image them under a microscope, and learn more about that particular cancer and how it's spreading," said Viator, who, in addition to heading Acousys, leads the biomedical engineering program at Duquesne University. "Instead of blindly prescribing chemotherapies, if you capture the individual cells that are spreading, you can verify the type of melanoma that responds well to a certain drug."

It also offers a number of advantages over other emerging methods for this application, he noted.

"As far as finding circulating tumor cells or other pathological particles in body fluids, photoacoustics, number one, is gentle," Viator said. "You're just sending some photons to it, not

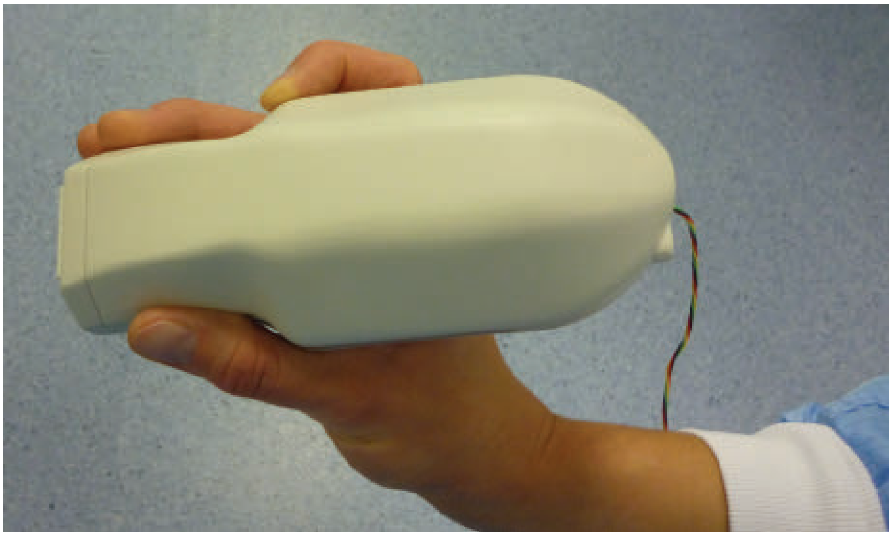

FIGURE 4. The FULLPHASE photoacoustic handpiece probe. (*Courtesy of Quantel Laser*)

chemically altering it or destroying the cell. You're not making contact through some sort of substrate, just keeping it in the body fluid and sensing it by adding a little laser energy and then listening to the acoustic response. And it is fairly rapid compared to competing technologies for finding pathological particles in body fluids."

Opportunity for photonics

These advances bode well for component manufacturers. Gregory Smolka, VP of sales and marketing for Quantel, describes a long history of creating OEM sources for biomedical devices, and years of effort in photoacoustics, working with groups using pulsed Nd:YAG directly, as well as those using different wavelengths via OPOs or dye lasers. "We're investing to help develop this rapidly emerging application," Smolka says—an application that portends great benefit for photonics developers, systems innovators, and for patients.

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Kathy Kincade *is the founding editor of* BioOptics World *and a veteran reporter on optical technologies for biomedicine. She is currently editor-in-chief of DrBicuspid.com, a web portal for dental professionals.*

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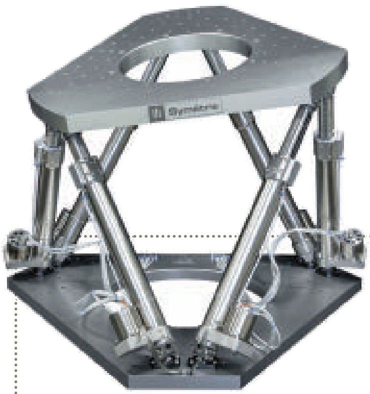

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Designed to position payloads of up to 400 kg with a resolution of 50 nm, the Zonda hexapod offers travel ranges of 400 mm in *xy*, 300 mm in *z*, and 40° in the three rotations *Rx*, *Ry*, and *Rz*. It is built with an iron-nickel alloy with a low thermal expansion coefficient of 1 μm/m/°C.

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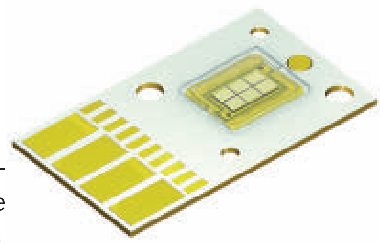

The Ostar Projection Power monochrome LEDs allow projectors to use LEDs as the sole light source. The LED consists of six 2 mm^2 chips operating in parallel, and measures 27 × 16 × 2.1 mm. At 36 A pulsed, typical brightness is 4500 lm for the red version, 11,000 lm for converted green, and 33 W for blue.

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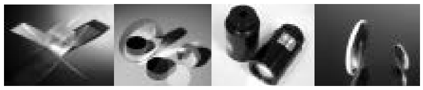

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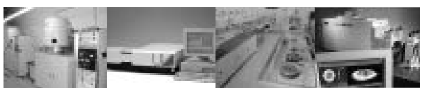

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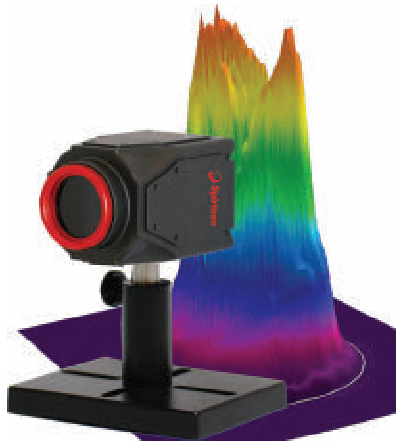

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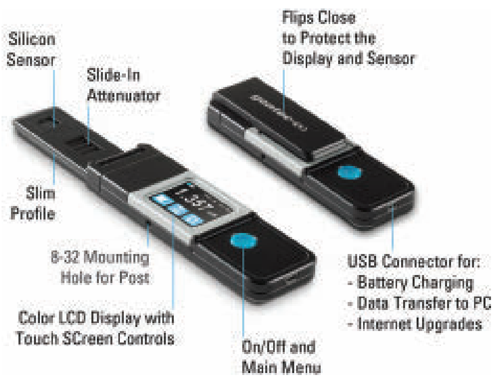

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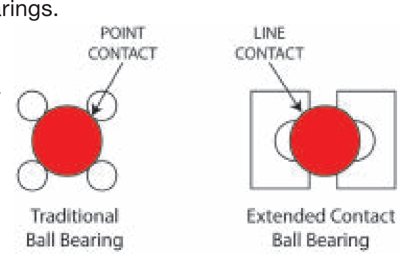

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engineers—certainly less willing to pay exorbitant salaries to attract them like it did at one time.

YSL: Indeed, the exchange between Silicon Valley and Hsinchu has slowed down in the past 15 years. Now, Taiwan is at a crossroads because innovation has stagnated during the same period of time and she must transform into an innovation-based and value-added industry to remain competitive globally. Not only are fewer Taiwanese students studying in the U.S., but returning talents are now attracted by many opportunities in China because of strong government support and investment. The relatively low salaries for engineers in Taiwan—now ranked almost at the bottom among the advanced countries—not only makes recruiting difficult, it has also caused talent drain in recent years.

Courtyard view of the Industrial Technology Research Institute headquarters in Hsinchu, Taiwan. *(Photo provided by ITRI)*

MC: ***How has all of that impacted Taiwan?***

YSL: The ingrained OEM business model that worked well for a long period of time has hindered the rapid transformation to an innovation-based economy. Companies like Acer, Asus, and Benq are having difficulty in building a brand name to compete in the marketplace. In addition, the rapid development in the Internet of Things (IoT), cloud computing, and social media have disrupted the B2C business models, and the rapid ascent of giant corporations like Alibaba, Tencent, Lenovo, and Hwawei in China have left the Taiwan industry behind. To compete in this rapidly changing, sometimes-stormy world, Taiwan must find a niche and excel in what she does best. Largan Precision is such a company that stands out as one of the leading suppliers in the world making plastic aspherical lenses for mobile phones, digital cameras, and tablets.

MC: ***What is the Taiwan government doing to promote the link between Taiwan and Silicon Valley?***

YSL: Government's National Development Fund (NDF) and Ministry of Science and Technology (MST) just announced a $120 million Taiwan-Silicon Valley fund for establishing an investment network in Silicon Valley in areas of biotechnology, medical devices, the IoT, and clean energy. Specifically, the government is setting up in Taiwan the Innovation and Entrepreneurship Center (TIEC) and Taiwan Rapid Innovation Prototyping League for Entrepreneurs (TRIPLE). TIEC will link startup teams with global potential in Taiwan to renowned accelerators in Silicon Valley. In addition, the center will assist startup teams internationally to tap into the resources of TRIPLE and enable Taiwan to serve as a key player in the global innovation supply chain. This two-way exchange will strengthen links between Taiwan, Silicon Valley, and the rest of the world.

MC: ***What else is in Taiwan's comeback strategy?***

YSL: Recognizing that software is critical to the knowledge-based industry in the 21st century, the government in 2000 started the first software technology park in Kaohsiung, focusing on information technology and digital content. With investment close to $1 billion, the Park is now operating in its full capacity with 250 companies. In 2007, the government created "Nankang Economic and Trade Park" in the suburb of Taipei to create a world-class environment for R&D in software, system-on-a-chip (SOC), digital content, and industrial design. In 2012, the government started another major software park in Taichung.

Some of these efforts have paid off, as evidenced by a recent announcement of Google choosing the Changhua County in Taiwan for her first datacenter in Asia, with a total long-term investment exceeding $1 billion. Google is building one of the most energy-efficient and environmentally friendly datacenters in the world by employing some innovative thermal management technology.

MC: ***Have your universities played a part in rejuvenating the economy?***

YSL: Increasingly, innovative ideas are found and generated in the early stages of learning processes. Universities are not only places for education and research, but also the sources of innovative ideas, entrepreneurship, and startups. Companies such as Microsoft, Google, Facebook, and Yahoo were founded by college students, graduates, or dropouts!

More and more universities are making entrepreneurship a part of their curriculum. In 2014, National Tsing Hua University was ranked 11th in the world in the number of patents granted to universities, on par with Columbia University and the University of Michigan. Colleges in Taiwan also perform well in global competitions such as Science Olympia and in global invention competitions.

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Part 2: Taiwan embraces photonics as regional competition intensifies

MILTON CHANG

Last month's interview with Dr. Y.S. Liu continues. His viewpoint on how to improve the economy in Taiwan may be applicable here in the U.S.

Milton Chang: *What is the purpose of your recent trip to Silicon Valley?*
Y.S. Liu: I accompanied a delegation from Hsinchu, Taiwan, led by Governor Chiu and consisting of government officials and the Secretary-General of the Science-Based Industrial Park (SBIP) to visit several innovation centers, including the Plug and Play Tech Center and H&Q's Global Innovation Center. We also met with local officials in Santa Clara, which is a sister county of Hsinchu. Silicon Valley is the undisputed leader in innovation and there is much to be learned from her culture, social and economic structures, and people's mindset.

MC: *What is your take on incubators?*
YSL: These incubators are intended to establish a global ecosystem for innovation by networking entrepreneurs, and bringing together corporations and investors to accelerate the process of innovation and commercialization. From this visit, I learned that Plug and Play has reviewed 4000 startups, invested in over 100, and worked with 180 leading Silicon Valley VCs and 300-plus corporate partners. So far, they have raised $3.5 billion in funding to support entrepreneurs.

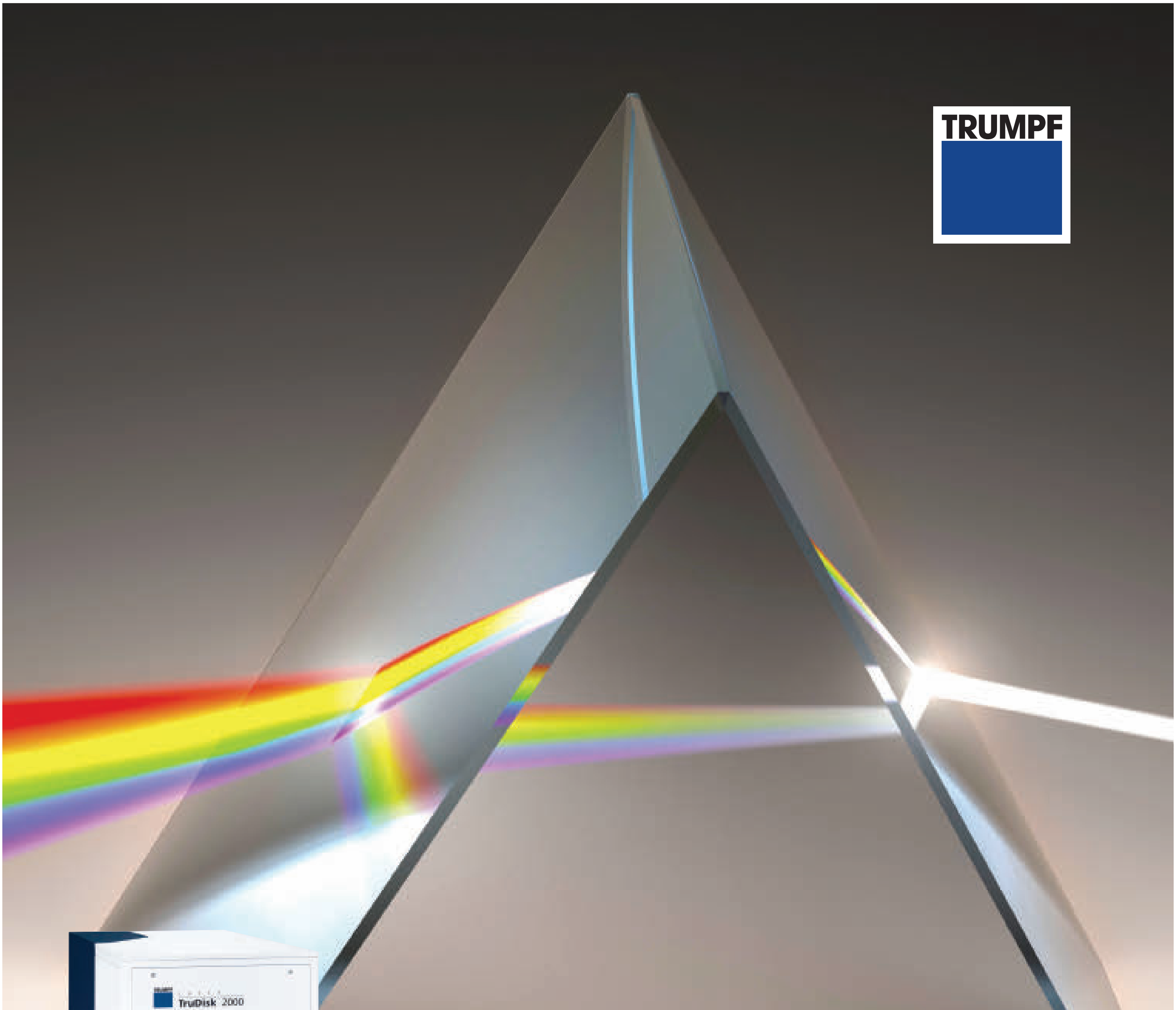
MC: *Can what we do here be applied in Taiwan?*
YSL: I think so because of the similarities—Hsinchu is often referred to as the Silicon Valley of Asia. In Hsinchu we have SBIP and ITRI—two leading research universities—and several major national research laboratories, including a new, state-of-the-art 3 GeV Synchrotron Light Source Facility. We have perhaps the world's most sophisticated semiconductor supply chains and advanced logistics, with the world's largest IC foundry, design houses, packaging, and test companies. These companies are all located within a 2- to 3-hour distance. In addition, there are abundant well-trained students supplied by National Tsing Hua University and National Chiao Tung University, much like Stanford University and UC Berkeley to Silicon Valley. And there is ample investment capital. These are the proven attributes that led to the growth of a very dynamic, innovative, and prosperous electronics industry in Taiwan from the 1980s and on.

MC: *Government support must have helped. What else has been attributed to the success?*
YSL: Liberal tax policies on profits such as stock option and tax incentives for companies in SBIP have made a difference. One of the factors that was beneficial to SBIP and ITRI was the close coupling with Silicon Valley and the likes in the U.S. Many companies here were formed by expatriates from Silicon Valley working in partnership with local industrialists. Many Taiwanese companies also set up research facilities in Silicon Valley. This kind of close coupling ensured the constant inflow of innovative ideas, talents, and technology.

MC: *Why the recent attention? My impression is Taiwan in recent years has not been actively recruiting overseas*

continued on page 66

MILTON CHANG of Incubic Management was president of Newport and New Focus. He is currently director of mBio Diagnostics and Aurrion. He is a Trustee of the California Institute of Technology and has served on the SEC Advisory Committee on Small and Emerging Companies and the Visiting Committee on Advanced Technology of the National Institute of Standards and Technology, and the authoring committee of the National Academies' Optics and Photonics: Essential Technologies for Our Nation. Chang is a Fellow of IEEE, OSA, and LIA. Direct your business, management, and career questions to him at miltonchang@incubic.com, and check out his book Toward Entrepreneurship at www.miltonchang.com.

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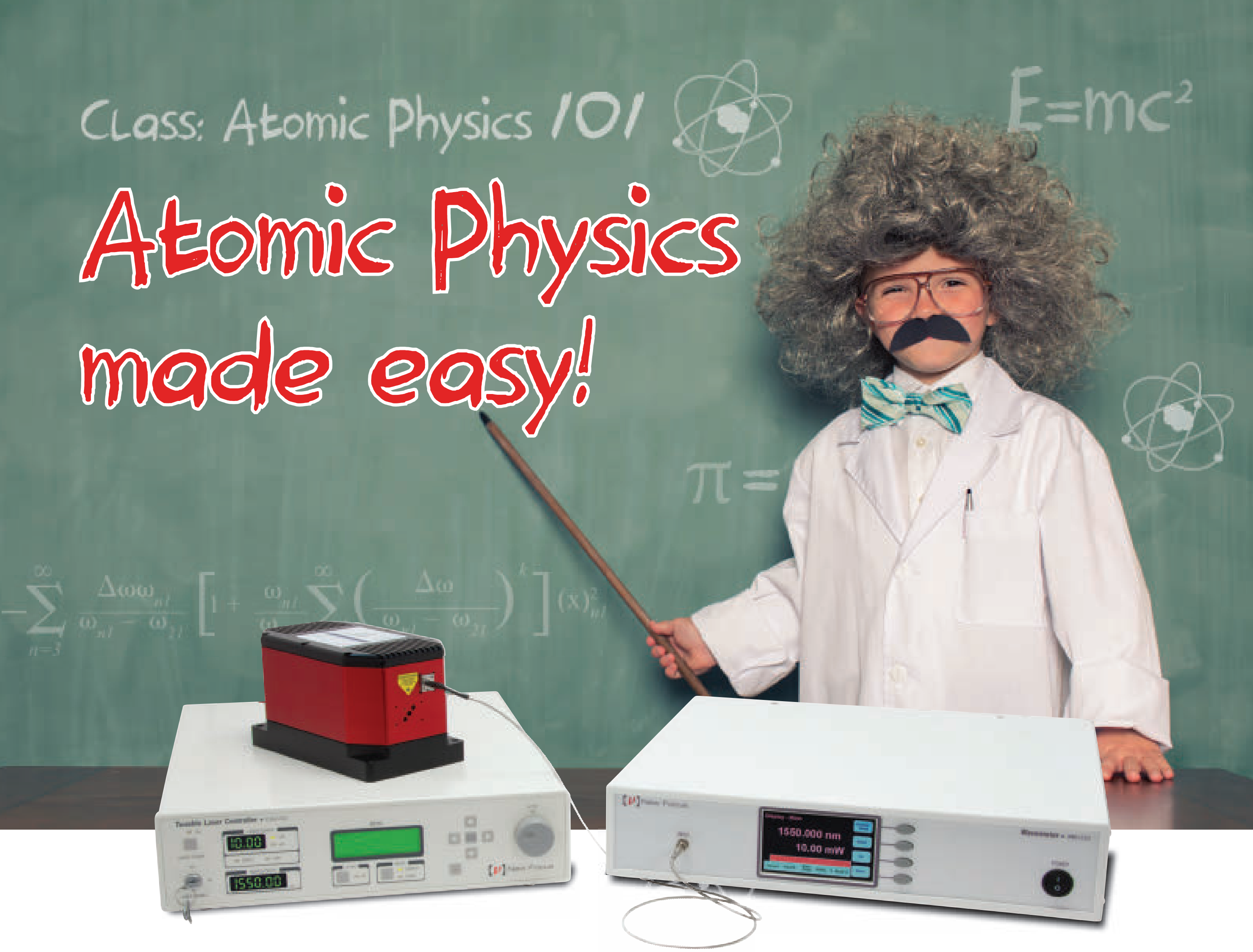

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