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What goes up...

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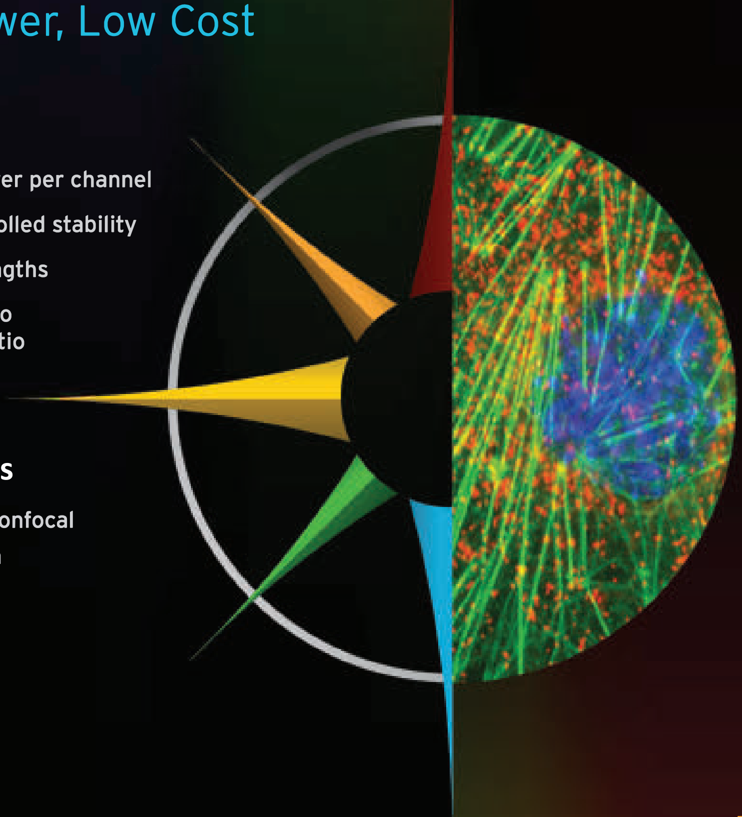

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JANUARY 2019 ▪ VOL. 55, NO. 1

features

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BioOptics WORLD

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editor's desk

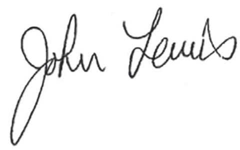
Another record year

As the skyline of 2018 fades behind us in the rearview mirror and we look ahead to the new year, I see much to be excited about in photonics technologies, applications, and markets. Despite economic headwinds and turmoil due to worldwide macroeconomic softening, uncertainties in key areas of foreign trade, and the threat of an all-out trade war between the U.S. and China, it looks like 2018 was another record year for laser sales. Our Annual Laser Market Review & Forecast article in this issue reports that total global laser sales are expected to grow 5.3% from \$13.07 billion in 2017 to \$13.76 billion in 2018. And for 2019, we expect a 6.11% increase, reaching \$14.6 billion (see page 40). Each segment of the laser market faces its own dynamics, of course, with lasers for materials processing the largest, followed by communications and R&D and military. The medical segment has been experiencing very interesting developments and resilient growth, along with certain niche industries maintaining positive momentum.

Kicking off 2019, we have a preview of SPIE Photonics West in San Francisco (February 2-7), which is expected to host more than 23,000 attendees, 1350 exhibitors, and 5200 technical presentations—see page 29 to find out which sessions are of particular interest to the *Laser Focus World* editors. Next, we have two articles on high-power diode lasers. The first (see page 77) covers R&D at Berlin Adlershof, which has resulted in design improvements for high-power diode lasers that are boosting efficiency, peak power, brilliance, and range of emission spectra. The second (see page 97) discusses recent advances in diode packaging and implementation that are transforming the utility and economics of applications for high-power diode lasers.

We also explore flexible optics (see page 16), superresolution fluorescence imaging (see page 24), and how deconvolution algorithms improve confocal imaging resolution (see page 86).

However, the list of topics reflecting other technology trends this issue goes on, ranging from nanoparticles that enhance optical coating performance (see page 71), quantum secured communications (see page 81), and spectrally tunable light sources (see page 89), to gravity-free optical fiber manufacturing (see page 93) and how novel, tunable lasers enable new nanoimaging techniques (see page 103). As always, I hope you enjoy this issue.



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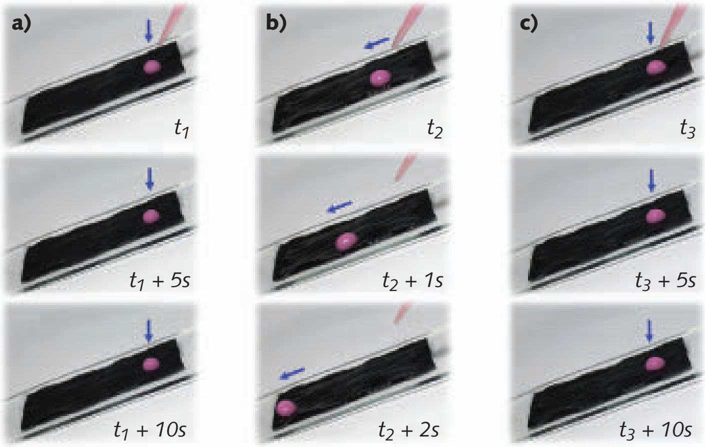
newsbreaks

Near-infrared light and paraffin enable microfluidics on graphene substrates

Microfluidic systems depend on the controllable movement of liquids or liquid droplets on the surface of a substrate. Unfortunately, such control is not always possible on two-dimensional substrates like graphene. But by using a paraffin-infused porous graphene film (PIPGF) and near-infrared (near-IR) illumination, researchers at Southeast University (Nanjing, China) and Suzhou University of Science and Technology (Suzhou, China) have enabled microfluidics on graphene, and have demonstrated the programmed movement of liquid droplets across a graphene surface.



After fabricating a 300-μm-thick porous honeycombed graphene structure through ionic bonding and acid reduction followed by a freeze-drying process, paraffin wax was liquified to permeate the porous graphene substrate. This PIPGF structure exhibits, at room temperature, strong capillary action that pins liquid droplets to the surface of the graphene. But when 808 nm near-IR light is applied, the wettability of the graphene can be controlled such that surface droplets slide down the substrate when tilted. This process is easily reversed by turning off the illumination and, furthermore, the intensity of near-IR light can control the amount of time before the paraffin is liquified to enable droplet movement. By creating a near-IR mask to control the spatiotemporal wettability of the graphene substrate, microfluidic channels in custom patterns can be created for a variety of applications. *Reference: J. Wang et al.,* Sci. Adv., *4, 9, eaat7392 (Sep. 14, 2018).*

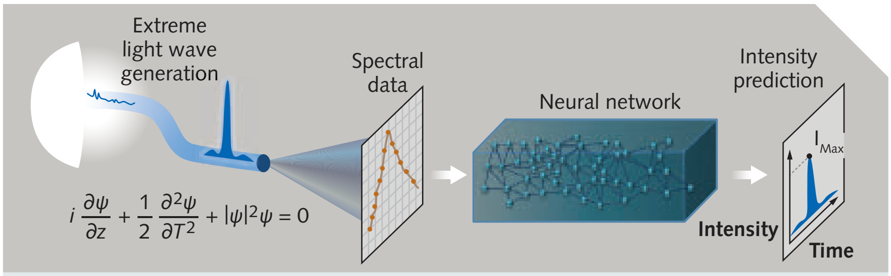
Sb_2Se_3/*p*-Si position-sensitive detector has high sensitivity and fast response

Lateral-effect position-sensitive detectors (PSDs) are an essential component of many laser-optical systems, especially those that require some sort of beam alignment (quad-cell PSDs, which operate on a different principle, are also important). Researchers at the Harbin Institute of Technology (Harbin, China) have demonstrated PSDs using antimony selenide/silicon (Sb_2Se_3/*p*-Si) junctions fabricated using pulsed laser deposition (PLD) that exhibit a large lateral photovoltaic (LPV) effect that is linear with laser spot position with a maximum position sensitivity of up to 448 mV/mm and an optical relaxation time (1/e) for the LPV effect of 4.98 μs. Tested at light with wavelengths of 635, 780, and 808 nm, the high LPV and rectifying behavior of the room-temperature device makes it a promising candidate for many general-purpose applications in optoelectronics, say the researchers.

Sb_2Se_3 films with a thickness of 108 nm were deposited on three separate Si substrates with resistivity ranges of 500–100, 8–12, and 0.1–1 Ω·cm, respectively. The highest position sensitivity of 448 mV/mm was seen for a Si resistivity of about 8 to 12 Ω·cm. LPV data as a function of laser power from 1 to 40 mW was taken for the three test wavelengths, showing that the LPV saturates rapidly with laser power—at about 1 mW or so in the case of light at 635 nm. *Reference: Y. Zhang et al.,* Opt. Express *(2018); https://doi.org/10.1364/oe.26.034214.*

AI to predict rogue waves in fiber-optics nonlinear instabilities

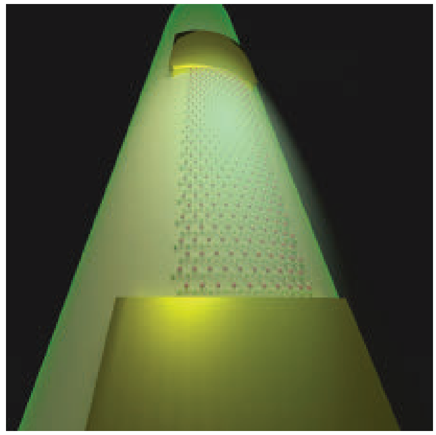
Spectral data are commonly used to study nonlinear instabilities in optical fibers. However, these provide very limited information on the properties of the wave field in the time domain. A new approach based on artificial intelligence (AI) applied by researchers at Tampere University (Tampere, Finland) and the University of Franche-Comté (Besançon, France) can provide insight into the time-domain characteristics of optical-fiber modulation instabilities, enabling the prediction of high-intensity peaks from the spectral intensity only.

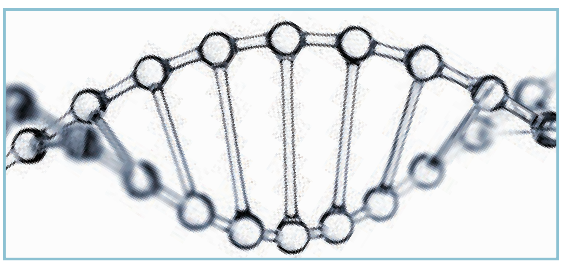


In the experiment, pulses from a Ti:sapphire mode-locked laser were injected into a nonlinear photonic-crystal fiber in which a random wave field developed as a result of modulation instability. The output spectrum of thousands of pulses was measured in real time with very high dynamic range by a moving mirror and grating system. Subsequent analysis of the recorded data using AI from a neural network trained from numerical simulations yielded information on the temporal properties of the wave field associated with those spectra, and in particular the probability distribution associated with the emergence of ultrahigh-intensity spectral peaks—known as rogue waves—that are generated in many natural environments. Modulation instability is a central process in physics that underpins the occurrence of extreme events, and in particular on the surface of the oceans. By showing that AI can predict the extreme intensity of an unstable wave field from only partial information, the work could represent a major step towards the predictability of rogue waves in general. *Reference: M. Närhi et al.,* Nat. Commun., *9, 4923 (Nov. 22, 2018).*

Robust quantum computing via photonic *d*-level cluster states

By exciting a nonlinear optical resonant element with a coherent set of multiple laser pulses in which the pulse separation is much larger than the photon lifetime in the resonator, researchers from the Institut National de la Recherche Scientifique



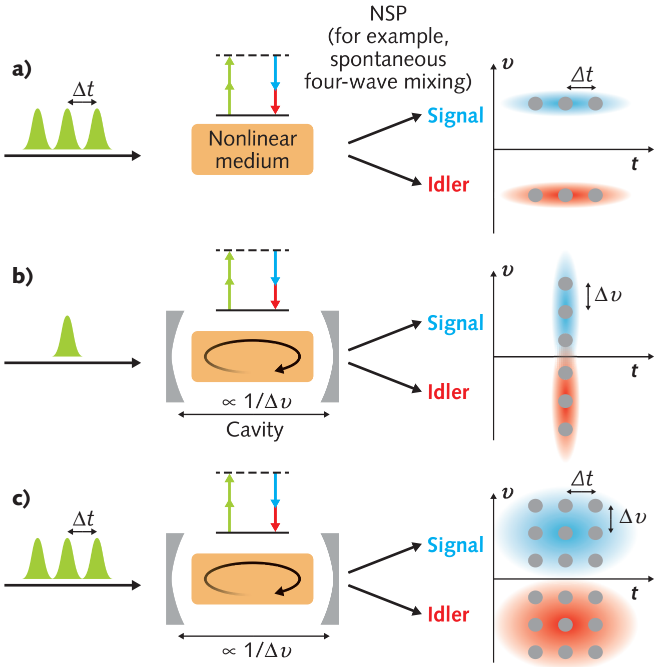


(INRS-EMT; Varennes, QC, Canada) have prepared and coherently manipulated discrete *d*-level multipartite quantum systems based on frequency-time hyper-entangled two photon states. To do so, they use integrated photonic chips and fiber-optic telecommunications components. The demonstration is the first experimental realization and characterization of so-called qudit cluster states that are equivalent to the realization of a quantum computer, as well as the first proof-of-concept demonstration of high-dimensional one-way quantum processing.

The photon pairs (signal and idler) are simultaneously generated in a four-wave mixing process as a superposition of several time modes ($d = 3$, given by the number of pulses) generating a time-based *d*-level two-photon state. One pulse exciting the nonlinear resonant medium (microring resonator) additionally generates a frequency-based *d*-level photon state. Together, this creates a *d*-level hyperentangled multipartite state. Next, frequency-to-time mapping is accomplished using a fiber Bragg grating (FBG) array in a phase-stable loop configuration, transforming the hyperentangled state into a three-level four-partite cluster state using an appropriate phase pattern. These *d*-level cluster states can tolerate up to 66.6% of incoherent noise compared to only 50% for four- and six-qubit cluster states. Furthermore, the team transformed these cluster states into different orthogonal bi-partite states and confirmed, through quantum interference measurements, that the states are mutually orthogonal and entangled, enabling powerful, noise-tolerant quantum operations using standard optical components. *Reference: C. Reimer et al.,* Nat. Phys. Lett.*; https://www.nature.com/articles/s41567-018-0347-x (Dec. 3, 2018).*

10-nm-thick photodetector with gold electrodes senses optical fiber's evanescent field

Researchers at Rice University (Houston, TX) have developed a method to make atom-flat sensors, including photosensors, that seamlessly integrate with devices to report on what they perceive. Electronically active 2D materials have been the subject of much research since the introduction of graphene in 2004. Even though they are often touted for their strength, they're difficult to transfer to where they're needed without destroying them. The new research provides a way to keep the materials and their associated circuitry, including electrodes, intact as they are moved to curved or other smooth surfaces. The Rice



team tested the concept by making a 10-nm-thick indium selenide (InSe) photodetector with gold electrodes and placing it onto the side of a stripped optical fiber. Because it was so close, the near-field sensor coupled with the evanescent field of the fiber and accurately detected the flow of information inside. The benefit is that these sensors can now be embedded into such fibers so that they can monitor performance without adding weight or hindering the signal flow—for example, to sense damage at any point along a long telecommunications fiber.

Raw 2D materials are often moved with a layer of polymethyl methacrylate (PMMA) on top, and the Rice researchers make use of that technique. But they needed a robust bottom layer that would not only keep the circuit intact during the move, but could also be removed before attaching the device to its target. (The PMMA is also removed when the circuit reaches its destination.) The ideal solution was polydimethylglutarimide (PMGI), which can be used as a device fabrication platform and easily etched away before transfer to the target. PMGI appears to work for any 2D material, as the researchers experimented successfully with molybdenum diselenide and other materials as well. The researchers have only developed passive sensors so far, but they believe their technique will make active sensors or devices possible for telecommunication, biosensing, plasmonics, and other applications. *Reference: Z. Jin et al.,* ACS Nano *(2018); https://doi.org/10.1021/acsnano.8b07159.*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PARTICLE ACCELERATORS

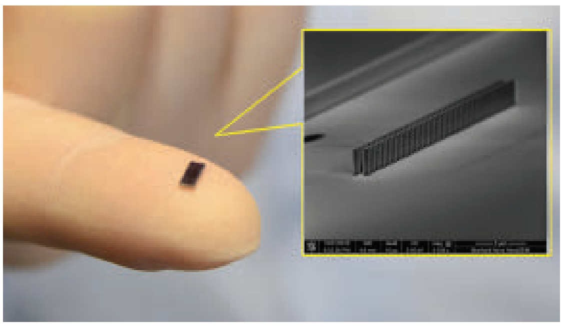
Laser-based microchip electron accelerator can benefit industry and medicine

If electron accelerators could be made small and cheap enough, not only would every university be able to afford its own accelerator laboratory, but inexpensive coherent x-ray beam sources for photolithographic processes in the semiconductor industry could be made available, which could reduce transistor size in computer processors and increase integration density. For medical use, accelerator-based endoscopes could be used to irradiate tumors deep within the body with electrons.

The Accelerator on a Chip International Program (AChIP), funded by the Gordon and Betty Moore Foundation in the U.S., aims to create an electron accelerator on a silicon chip. The fundamental idea is to replace accelerator parts made of metal with glass or silicon, and to use a laser instead of a microwave generator as an energy source.

Because of glass's higher electric-field load capacity, the acceleration rate can be increased and thus the same amount of energy can be transmitted to the particles within a shorter space, making the accelerator shorter by about a factor of 10 than traditional accelerators delivering the same energy.

One of the challenges is that the vacuum channel for the electrons on a chip has to be made very small, which requires that the electron beam be extremely focused. Because the magnetic focusing channels used in conventional accelerators are much too weak for this, a new focusing method must be developed if the accelerator on a chip is to become reality.



A laser-driven electron accelerator chip made up of two parallel rows of nanopillars is shown on the tip of a finger along with an electron microscope image of the chip. *(Image credit: Hagen Schmidt and Andrew Ceballos)*

2D design enables photolithographic fabrication

Researchers at Technische Universität (TU) Darmstadt, led by researcher Uwe Niedermayer, are now using the laser's electromagnetic field itself to focus electrons within a channel only 420 nm wide.[1] The concept is based on abrupt changes to the phase of the electrons relative to the laser, resulting in alternating focusing and defocusing in the two directions in the plane of the chip surface. This creates stability in both directions.

Perpendicular to the chip's surface, weaker focusing is sufficient, and a single quadrupole magnet encompassing the entire chip can be used. This concept is similar to that of a conventional linear accelerator. However, for an accelerator on a chip, the electron dynamics have been changed to create a two-dimensional (2D) design that can be realized using lithographic techniques from the semiconductor industry.

The device consists of a photolithographically fabricated standing-wave dual-pillar structure irradiated by *z*-polarized laser pulses with a 2 μm wavelength and 100 fs duration incident from both sides of the structure, which is about 5 mm long (see figure). The incident lasers' field strength from both sides is 187 MeV/m and 500 MV/m. The structure keeps the accelerated electron beam focused along the entire 5 mm length of the accelerator to within ±0.21 μm. The full-width at half-maximum (FWHM) of the resulting electron pulse is 0.11 fs in duration.

Niedermayer is currently a visiting scientist at Stanford University (Palo Alto, CA), which is leading the AChIP program along with the University of Erlangen in Germany. At Stanford, Niedermayer is collaborating with other AChIP scientists with the aim of creating an accelerator on a chip in an experimental chamber the size of a shoebox. A commercially available system combined with nonlinear optics is used as a laser source. The aim of the AChIP program, which has funding until 2020, is to produce electrons with 1 MeV of energy from the chip. An additional aim is to create ultrashort (less than 10^{-15} s) electron pulses.—*John Wallace*

REFERENCE

1. U. Niedermayer et al., *Phys. Rev. Lett.* (2018); https://link.aps.org/doi/10.1103/physrevlett.121.214801.

BioOptics WORLD FLEXIBLE OPTICS

Phone-based optical lead testing exceeds EPA standards

Among technologists who responded with innovation to the devastating 2014 discovery of lead in the Flint, MI water supply (and subsequent discoveries by other municipalities) is a group of researchers at the University of Houston (Houston, TX), who devised a portable, inexpensive, and easy-to-use optical system that exceeds EPA detection standards in detecting lead contaminants in water.[1]

Detecting lead (Pb^{2+}) in water is typically a time-consuming process requiring laboratories and bulky and costly analytical instruments. The researchers' low-cost smartphone-based nanocolorimetry (SNC) enables individuals to quickly quantify Pb^{2+} content in drinking water themselves in virtually any setting. Their SNC system is a self-contained microscope—including an inexpensive Lumina 640 smartphone and an 8 Mpixel camera—that operates in both fluorescence and dark-field imaging modes.

The essential lens

Because the microscopy capability is what allows the system to detect low levels of lead, a key feature of the system is its inexpensive, inkjet-printed elastomer optical lens. It attaches to a basic smartphone camera without accessories and produces high-resolution (1 μm) microscope images.

The lens is a discovery made years earlier by researchers in the lab of Wei-Chuan Shih, associate professor of electrical & computer engineering.[2] The group's highly repeatable, lithography-free, and mold-free method enables production of flexible optical lenses by placing liquid polydimethylsiloxane (PDMS) droplets on a preheated surface. The researchers discovered that they could control focal length by varying droplet volume and surface temperature and proved the ability to create lenses with a focal length as short as 5.6 mm.

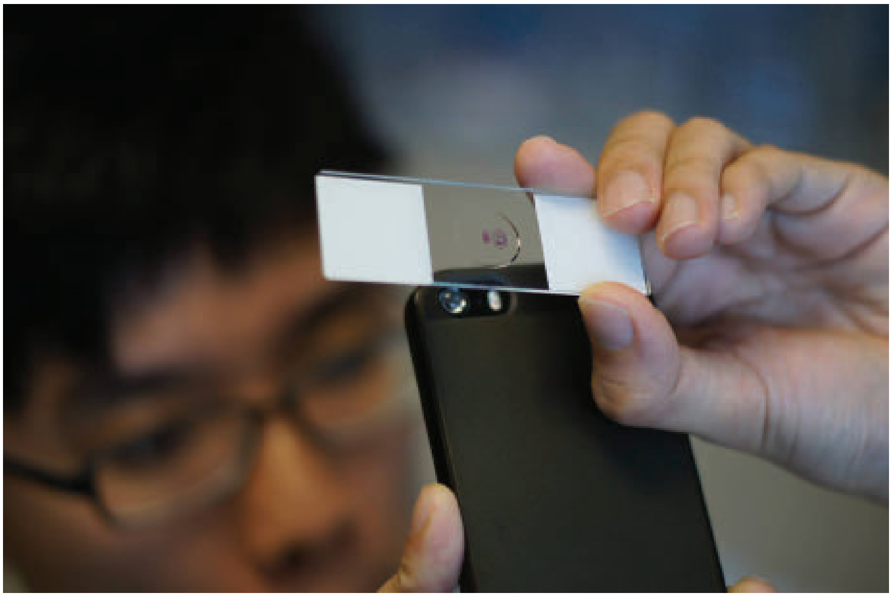
In 2017, *Biomedical Optics Express* published its most frequently downloaded paper: an open-source design from Shih's team that explains how the lens can turn a smartphone into a fluorescence microscope.[3] The produced lens, called DotLens (www.dotlens.net), is made from a patent-pending rubber-derived optopolymer that allows it to securely attach to any smartphone or tablet camera (a bit like a contact lens, without glue or attachments), and to be removed just as easily without leaving residue. It is scratch-resistant and can be reused repeatedly without losing its ability to adhere. Now, DotLens is produced with a 3D printing system that leaves the lenses free of layering defects typical for extrusion-type 3D printers.

Exceeding standards

According to the World Health Organization, no amount of lead exposure is considered safe. Even small amounts can produce serious health problems, and lead is particularly harmful to young children. EPA standards require drinking water to test at less than 15 parts per billion (ppb), but according to Shih, test kits currently sold to consumers aren't sufficiently sensitive to detect lead concentrations at that level. By contrast, the researchers' dark-field imaging mode proved able to detect lead at 5 ppb in tap water and 1.37 ppb in deionized water (see figure).

Applying their 2017 dataset, the researchers used a single-step sedimentation approach to detect and quantify the Pb^{2+} in water. They dissolved varying amounts of Pb^{2+} (1.37–175 ppb) in tap water and added chromate ions (CrO_4^{2-}), which react with Pb^{2+} to produce highly insoluble lead chromate ($PbCrO_4$) nanoparticles. The system proved able to detect the resulting vivid yellow $PbCrO_4$ precipitates, and the researchers discovered that the sum of the yellow pixels' intensity has a highly reproducible relationship with Pb^{2+} concentration (5–175 ppb in tap water, and 1.37–175 ppb in deionized water).

Because the quantity of sediment was too small for imaging by an unaided smartphone camera, the lens was essential for detecting relatively low levels of lead. And whereas traditional colorimetric techniques analyze bulk color changes, the SNC device produces superior sensitivity through nanocolorimetry and dark-field microscopy.—*Barbara Gefvert*



The U.S. Environmental Protection Agency (EPA) says that drinking water should contain <15 parts per billion (ppb) of lead; a smartphone-based dark-field imaging microscope can detect lead at 5 ppb in tap water and 1.37 ppb in deionized water using a single-step sedimentation approach that relies on a powerful optopolymer-based flexible lens. *(Image credit: DotLens)*

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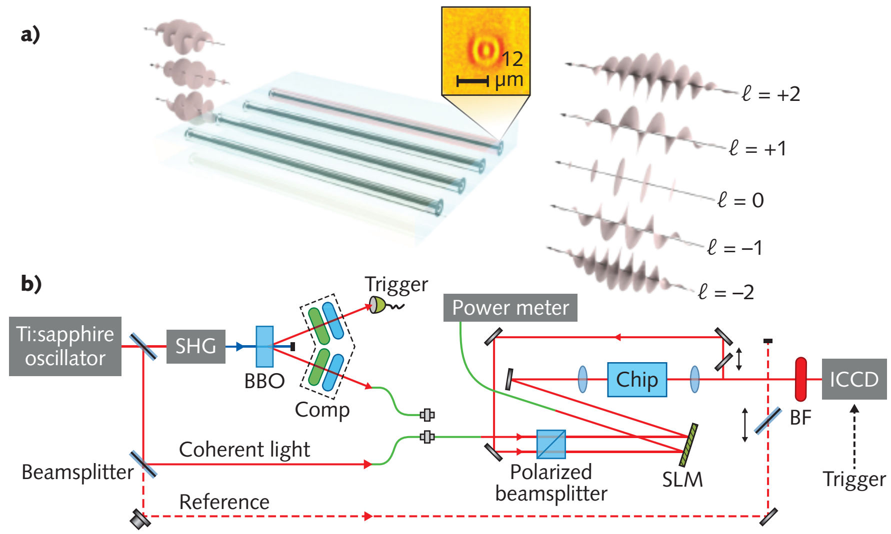
ORBITAL ANGULAR MOMENTUM

Laser-direct-written waveguides enable on-chip twisted light propagation

The orbital angular momentum (OAM) carried by twisted light provides an added degree of freedom that can be exploited to expand the bandwidth of modern fiber-optic communications systems. Recognizing that bulk optical and fiber-optic systems are increasingly being integrated into chip-based photonic systems, researchers at Shanghai Jiao Tong University (Shanghai, China) have been able to develop laser-direct-written on-chip waveguides that transmit OAM beams while maintaining signal integrity. The team also demonstrated both on-chip and off-chip coupling—attributes necessary to producing chip-based OAM systems for high-bandwidth integrated classical and quantum communication networks.



The concept of coupling OAM modes into and out of a photonic chip is shown schematically (a); the donut waveguide maintains the integrity of various OAM modes as measured by the experimental setup (b). *(Image credit: Shanghai Jiao Tong University)*

Donut waveguides

Knowing that the typical transverse intensity pattern of an OAM beam is donut-shaped, the researchers created a waveguide with a donut-shaped cross-section that is cylindrically symmetric. And, understanding that total internal reflection can lead to polarization anomalies such as phase shifts at index discontinuities, the researchers were able to design a waveguide through solution of Maxwell's equations for OAM modes using a first-order perturbative analysis to create a three-dimensional, femtosecond-laser-direct-written waveguide designed to preserve OAM mode integrity.

For a 19.64 mm donut-shaped waveguide within a chip, OAM light is coupled in through polished ends of the chip and then measured after interfering with a Gaussian beam. The resultant spiral interference patterns are obtained directly by a CCD camera. The chirality and the number of arms in the measured interference patterns can clearly tell the topological charge of the OAM light. To be specific, the clockwise (counterclockwise) chirality indicates the positive (negative) topological charge, and the number of arms indicates the order.

The waveguide designed for the experiments supports OAM_0, OAM_{+1}, and OAM_{-1} modes. Analysis of higher-order modes was made possible by optimizing the donut-shaped structure in terms of its size and refractive index distribution.

For experiments with both standard low-order modes and higher-order modes (see figure), it was found that the waveguide transmitted lower-order modes with an approximate 60% efficiency, meaning that OAM light can be easily mapped into and out of the chip (the total loss—including the transmission process—is only 40%). However, this efficiency drops rather dramatically to around 25% for higher-order modes because of the fact that the OAM waveguide hasn't yet been optimized to support higher-order modes.

"Our work provides the first photonic chip being capable of supporting OAM modes, which opens up an entirely new field, 'twisted-light-inside integrated photonics,' not only for optical communications, but also for optical processing, imaging, and quantum computing," says Xianmin Jin at Shanghai Jiao Tong University. "To simultaneously support many more OAM modes is very likely; in fact, we are working on extending the supported modes to very high order and have recently obtained results that are very encouraging. Another fascinating thing is to directly generate OAM light inside our OAM waveguide chip; however, this mission is much more challenging."

—*Gail Overton*

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1. Y. Chen et al., *Phys. Rev. Lett.*, 121, 233602 (Dec. 7, 2018).

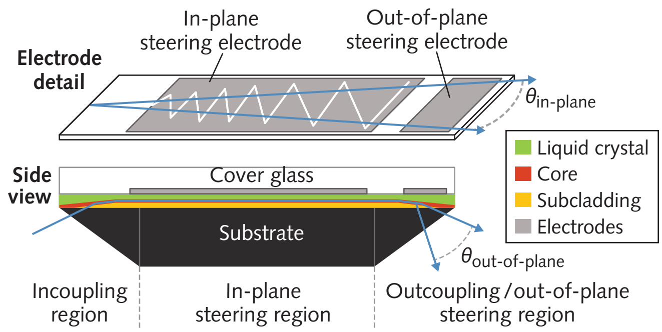
INFRARED OPTICS

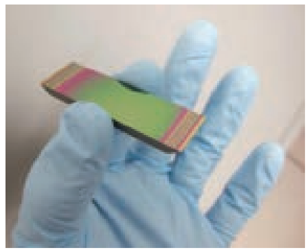
Nonmechanical on-chip waveguide device steers mid-infrared beams

Mechanical devices for steering optical beams such as gimbal-mounted mirrors or rotating Risley prisms are subject to fatigue and mechanical breakdown, and also suffer from large size, weight, and power (SWaP) requirements. To avoid these drawbacks, researchers from the Naval Research Laboratory (NRL; Washington, DC) have devised a voltage-controlled, nonmechanical beam steering device that routes mid-wavelength infrared (MWIR or mid-IR) beams in two dimensions.[1] This solid-state, mid-IR optical component relies on liquid-crystal-clad optical waveguides.

No moving parts

Compared to mechanical devices, the beauty of integrated optical components is their solid-state, rugged nature and amenability to miniaturization. And although other nonmechanical devices such as spatial light modulators (SLMs), optical phased arrays (OPAs), and polarization grating (PG) devices can provide beam steering, all of these are limited and operate in a fixed wavelength, with fixed steering angles, and/or limited power transmission capability.





The all-optical device (inset) routes mid-IR beams in two dimensions within an optical chip that contains a waveguide, liquid crystals, and coupling optics. *(Image credit: NRL)*

Based on an architecture first proposed by Vescent Photonics (Boulder, CO), the NRL device is called a steerable electroevanescent optical refractor (SEEOR) and steers mid-IR beams continuously up to 14° in-plane and 0.6° out-of-plane in the 3–5 μm wavelength range.

To fabricate the SEEOR, multiple thin-film waveguide layers are first applied to a 48.5-mm-long, 14.5-mm-wide, faceted (3 mm long with 39° angle) 2.75-mm-thick doped-silicon substrate. The waveguide subcladding has a refractive index lower than either the substrate or the core and is tapered in the incoupling and out-coupling regions of the SEEOR (see figure). Light is coupled in or out of the faceted region of the slab waveguide in an Ulrich coupler configuration and travels to the core, which is comprised of chalcogenide glass (amorphous semiconductors that contain one or more of the "chalcogen" elements—sulfur, selenium, and tellurium—as a major constituent) of the formula arsenic selenide (As_2Se_3) with a higher refractive index than the arsenic sulfide (As_2S_3) subcladding. The core, subcladding, and substrate can transmit beams through the entire mid-IR spectrum.

The top cladding of the waveguide is a liquid crystal (LC) layer that resides between the core and an electrode-patterned cover glass. On top of the core as well as on the electrode side of the cover glass is a few-nanometer-thick LC alignment layer that induces the rod-shaped LC molecules to align. When a voltage is applied to the LC between the top electrode and the substrate, which serves as a bottom electrode, it causes the LC molecules to re-orient, changing the effective index in the waveguide and thus steering the beam.

To test the device operation, a 4.6 μm, 40 mW quantum-cascade laser (QCL), conditioned by collimating optics, was coupled in free space to the input facet of the SEEOR. The beam was captured by an infrared camera as voltage was applied to the in-plane and out-of-plane electrodes on the cover glass. Beam steering capabilities previously mentioned were confirmed through experimentation with steering voltages up to 500 V.

To increase the in-plane and out-of-plane steering capability and transmission, modifications can be made to the propagation length, facet angle optimization, electrode design modification, or the application of antireflective coatings on the face surfaces.

"Developing this MWIR beam-steering technology required us to solve a series of challenging problems—new waveguide designs and fabrication techniques, new LC compositions, new LC alignment techniques, all of which had to be compatible with MWIR light," said Jesse Frantz, head of the NRL Specialty Waveguides Section. "We hope to see NRL's MWIR SEEOR technology replace mechanical beam steerers, especially in situations where SWaP is a big concern. To give an example, consider a small UAV [unmanned aerial vehicle] surveying for methane leaks. It can't carry a big payload, but steering a MWIR beam is critical for this application."—*Gail Overton*

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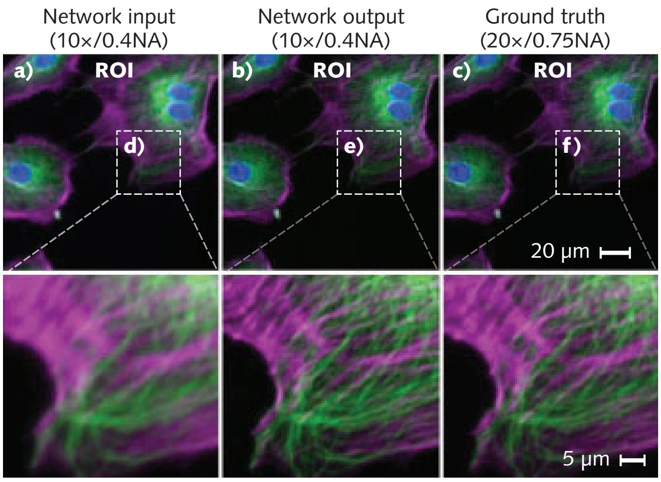
BioOptics WORLD SUPERRESOLUTION FLUORESCENCE IMAGING

Laptop system produces superresolution fluorescence imagery

About a year ago, we asked whether it might be possible to significantly boost the performance of an optical microscope without altering its hardware or design or requiring user-specified postprocessing. This year, we ask the same question, with an important change: the performance boost involves turning low-resolution fluorescence images into the types of subcellular superresolution images that were the subject of the 2014 Nobel Prize in Chemistry.

Is that possible? The answer, of course, is the same as it was last year: Yes. What's more, it's possible for such a system to overcome some limitations of super-imaging in the process.



A laptop-based deep learning system converts low-resolution fluorescence microscopy images (a) into superresolution images (b) that compare favorably with images produced using high-resolution equipment (c); images on the bottom row depict detail from those on the top row. *(Courtesy of Ozcan lab, UCLA)*

Researchers at the University of California Los Angeles (UCLA), led by professor Aydogan Ozcan, associate director of the California NanoSystems Institute, proved it by using an off-the-shelf laptop computer (similar to a standard gaming system). In a fraction of a second, the laptop produced superresolution images previously produced only by specialized equipment requiring specialized skill to operate. But the new system is easily accessible by scientists without such expertise, according to postdoctoral scholar Yair Rivenson, co-first author of a paper describing the work.[1]

The technique's data-driven approach requires no numerical modeling or estimation of a point-spread function. Instead, it uses a type of artificial intelligence (AI) called deep learning, whereby machines "learn" through exposure to data patterns. This is the engine for transforming microphotographs generated by simple, inexpensive microscopy systems into images with superresolution detail just like those generated by highly complex and costly instruments. Like much of the work that Ozcan's group does, the new development "democratizes" sophisticated capabilities. The inexpensive, easy-to-use deep-learning setup makes superresolution imaging accessible to researchers without access to expensive, high-end equipment, and thus will no doubt facilitate discovery.

Teaching intelligence

As part of their experiments, the researchers used thousands of microphotographs of cell and tissue samples taken by five types of fluorescence microscopes. They input the images into their computer in matched pairs of low- and superresolution depictions of the same sample.

The computer learned from those images using a "generative adversarial network," an AI model in which two algorithms compete. One algorithm works to produce computer-generated superresolution output from a low-resolution input image. The second algorithm attempts to differentiate between the resulting computer-generated image and its superresolution counterpart produced by an advanced microscopy system.

Each type of subject requires only one such "training"—after that, the network can transform unfamiliar low-resolution images to achieve the level of detail produced by a superresolution microscope. The study demonstrated that contrast and depth of field were also improved.

In the study, the system transformed wide-field images acquired with low-numerical-aperture (NA) objectives into images matching the resolution of images captured using high-NA objectives (see figure). It also accomplished cross-modality conversions, converting confocal images to match the resolution of images produced by a stimulated emission depletion (STED) microscope, for instance, and using standard total internal reflection fluorescence (TIRF) microscopy imagery to achieve results obtained with TIRF-based structured illumination microscopy.

Naturally, the approach avoids subjecting new samples to the intense light used in standard superresolution microscopy, which can alter the behavior of cells, or damage or kill them. And in the study, it outperformed other resolution-enhancement algorithms.

"Our system learns various types of transformations that you cannot model because they are random in some sense, or very difficult to measure, enabling us to enhance microscopy images at a scale that is unprecedented," says graduate student Hongda Wang, the other co-first author of the study.

Honor-worthy

It's work like this that got Ozcan elected a fellow of the National Academy of Inventors in December 2018. The honor is given to academic inventors demonstrating "a prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and welfare of society."

The month prior, he was elected a fellow of the American Association for the Advancement of Science. That honor recognizes major efforts that have advanced science or its applications either scientifically or socially. It cited Ozcan for his "distinguished contributions to photonics research and technology development on computational imaging, sensing, and diagnostics systems, impacting telemedicine and global health applications."

NAI highlighted Ozcan's pioneering and high-impact inventions (in mobile health, telemedicine, microscopy, sensing, and diagnostics) with the potential to dramatically increase access to medical technologies in resource-limited settings and developing countries. His company Cellmic's smartphone-based diagnostic test reader facilitates medical field work in remote locations, providing ease of use, speedy test results, and linkage to a central database.—*Barbara Gefvert*

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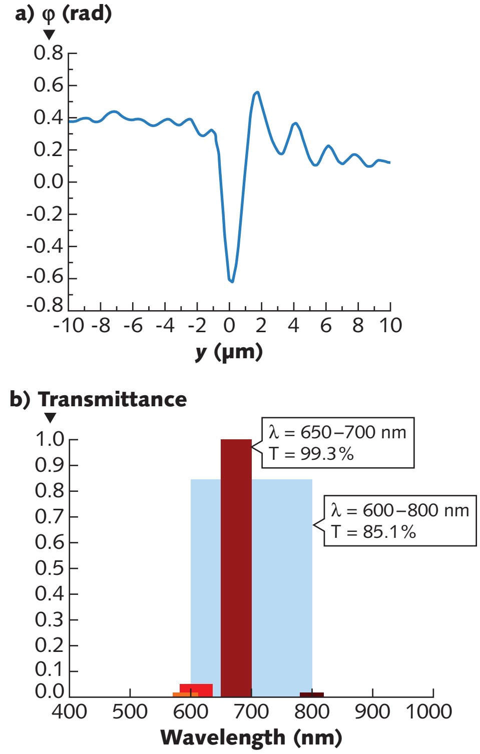
LASER MICROFABRICATION

Laser-written flexible waveguide in polymer could spawn new medical devices

Writing optical waveguides in transparent optical materials is a decades-old technique, at least for rigid materials like glass and polymers. In addition, optical waveguides have been written in polymers using electron beams and gamma rays. Now, researchers at the École Polytechnique Fédérale de Lausanne (EPFL; Lausanne, Switzerland) have for the first time fabricated flexible waveguides about 1.3 μm wide in polydimethylsiloxane (PDMS), a clear silicone commonly used for biomedical applications. The waveguides can be used to make light-based devices such as biomedical sensors and endoscopes that are smaller and more complex than currently possible.

The optical waveguides have a transmission loss of only 0.03 dB/cm in the 650–700 nm spectral range, meaning that a light-based signal can travel through the new waveguides for 10 cm or more before an unacceptable degradation of the signal occurs.

The researchers made the new waveguides by optimizing laser direct writing, a microfabrication approach that creates detailed 3D structures by polymerizing a light-sensitive chemical with a precisely positioned focused laser. Polymerization



The extracted average phase profile of a laser-written flexible waveguide (a) indicates a refractive-index difference between core and cladding of about 0.06. The researchers obtained waveguide transmissivity by measuring transmission through waveguides of different lengths; experimental transmissivities for different wavelength over a 1 cm length are shown (b) for wavelengths of 600 to 800 nm (light blue), 570 to 613 nm (orange), 582 to 635 nm (red), 650 to 700 nm (brown), and 780 to 820 nm (black).

converts relatively small molecules called monomers into large, chainlike polymers. They used femtosecond titanium sapphire (Ti:sapphire) laser tuned to a 680 nm central wavelength and emitting pulses at an 80 MHz repetition rate and a 140 fs duration. Writing speeds were between 0.5 and 1.5 mm/s—using a microscope objective with a 0.7 numerical aperture (NA), the researchers estimate that the peak intensity at the lens focus was about 2×10^{12} W/cm^2.

The new approach does not require a photoinitiator, which is typically used to efficiently absorb the laser light and convert it into chemical energy that initiates polymerization. "By not using a photoinitiator, we simplified the fabrication process and also enhanced the compatibility of the final device with living tissue," says research team member Ye Pu. "This enhanced biocompatibility could allow the approach to be used to make implantable sensors and devices."

To achieve a small optical waveguide that efficiently confines light, there must be a large difference between the refractive index of the material making up the waveguides and the surrounding PDMS. The researchers loaded phenylacetylene into the PDMS for the waveguides (by soaking the PDMS in liquid phenylacetylene) because, compared to traditionally used materials, phenylacetylene has a higher refractive index once polymerized.

Multiphoton absorption

The focused ultrafast laser pulses induced multiphoton absorption in the material. Multiphoton laser direct writing produces much finer structures than one-photon processes because the volume of polymerization at each writing spot is much smaller. Using multiphoton laser direct writing also allowed the researchers to directly initiate phenylacetylene polymerization without a photoinitiator. They then evaporated any unpolymerized phenylacetylene by heating the PDMS.

"To the best of our knowledge, these are the smallest optical waveguides ever created in polydimethylsiloxane, or PDMS," Pu says. "Our flexible waveguides could be integrated into microfluidic lab-on-a-chip systems to eliminate bulky external optics needed to perform blood tests, for example. They might also deliver light for wearable devices such as a shirt featuring a display."

The new flexible waveguides could also serve as building blocks for photonic printed-circuit boards.

The researchers are now working to improve the yield of the fabrication process by developing a control system that would help avoid material damage during laser writing. They also plan to create an array of narrow waveguides in PDMS that could be used to construct a very flexible endoscope with a diameter <1 mm.

"Such a small, mechanically flexible endoscope would allow a number of hard-to-reach places in the body to be imaged for diagnosis in the clinic, or for monitoring in a minimally invasive surgery," Pu says.—*John Wallace*

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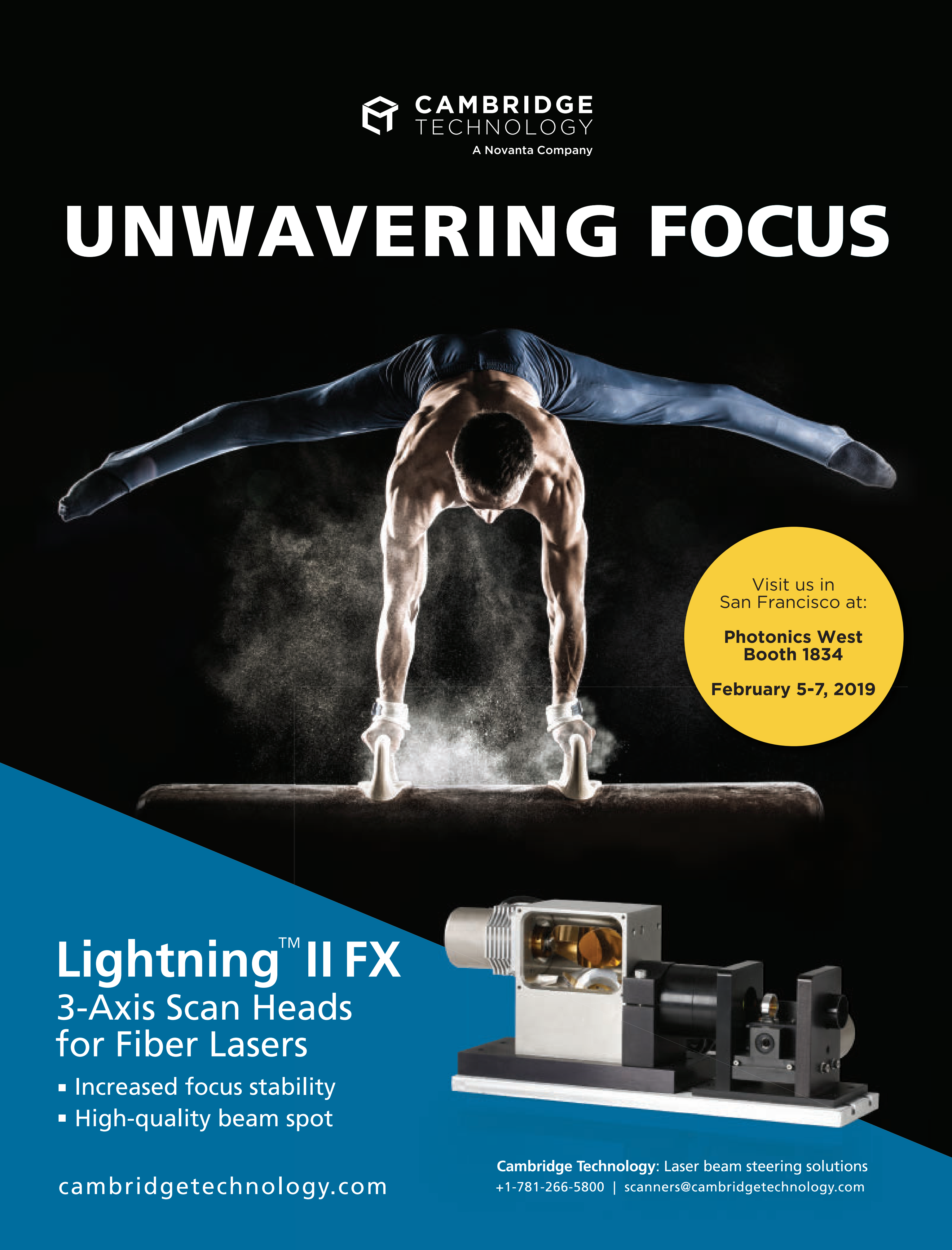
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SPIE Photonics West gets bigger (and better) in 2019

GAIL OVERTON, JOHN WALLACE, and BARBARA GEFVERT

FIGURE 1. In addition to technical presentations and exhibits, SPIE Photonics West 2019 also offers more than 70 educational courses (that offer continuing education units) and free industry workshops. (*Image credit: Laser Components*)

With a sold-out exhibit, largest square-footage exhibition space, highest number of technical presentations, and its biggest industry program ever, SPIE Photonics West's 25th year promises to be its best yet.

"Photonics West will set new records again in 2019, firmly solidifying it as the world's leading annual photonics exhibition and conference," says SPIE senior director of Global Business Development Andrew Brown. "Filling the newly renovated Moscone Center in the heart of San Francisco, we will have the largest event to date, creating a world-class experience for our more than 23,000 attendees and 1350 exhibitors; in fact, the expanded exhibition floor space has already sold out." Brown adds, "Photonics West sets the stage for the year ahead in the global photonics community and, based on demand, we can expect a very upbeat year."

Brown says that not only will the 2019 event be the largest, but with a total of 5200 presentations representing nearly every aspect of the burgeoning photonics research and development ecosystem, it may be the best yet. "With an inspiring list of plenary and keynote speakers for each of the BIOS, OPTO, and LASE symposia, we are delighted to include recent Nobel laureate Donna Strickland in the program," Brown says. He also notes that BiOS will once again feature the Saturday night Hot Topics session, with the associated BiOS exhibit, driving translational technologies and advances in healthcare, taking place on the first weekend.

SPIE Photonics West runs February 2-7, 2019. To support impactful photonics products and innovations, the conference will also host the SPIE Startup Challenge and the Prism Awards. And for those exploring career opportunities, the Job Fair will feature many of the industry's leading companies in search of talented new employees. New this year, the industry hub on the show floor will create an "exciting focal point for the community," according to Brown. It features 40 free events spanning five days, and is dedicated to advancing the business of photonics, including the highly popular two-day AR/VR/MR conference.

In addition to the exhibit and conference, SPIE Photonics West will offer more than 70 full- and half-day educational courses (for a fee, and providing continuing education units [CEUs]) and three free industry workshops, including workshop WS9012 on Wednesday, February 6 from 9-4:30 p.m. sponsored by Laser Components and entitled "How to Get the Most Out of Optics, Lasers, and Detectors" (see Fig. 1).

In the free WS9012 workshop, attendees can select one or more 30-minute sessions on three major topics: Optics, Lasers, and Detectors. The Optics presentations detail fundamentals of digital optics with spatial light modulators, insights into laser-induced damage threshold (LIDT) and high-power laser optics, custom laser optics coatings, and key parameters of polarizers. In the Lasers sessions, participants will review working principles of flash lidar, TIAs for photodiodes to maximize the range of lidar systems, how to drive FET-based pulsed laser hybrid circuits for optimized device performance, and benefits of laser-generated white light. And finally, the Detectors session describes working principles and comparison of different IR detectors and information on IR detector nonlinearity correction.

And don't forget, for those with a particular interest in the laser industry, *Laser Focus World* will once again present its 2019 Lasers & Photonics Marketplace Seminar on February 4th at the Marriott Marquis, just adjacent to the Moscone convention center. The Seminar features keynote presentations from Ralf Kimmel of Trumpf and Matthijs Glastra of Novanta, along with interactive panels on precision optics and quantum technologies that are facilitating new innovations in photonics and driving laser sales.

LASE Symposium

Speaking of lasers, this year's LASE Symposium features four conference tracks: Laser Sources (Conferences 10896-10901), Nonlinear Optics and Beam Guiding (10902-10904), Micro/Nano Applications (10905-10908), and Macro Applications (10909-10911).

With 810 total presentations, the LASE Symposium spans nearly all fields related to laser R&D and commercialization, including sources, laser-matter interactions, materials processing, and 3D printing.

Among the LASE highlights are the plenary presentations on Monday, February 4th, from 3:30-5:40 p.m. Earl H. Maize of NASA's Jet Propulsion Laboratory will present "Cassini's Grand Finale: Going Out in a Blaze of Glory," describing the Cassini Program—from its beginning in 2004 exploring the Saturn system and concluding with a spectacular plunge into Saturn's atmosphere in September 2017. He will present highlights from 13 years of exploration as well as the engineering and scientific rationale behind the mission's final scenario and some of the complexities of an entirely new mission for an aging spacecraft. Yuji Sano of Japan Science and Technology Agency will present "Quarter Century Development of Laser Peening and Recent Strides toward Expansion of Applications," discussing underwater laser ablation (laser peening) that generates high-pressure plasma exceeding the gigapascal level and will also discuss the recently developed femtosecond laser peening, which extends applications to integrated systems and components in space. And a third plenary by Günther Tränkle from Ferdinand Braun Institute describes, as its title states, "High Power Laser Diodes: Improvements in Power, Efficiency, and Brilliance."

Among the four LASE conference tracks, the Laser Sources track alone includes 301 total papers, comprised of a plenary presentation, two keynotes, 41 invited presentations, 205 contributed papers, and 52 poster papers. In addition to these presentations, a panel discussion on the "Future Direction of High-Power Diode Laser Technology and Applications" is planned on Monday, February 4th from 8-9 a.m. in Conference 10900: High-Power Diode Laser Technology XVII.

Laser Sources track chairs Kunihiko Washio of Paradigm Laser Research and John Ballato of Clemson University said that conference submissions reveal a couple of noteworthy key technology trends—namely, a remarkable increase in power and brightness in a broad spectral range for lasers, including eye-safe and mid-infrared (mid-IR), as well as visible and the near-IR region, and many novel laser concepts and technologies that are emerging for solid-state, fiber, and diode lasers.

In addition to recommending attendance at the aforementioned plenary sessions and the keynote presentation on "Mid-IR VECSELs" from Marcel Rattunde of the Fraunhofer-Institut für Angewandte Festkörperphysik, Washio and Ballato wanted to highlight the following papers. Please note that if you enter the full title of the paper in the search bar at https://spie.org/conferences-and-exhibitions/photonics-west/lase, the date and time of the paper is listed below the link that takes you to the individual paper listing with paper number, authors, a link to the abstract, as well as a link that lets you add the paper to your schedule.

Among the invited LASE papers, the chairs recommend 1) "Compact, efficient Tm:YAP pumped mid-IR OPO"; 2) "High-power ultrafast Tm-doped fiber lasers for the generation of mid-infrared radiation in the molecular fingerprint region"; 3) "High-power, all-fiber-integrated super-continuum source from 1.57 to 12 microns"; 4) "Soliton Self-Mode Conversion (SSMC): Power-scalable frequency conversion with multimode fibers";

5) "Recent development of the Orion Laser facility and future perspectives"; and 6) "Breath acetone analysis using a broadly-tunable mid-IR VECSEL".

Washio and Ballato also recommend numerous papers on high-power blue lasers for materials processing applications, including 1) "500 Watt blue laser system for welding applications"; 2) "1000 W blue fiber-coupled diode-laser emitting at 450 nm" (see Fig. 2); 3) "High brightness fiber coupled diode lasers at 450 nm"; 4) "High-power and brightness 105-micron fiber coupled blue laser diode modules"; and 5) "Development of BLUE IMPACT, a 450-nm-wavelength light source for laser processing." In addition, they wanted to highlight "Light detection and ranging with a single free-running dual-comb semiconductor disk laser" from ETH Zurich.

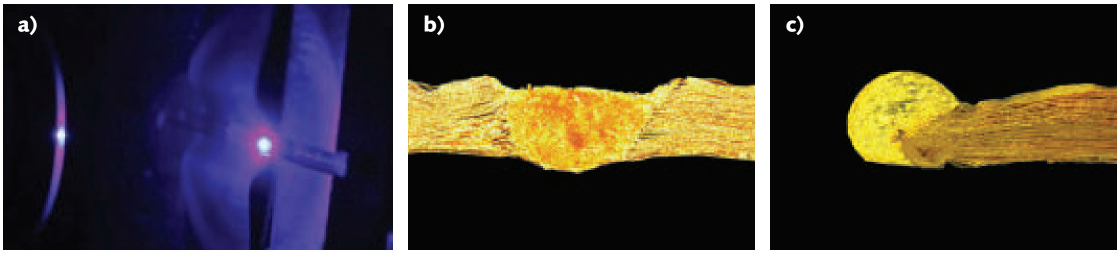


FIGURE 2. One of the papers recommended in the LASE Symposium is "1000 W blue fiber-coupled diode-laser emitting at 450 nm" to be presented by Anne Balck at Laserline (Germany). This blue laser is powerful enough to weld copper (a), as evidenced by the cross-section of a butt-welded joint (b) and an edge-welded configuration (c) for 34 stacked copper foils (each 11 µm thick). (*Image credit: Laserline*)

OPTO Symposium

Optics and photonics have a big role in shaping our future, a fact emphasized in the three OPTO plenary sessions, all held on Monday morning. Katharine Schmidtke, who is responsible for optical technology strategy at Facebook, gives a talk, "Hyperscale Data Center Applications of Optoelectronics," in which she details the various uses of optoelectronics in the networks for hyperscale data centers that provide the base for our digital world. She discusses the next move for photonics, which is to handle distances of <3 m for in-rack applications. Next, Susumu Noda of Kyoto University presents "Two Decades of Progress for Photonic Crystals: From the Realization of Complete 3D Crystals to the State of the Art for Society 5.0," in which he provides both an overview and the very latest technology on photonic crystals, including for lidar, materials processing, and thermal-emission shaping. Finally, Aydogan Ozcan of the California NanoSystems Institute and the University of California, Los Angeles (whom the *Laser Focus World* audience knows well from his research into field-portable smartphone microscopes) will delve into the use of deep learning for optical microscopy and microscopic image reconstruction, including the fabrication of a deep-learning neural network (see Fig. 3).

OPTO conference program tracks this year include Optoelectronic Materials and Devices; Photonic Integration; Nanotechnologies in Photonics; MOEMS-MEMS in Photonics; Advanced Quantum and Optoelectronic Applications; Semiconductor Lasers, LEDs, and Applications; Displays and Holography; and Optical Communications: Devices to Systems.

Tuesday's "Electrical-Optical PCB Technologies" session topic fits right in with Schmidtke's Optoelectronics plenary talk. For example, a group from Shanghai Jiao Tong University gives the session's invited paper on single-mode polymer waveguides and devices for high-speed on-board optical interconnect applications, while a team of Chinese and Finnish scientists presents on large-size directly inscribed polymer waveguide devices for card-to-card optical interconnect application (paper 10924-5); both these topics will aid tighter optical integration of the datacenter. In Tuesday's "Hybrid Integrated Optical Link Modules" session, a group from integrated-optics giant LioniX discusses "Hybrid interconnection of InP [indium phosphide] and TriPleX [silicon nitride] photonic integrated circuits for new module functionality"; the InP-TriPleX combination are two complementary technologies enabling new functionalities—for example, the use of tunable ultranarrow-linewidth lasers for telecom and sensing applications.

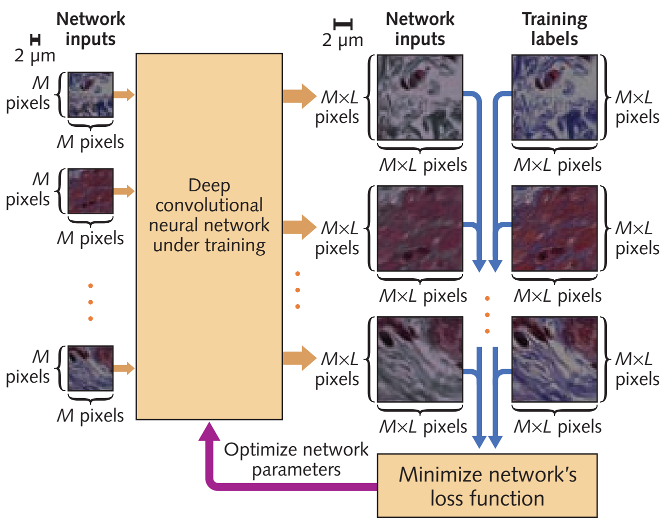


FIGURE 3. Here, a deep neural network developed by Aydogan Ozcan and his colleagues is trained to increase the resolution of images by providing low-resolution input images and corresponding high-resolution training labels to the neural network. Once training is complete, the network can take any low-resolution image and quickly generate, in a single pass forward, a higher-resolution version with improved field of view and depth of field. *(Courtesy of UCLA)*

The "Vertical-Cavity Surface-Emitting Lasers XXIII" session topic features the latest on this rapidly expanding laser technology. For example, Wednesday's presentation, "Watt-class high-power and high-beam-quality VCSEL amplifiers" (paper 10938-8), by researchers from Fuji Xerox and the Tokyo Institute of Technology, covers single-mode continuous-wave (CW) millimeter-scale VCSEL structures useful for direct semiconductor laser processing and 3D sensing. "VCSELs in short-pulse operation for time-of-flight applications" (paper 10938-13), by a group from Philips Photonics, describes pulsed VCSEL modules as well as results from reliability experiments that indicate the limits of overpulsing, as well as the sweet spot for array design.

"Gallium Nitride Materials and Devices XIV" covers leading-edge short-wavelength semiconductor light sources such as optically pumped deep-UV lasers grown on native aluminum nitride (AlN) substrates (paper 10918-17), where a 193 nm excimer laser pumps an AlGaN structure, resulting in a laser peak at 278 nm with a 0.08 nm linewidth at room temperature.

A team from Sandia National Labs and the University of New Mexico discusses "Nonpolar InGaN/GaN core-shell single nanowire lasers" (paper 10918-37), covering results showing optically pumped, room-temperature lasing from individual nonpolar *p-i-n* InGaN/GaN core-shell nanowires.

The "Advances in Display Technologies IX" session topic includes talks on augmented and virtual reality (AR/VR) displays—of which there are many experimentally realized varieties. A "Continuous-depth augmented-reality display device" (paper 10942-1) developed by researchers at Seoul National University is based on foveated retinal optimization, which enhances the central contrast by considering human visual characteristics. The "Augmented reality 3D display system based on holographic optical element" presentation (paper 10942-2) includes descriptions of two AR 3D display systems based on integral imaging using a microlens array of holographic optical elements (HOEs). The first is a dual-view-zone 3D display based on angle-multiplexing technology, while the second contains a compact lenticular lens-array HOE using divergent light as the reference beam. A team from CREOL, The College of Optics and Photonics, University of Central Florida discusses "Emerging high-dynamic-range mini-LED displays" (paper 10942-4), an analysis of the system configuration and performance of mini-LED backlit LCDs, including their advantages and remaining technical challenges.

AR/VR/MR Conference

The second annual AR/VR/MR (augmented, virtual, and mixed reality) Conference will be held Feb. 3-4 (Sunday and Monday; note that, although the conference is free, you must register. Speakers for 2019 include well-known names from both the commercial world and academia: Bernard Kress (Microsoft HoloLens), Jerry Carollo (Google), Ronald Azuma (Intel), Behnam Bastani (Oculus Facebook), Federico Capasso (Harvard), Hong Hua (University of Arizona), Jannick Rolland (University of Rochester), Robert Schultz (Vuzix), and many others.

An interactive panel session with some of the biggest names in VR, AR, and MR includes pioneers in smart glasses, cryptography and more: Jaron Lanier, a VR pioneer as well as a computer philosophy writer, computer scientist, visual artist, and composer of classical music; Mark Bolas, a VR pioneer who helped jumpstart the technology, now at Microsoft working on the "vision strategy" for Microsoft's Mixed Reality platform; Mary Lou Jepsen, a veteran technologist whose new startup is developing wearable diagnostics made from consumer electronic parts that cost as much as a smartphone; Ronald Azuma, innovator in AR, visualization, and mobile applications at HRL Labs, Nokia Research Center, and Intel Labs; Thad Starner, early smart glasses pioneer, and founder and director of the Contextual Computing Group at Georgia Tech's College of Computing; and Jim Melzer (Thales Visionix), one of the pioneers for defense and military head-mounted displays (HMDs). Don't forget to bring your questions to this panel session.

Courses at the AR/VR/MR Conference include Design Techniques and Applications; Optical Technologies and Architectures for VR, AR, and MR HMDs; Introduction to VR, AR, MR, and Smart Eyewear; Designing and Specifying Digital Cameras; HMD Requirements and Designs for AR; and others. Hands-on headset demos will be ongoing both Sunday and Monday.

In addition, the 2019 Optical Design Challenge will be held on Sunday. There, students from a variety of institutions will show off their leading-edge R&D aimed at improving any aspects of the optics in VR, AR, and MR. The day will include poster sessions, pitches, an award ceremony, and a reception.

BiOS Symposium

The Biomedical Optics Symposium (BiOS)—SPIE's largest symposium at Photonics West—has been chaired for many years by two distinguished leaders in the field, James Fujimoto of MIT and R. Rox Anderson of the Wellman Center for Photomedicine, Massachusetts General Hospital and Harvard School of Medicine. While continuing in their capacity for the 2019 event, the duo is joined by another pair of respected researchers as BiOS's first co-chairs: Jennifer Barton from the University of Arizona, and Wolfgang Drexler from the Medical University of Vienna, Austria. Barton and Drexler have in past years chaired the International Biomedical Optics Society (IBOS), and while the IBOS evening gathering will not take place in 2019, there are plenty of alternatives for attendees, starting with the BiOS Expo.

Featuring more than 200 exhibits, the expo will open February 2 (10 a.m. to 5 p.m. Saturday and Sunday). Expo-goers can expect an array of product demonstrations and new-product debuts, including Hamamatsu's SMD-series grating-based mini-spectrometers with micro-opto-electro-mechanical systems (MOEMS)-fabricated shortwave near-infrared (SWNIR) sensor heads (see Fig. 4), and Cyberdyne's LED-based photoacoustic/ultrasound imaging system with functional, molecular, and structural imaging capabilities.

Even after a full day at the exhibits, so many attendees will flock to the BiOS Hot Topics Plenary on Saturday from 7-9 p.m. that few open seats will remain in the cavernous theater. The evening will begin with the presentation of the 2019 Biophotonics Technology Innovator Award to Stephen Boppart of the University of Illinois at Urbana-Champaign. The award honors Boppart's achievement in computational optical coherence tomography (OCT) and

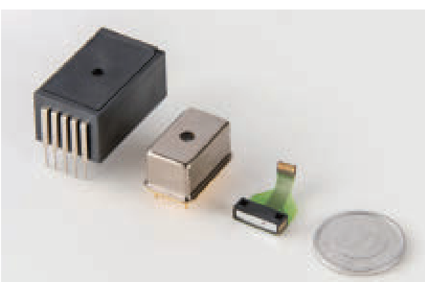


FIGURE 4. Among new products on display at BiOS Expo is Hamamatsu's SMD-series grating-based mini-spectrometers featuring SWNIR sensor heads fabricated using MOEMS systems technology.

its applications to basic and clinical sciences. Boppart's work will be represented in three presentations at BiOS, one covering molecular histopathology with simultaneous label-free auto-fluorescence multi-harmonic (SLAM) microscopy, another on real-time multimodal multiphoton imaging for assessing tumor microenvironments intraoperatively, and a third discussing coherent control of opsins in living brain tissue.

Following that will be presentation of the SPIE-Franz Hillenkamp Postdoctoral Fellowship in Problem-Driven Biophotonics and Biomedical Optics. This award was launched in 2018, and the inaugural honoree was Haley Marks, a postdoctoral researcher at the Wellman Center for Photomedicine at Massachusetts General Hospital, working on a luminescent oxygen-sensing, drug-releasing SMART (for Sensing, Monitoring, And Release of Therapeutics) bandage that provides quantitative visual feedback for clinical treatment guidance. The 2019 winner will be announced at the event.

The final award presentation of the evening is the Britton Chance Biomedical Optics Award, which goes to Samuel Achilefu of Washington University School of Medicine in St. Louis for 2019 (see Fig. 5). This award is presented each year for outstanding lifetime contributions through development of innovative technologies that have facilitated advancements in biology or medicine. Achilefu is being honored for his work in optical and molecular imaging that enable cancer care and treatment. Following his award presentation, Achilefu will make the evening's first technical presentation.

Then, Sergio Fantini of Tufts University will facilitate the remaining presentations, starting with two on spectroscopy: Clare Elwell of University College London will discuss frontiers in near-IR spectroscopy, and Zhiwei Huang of National University of Singapore will explain spectroscopic cancer detection. Multispectral optoacoustic tomography is the topic that Daniel Razansky of University of Zurich and ETH Zurich will cover, and Eva Sevick of the University of Texas Houston will present a view on aging through the lens of translational biomedical optics. Another Washington University at St. Louis faculty member, Srikanth Singamaneni, will present a fluorescence enhancer called the plasmonic patch, and Alexander Vahrmeijer of Leiden University Medical Center will explain how targeted molecular imaging facilitates precision surgery. Finally, Chris Xu of Cornell University will report new advances in multiphoton imaging, and Yoshiaki Yasuno of University of Tsukuba will close out the evening by introducing the concept of extending OCT toward multiple-contrast imaging.

FIGURE 5. Samuel Achilefu will be honored with the Britton Chance Biomedical Optics award during the BiOS Hot Topics 2019 plenary event Saturday evening. (Image credit: Samuel Achilefu)

In a similar vein, the 2019 Neurotechnologies Plenary Session (part of the SPIE Brain Symposium) on Sunday, 3:30-5:30 p.m., will highlight advances in neurophotonics through talks by eight researchers. Subjects include Miniscope, a project for developing imaging technology via an open-source platform; 3D brain imaging in freely moving mice with multiphoton microscopy; the use of functional near-infrared spectroscopy (fNIRS) to objectively assess surgical skills; human brain interferometers to improve blood flow monitoring; and the creation of tools for the functional analysis of neural circuitry. An expert in imaging of cleared specimens, Raju Tomer of Columbia University will report the use of light-sheet theta microscopy to quantitatively image large cleared samples. The plenary will conclude with a panel discussion moderated by Edmund Talley, a program director at the National Institute of Neurological Disorders and Stroke (NINDS).

A third plenary session on Sunday from 7:15-8 p.m. will feature Nobel laureate and former Optical Society (OSA) president Donna Strickland of the University of Waterloo (see Fig. 6). Strickland shared the 2018 Prize "for groundbreaking inventions in the field of laser physics." One half of the prize went to Arthur Ashkin "for the optical tweezers and their application to biological systems" and the other half jointly to Strickland and Gérard Mourou "for their method of generating high-intensity, ultra-short optical pulses"—inventions that served to enable precision instrumentation for research, medicine, and other applications.

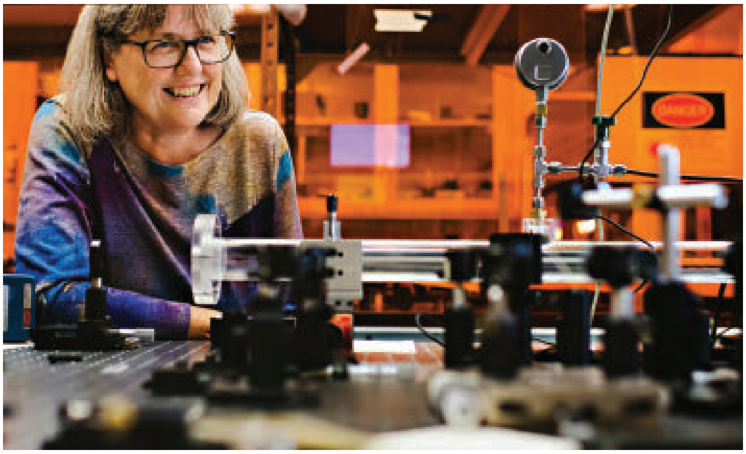


FIGURE 6. Donna Strickland of the University of Waterloo is the featured speaker at a BiOS plenary session on Sunday from 7:15-8 p.m. The former OSA president became the third woman ever to receive a Nobel Prize in Physics (and the first in 55 years), when the 2018 Prize committee recognized her work in ultrashort light pulses. (*Image credit: University of Waterloo*)

Finally, at the Nano/Biophotonics Plenary (Tuesday 10:30-11:30 a.m.), Henry Hess of Columbia University will explain how "motor proteins" such as kinesin can serve as biological components in engineered nanosystems, and describe a proof-of-principle application: a "smart dust" biosensor for remote detection of biological and chemical agents.

Saturday's Translational Research Lunchtime Forum (12:30-2 p.m.) will include presentations by selected participants from the Translational Research virtual symposium demonstrating innovative application of optical/light-based techniques that aim to improve outcomes for patients.

Monday's SPIE Fellow Member Luncheon, while not a BiOS event, will focus on biomedical optics.

Elizabeth Krupinski of Emory University will explain how artificial intelligence (AI) boosts the efficacy and efficiency of medical imaging, and important considerations for AI to enable success and improved patient care.

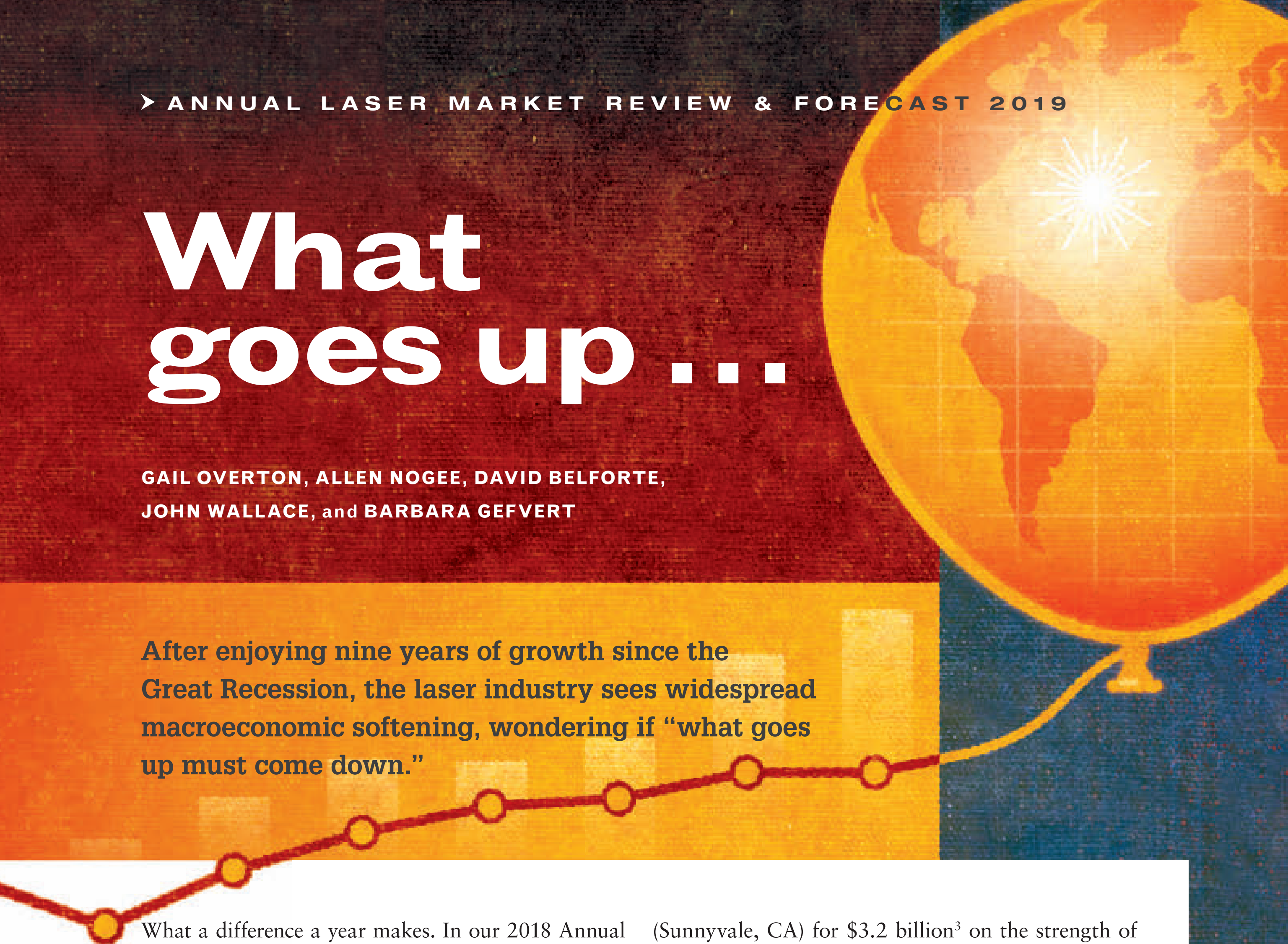
BiOS poster sessions will take place toward the end of each day Saturday (5:15-6:45 p.m.) through Monday (5:30-7 p.m.). Student presentations selected from these will participate in Monday's (4:15-5:15 p.m.) 3-Minute Poster Presentation session sponsored by two journals, the *Journal of Biomedical Optics* and *Neurophotonics*. Judges will award cash prizes for the top three vote-getters based on content and presentation effectiveness.

Another competition, the Startup Challenge, has awarded most of its prizes to biomedical optics entrepreneurs in past years. For 2019, the Startup Challenge will break out semifinalist events by application area. The Biophotonics & Point of Care Semi-Finals (Tuesday, 2-4 p.m.) will feature semifinalists pitching their business concepts to judges who will determine which contestants will move on to the finals. Then on Wednesday (3:30-6 p.m.), the main event—the SPIE Startup Challenge Finals—will give the top two entrants from each semi-final track five minutes each to explain their photonics-based business vision to a panel of judges. The top presenter will go home with $10,000 in cash from Jenoptik and $5000 of equipment from Edmund Optics.

BiOS 2019 will feature a baker's dozen different Best Paper Awards to recognize, for instance, outstanding research in point-of-care diagnostics, or high-speed biomedical imaging and microscopy.

Finally, a popular Food and Drug Administration (FDA)-focused annual session (Monday, 3:30-5:30 p.m.) will help academic investigators and entrepreneurs incorporate regulatory requirements into product development plans, produce successful regulatory strategies, understand review and regulatory approval for medical devices, and communicate effectively with the FDA.

As in 2018, the BiOS conferences are organized into six tracks (Photonic Therapeutics and Diagnostics; Neurophotonics, Neurosurgery, and Optogenetics; Clinical Technologies and Systems; Tissue Optics, Laser-Tissue Interaction, and Tissue Engineering; Biomedical Spectroscopy, Microscopy, and Imaging; and Nano/Biophotonics). Plus, Photonics West features three new "application tracks" (apparently virtual, meaning the presentations are coordinated in terms of theme, but not organized in time or space), two of which are bio-focused: SPIE Brain 2019 includes papers describing innovative technologies that promise to increase our understanding of brain function, and SPIE Translational Research 2019 highlights papers showcases technologies, tools, and techniques with potential for important impact on healthcare.



What goes up …

GAIL OVERTON, ALLEN NOGEE, DAVID BELFORTE, JOHN WALLACE, and BARBARA GEFVERT

After enjoying nine years of growth since the Great Recession, the laser industry sees widespread macroeconomic softening, wondering if "what goes up must come down."

What a difference a year makes. In our 2018 Annual Laser Market Review & Forecast,[1] growth in consumer electronics applications like sensing and lidar propelled demand for lasers in semiconductor and materials processing applications to 2017 worldwide sales of $13.07 billion—a 21.6% jump from 2016. And true to our prediction that "We do see 2017, however, as an aberration and expect laser sales growth to return to more moderate growth for 2018 as capital equipment spending cools," laser sales for 2018 are expected to grow 5.3% to $13.76 billion. But who could predict the volatile macroeconomic conditions that we face heading into 2019? For the first time in nearly a decade, laser manufacturers are concerned that even a "slow and steady" 5–6% sales growth rate could be in jeopardy.

While the same factors that grew laser sales in recent years could easily shrink those sales if the worldwide economies head back into recession territory,[2] the laser industry continues to consolidate to maintain market dominance or to create new, vertically organized structures to serve existing and evolving markets amid the economic turmoil. In late 2018, Illumina (San Diego, CA) acquired rival Pacific Biosciences (Menlo Park, CA) to maintain its top position in DNA sequencing instrumentation. And II-VI (Saxonburg, PA) acquired Finisar (Sunnyvale, CA) for $3.2 billion[3] on the strength of Finisar's VCSEL products that are sold into 3D sensing applications for Apple iPhones.

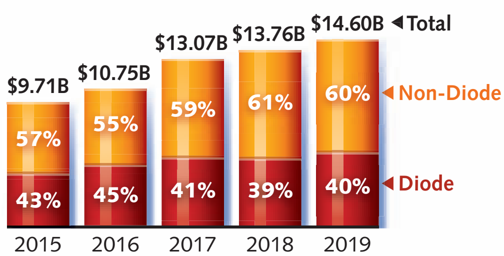
Unfortunately, supplying high volumes of lasers to a single corporate giant like Apple also increases exposure to risk; in late 2018, a series of downward forecasts[4] saw stock prices suffer for both Apple and its suppliers.[5] Companies like Lumentum (Milpitas, CA) saw its stock drop nearly 29%[6] on shipment pullbacks from Apple for 3D sensing lasers.

Besides high-volume supplier risks, an even bigger concern is tariffs. "These tariff and trade-related headwinds were the primary driver of weaker-than-expected performance for our business in China and Europe," said IPG Photonics (Oxford, MA) CEO Valentin Gapontsev in his Q3 2018 preliminary financials,[7] after reporting record Q1 and Q2 earnings of approximately $360 million and $414 million, respectively. The Q3 book-to-bill ratio was just below 1.0, with IPG reporting Q3 sales of $356 million[8]—down 9% from the same quarter last year. Anticipating more softening in order flow in Q4 2018, Gapontsev sees some relief in Q1 2019 on strength in consumer electronics and metal welding. "However," he cautions, "our visibility of a trough in the current downcycle is limited by the uncertainty surrounding the global macroeconomic trade and geopolitical environments."

For Trumpf (Ditzingen, Germany), annual revenue through calendar Q2 (ending June 30, 2018) was up 15.1% from the same period last year to a record $4.13 billion. "Even so, we are monitoring the global economy's development very closely," said Trumpf CEO Nicola Leibinger-Kammüller in Trumpf's preliminary 2017/18 fiscal summary.[9] "There are increasing signs that this long phase of recovery could soon be over. We want to be prepared for that," she added.

Echoing Leibinger-Kammüller, Trumpf CEO for Laser Technology Christian Schmitz said, "For 2019, risks remain that could jeopardize the currently positive trend. These include uncertainties in the areas of foreign trade and the threat of a full-blown trade war between the U.S. and China, most notably. Brexit and the prevailing trends toward nationalism and protectionism may also have repercussions for the real economy."

Laser revenues and 2019 forecast



Source: Strategies Unlimited

Having doubled annual sales from $857 million in 2016 to $1.72 billion in 2017 thanks to the Rofin acquisition and organic growth, Coherent (Santa Clara, CA) fared well in its fiscal 2018 year ended September 30, 2018 with record sales of $1.903 billion.[10] However, Coherent president and CEO John Ambroseo expects fiscal 2019 year-on-year sales to decline between 8 and 12% with a weaker first fiscal half, stating that "The demand challenges in China are largely due to U.S. tariffs on Chinese manufactured goods."

And for our fourth more-than-a-billion-in-annual-sales bellwether laser manufacturer, Han's Laser (Shenzhen, China), sales grew more than 66%[11] to $1.65 billion in 2017. But sales growth slowed for calendar Q3 2018 to 5.4% on sales of $509 million.

The global economic recovery phase since 2008/2009 has indeed been long, but also spectacular. Since reaching more than 16,800 in October 2007 and halving to around 8400 in February 2009, the U.S. Dow Jones Industrial average[12] has seen unprecedented growth, fluctuating between 24,000 and 26,000 since late 2017—more than triple its bottom value during the Great Recession. The UK's FTSE 100[13] bottomed at around 3500 in spring of 2009, returning to highs nearing 8000 in the summer of 2018. And at only 7000 in early 2009, the Nikkei 225[14] recovered to between 22,000 and 24,000 by 2018—again more than tripling in value.

Should we be worried that by August 2018, the U.S. stock market achieved the longest bull run[15] in American history? Will fears of a downward forecast in consumer-driven laser markets continue to pummel stock prices? Does a bull run have to be followed by a bear market? Or concerning laser sales in 2019, should we embrace the phrase—commonly attributed to Isaac Newton as he pondered gravity—that "what goes up must come down"?

Today, the economic indicators cannot be ignored. The World Trade Organization (WTO; Geneva, Switzerland) reduced its world real GDP growth[16] from 3.1% in 2018 to 2.9% for 2019. And the International Monetary Fund (IMF; Washington, DC) cut its 2018 and 2019 global economic growth forecast[17] from 3.9% to 3.7%, citing uncertainty in NAFTA and EU Brexit negotiations; signs of decreased investment and manufacturing; weakness in Argentina, Mexico, Brazil, Iran, and Turkey; and trade tensions between the U.S. and trading partners.

The trouble with tariffs

Statistics show in general that the first year of a U.S. president's administration[18] is a reflection of the momentum and policies put in place by the previous administration. In January 2016, President Trump inherited 4.9% unemployment that had steadily improved[19] under Obama from a high of around 10% in 2007/2008, a 2016 $585 billion Federal deficit[20] that had shrunk each year since the whopping $1.413 trillion of 2009 (but has since grown to $833 billion in 2018), and a steadily rising stock market (prior to recent setbacks) after its catastrophic

ABOUT THE NUMBERS The estimates and forecasts of laser revenue are based on detailed market analyses by Allen Nogee, president of Laser Markets Research, for Strategies Unlimited, a PennWell business that has been conducting market research in photonics for more than 31 years. The research considers both quarterly and long-term historical trends—results are then compared and adjusted each year to correct for known errors and sales additions/subtractions from fourth-quarter financial reports. Significantly more information is presented each year at the Lasers & Photonics Marketplace Seminar (www.marketplaceseminar.com), held in conjunction with SPIE Photonics West, and in the annual Worldwide Market for Lasers: Market Review and Forecast, available from Strategies Unlimited (http://www.strategies-u.com).

drop because of the housing crisis and derivatives speculation.

But for 2018, a growing U.S. Federal deficit[21] and protectionist tariffs threaten to undermine the economic gains enjoyed for nearly a decade. On February 5, 2018, the largest single-day drop in the Dow (closing down 1175 points after dropping nearly 1600 at one point) may have been a warning sign. The Dow was down again almost 800 points (3.1%) on December 4, 2018, before continuing its slide in late December to just below 22,000 after reaching more than 26,000 in late 2018. We all know that a U.S. economic crisis impacts the global laser markets: The Great Recession saw laser sales fall 24.1%, while the 2000 telecom bubble caused a 36.1% drop in laser sales[22]—especially harsh, but understandable in that telecom laser sales accounted for 58% of the total laser market in 2000.

Historically, tariffs have been disastrous.[23] There is a reason why the Smoot-Hawley protectionist tariffs implemented in 1930 by U.S. President Hoover after the 1929 stock crash are widely believed to have initiated and prolonged the Great Depression: tariffs stifle global trade and ultimately hurt consumers with higher prices and job losses. In stark contrast to U.S. tactics, Japan and the European Union signed a trade deal[24] in the summer of 2018 that eliminates nearly all tariffs.

Regarding the recent tariffs imposed by the U.S. on China, laser and photonics companies worldwide are spooked. "The [U.S.] administration will kill American high-tech companies," said IPG Photonics' Gapontsev in an early August 2018 *Washington Post* article.[25] On September 17, 2018, the Telecommunications Industry Association (TIA; Arlington, VA) issued a press release stating that "These tariffs will impact a broad range of communications equipment, with the financial damage expected to reach hundreds of millions of dollars for the telecom equipment industry in the United States."

On November 19, 2018, the U.S. Bureau of Industry and Security issued a call for possible export restrictions[26] (with comments due December 19th) on 14 technologies that could seriously impact the photonics and laser industry, including biotechnology, artificial intelligence (AI), quantum information and sensing technology, additive manufacturing, and advanced surveillance technologies. Just the potential for these technology restrictions prompted Zacks Equity Research (Chicago, IL) to predict that growth prospects are dull[27] for the Laser Systems and Components Industry.

Even steel and aluminum tariffs are hurting laser manufacturers. Bicycle assembler Kent International (Manning, SC) has halted hiring and equipment purchases.[28] "The idea was to work first on the welding and then eventually purchase the automatic bending and laser cutting equipment, but this is now on hold," said Kent CEO Arnold Kamler in mid-2018.

So who is benefiting from the tariffs? Some say it is Chinese laser manufacturers like Han's Laser and Wuhan Raycus Fiber Laser, with the latter's revenue[29] growing 66% for the first nine months of 2018 to about $156 million. At the expense of companies like IPG Photonics, a Seeking Alpha article[30] argues that "With the tariffs now in place, Chinese companies have an even more compelling argument to go with local suppliers [for fiber lasers] in those applications where performance is equivalent or at least close enough."

China's new normal

The IMF[31] puts China's GDP at 6.6% for 2018, falling slowly from double-digit values prior to the 2008/2009 Great Recession to 6.9% in 2017. Contrast this with 2017 GDP values for the U.S., UK, France, and Germany of 2.2, 1.7, 2.3, and 2.5%, respectively, and it is obvious that China—despite slowing growth—is still a very important market for laser manufacturers.

"China is transforming from a steel and concrete economy towards a consumption- and advanced-manufacturing-driven economy. And although its annual GDP growth has slowed to less than 7%, its photonics industry may see much higher growth," says Bo Gu, founder of BOS Photonics (North Andover, MA) and an independent consultant advising photonics companies doing business in China and Asia. Gu believes that both the U.S. and China are trying to avoid the trade war and may reach some short-term agreement to alleviate worldwide anxiety. "However," he adds, "It will be difficult to reach a long-term agreement before some fundamental issues are resolved."

Gu cautions, "Unfortunately, aggressive price reductions may have the 2019 laser market seeing single-digit growth. This price competition might be beneficial for end-user consumers for the short term, but it means that the laser industry is not making the margins it deserves, especially in China. And this is not healthy for everyone in the long term."

Nothing to fear

Regardless of what happens in 2019, it is important to remember that even though the Great Recession saw that 24.1% laser sales decline from 2008 to 2009, our answer to the question we posed back then, "How wide is the chasm?",[32] was less than two years: by 2010, laser market sales had nearly recovered to 2008 levels.[33]

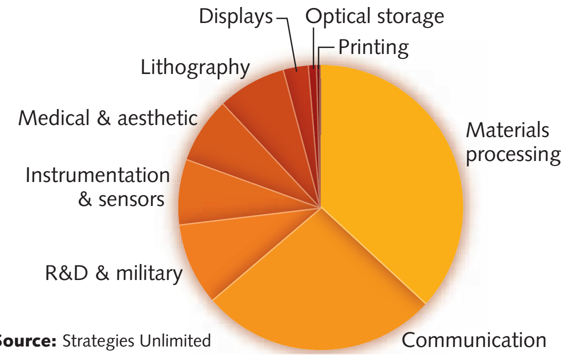
And despite the economic downturns of the past 20 years, some consumer demands that drive laser sales never retreat. According to Nielsen's Law of Internet Bandwidth,[34] for example, user Internet connection speed has grown 50% per year from 1983 to 2018. For lidar lasers enabling autonomous vehicles,[35] global automobile sales[36] have ramped exponentially from around 40 million in the nine-year period from 1990 to 1999 to an estimated 80 million in 2018 alone. And for fans of sustainable technology, "Electric vehicle growth will drive applications associated with conductive materials joining for battery and motor production, with a shortage of skilled manual welders driving the demand for automated laser-based solutions," says Geoff Shannon, director of strategic marketing, materials processing at Coherent. "Just in America, this shortfall is expected to be around 400,000 welders by 2020, representing significant growth potential."

Laser companies that survived the telecom bubble of the early 2000s reinvented themselves, investing in R&D and transitioning from telecom-only to a diverse range of laser products that served growing markets. And should another recession materialize and significantly impact industrial laser sales, for example, other laser market segments will emerge and thrive.

While not entirely recession-proof, medical laser markets see no sign of slowing as we head into 2019. Deloitte (New York, NY) predicts global healthcare spending[37] to grow at an annual rate of 4.1% from 2017 to 2021, driven by aging and increasing populations, developing market expansion, medical treatment advances, and rising labor costs. Similarly, global military spending[38] will grow for its fifth consecutive year to reach $1.67 trillion in 2018, according to IHS Markit (London, England), on Middle Eastern and, increasingly, Eastern European geopolitical instability.

For 2019, despite obvious signs that the past decade of global growth may not be sustainable, we forecast 6.11% growth to $14.6 billion as medical, military, and certain niche industries maintain positive momentum for the laser industry. We can only hope that tariffs will be reversed, stock markets will not crash, and fears of an impending economic downturn are “fake news.”

Laser segments 2018



Source: Strategies Unlimited

LASER MARKET SEGMENTS

Materials processing and lithography continue to dominate laser sales in 2018—not far behind is communications and data storage, with instrumentation, medical, and displays following the lead. Unfortunately, materials processing continues to be subject to external threats from tariffs and macroeconomic challenges, while laser sales for communication applications surge ahead as the thirst for bandwidth continues.

Materials processing and lithography

We can’t recall a time, in recent years, when we have seen the term ‘headwinds’ used so widely in comments made by senior management at the leading manufacturers of industrial lasers. That, and the aforementioned tariff issues, are identified as major concerns in the financial reports of many of the companies whose laser revenues represent about 80% of the total market. The obvious unstated conclusion is that turmoil in the markets for industrial lasers has led to modest growth in 2018 (2017 was a banner year), with prospects for the same in 2019. Even so, 2018 was another record year for industrial laser sales, cracking the $5 billion revenue level.

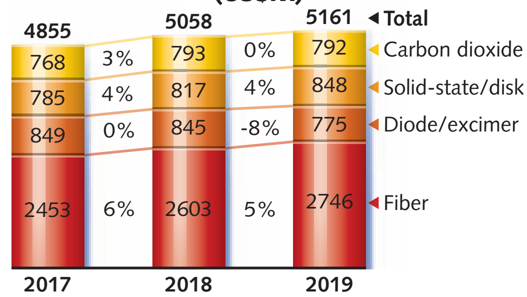
To begin, understand that 2017 was a great year for industrial laser revenues, so no matter how 2018 was forecast or turned out, it was going to be hard to match the prior year growth numbers—and analysts knew that going in.

We also knew world economies were living against the odds—many key market-driving economies had been strong for months, long overdue for an adjustment. We heard the same uncertainty in late 2017 from various segments of the global manufacturing sector about possible soft- or flat-growth pictures for manufacturers in the automotive, semiconductor, farm, and heavy-duty equipment sectors. Considering that 2017 was a strong growth year, a modest contraction was palatable and so we tempered our 2018 growth projections for industrial laser revenues. Consequently, *Industrial Laser Solutions* (*ILS*) forecast single-digit growth in 2018.

Exceptional growth in Q4 2017 (which exceeded guidance numbers) and a strong Q1 2018 caused leading industrial laser companies to issue very positive views on the health of their global market in 2018. However, as the year progressed, turmoil in the key China market (one-third of all industrial laser sales) as it tightened money lending policies, along with overcapacity in strategic fiber laser markets such as sheet-metal cutting (where a selling-price war broke out), and the threat and then imposition of tariff policy changes by the U.S. president, precipitated a slowdown in sales for cutting and welding lasers.

The immediate impact was that two of the four largest laser manufacturers backed off on guidance for Q3 2018 and again in Q4 as these effects heightened concerns. The result was 2018 growth in the low single digits, which mirrored the late 2017 *ILS* projection.

Industrial Laser Revenues by Laser Type (US$M)

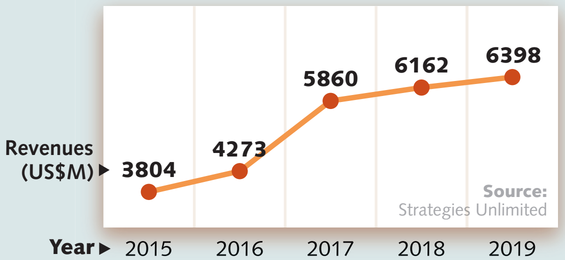


Source: Strategies Unlimited

The bar chart above shows *ILS* revised 2017 laser revenues and our estimates for 2018 revenue and projections for 2019. We are projecting total industrial laser revenues will rise by about 4%, led again by sales of high-power fiber lasers for metal-cutting operations, up by about 4%. Strength in newly developing fine-metal-processing applications in Europe and China and growth in non-metal processing (led by the aircraft and automotive industry conversion to composites) was not enough to offset diminished capital investment in the semiconductor/display sectors and current overcapacity in additive manufacturing, holding microprocessing to a bit more than 5% growth.

Materials processing & lithography

Includes lasers used for all types of metal processing (welding, cutting, annealing, drilling); semiconductor and microelectronics manufacturing (lithography, scribing, defect repair, via drilling); marking of all materials; and other materials processing (such as cutting and welding, rapid prototyping, and micromachining). Also includes lasers for lithography.



While 2017 was a fantastic growth year for materials processing lasers, it should come as no surprise that these large gains were not sustainable. Going into 2018, laser revenue remained strong, but several negative influences predominated. First, China—the largest consumer of lasers for materials processing—continued to slow economically. Second, Europe's economy was hit from all sides; the European Central Bank estimates that eurozone growth will slow to 2% this year from 2.5% in 2017. Europe, which had been growing more quickly than the U.S. as recently as last year, is falling behind. And then there are the trade tariffs that President Trump has been so freely enabling against China, Europe, and some other countries. In response, these countries are enacting their own tariffs against the U.S. that include lasers and other optical components. While the tariffs have caused some slowdowns in laser revenue directly, perhaps an even bigger impact is the effect they have on dampening expectations for future growth and delaying or eliminating future laser purchases and other capital expansions. Blended together, 2018 was a year of modest gains in materials processing. As for photolithography and semiconductor manufacturing, 2018 is the year that EUV lithography systems finally ship. However, EUV technical challenges remain and Intel recently announced a delay in the commercial use of EUV until 2021. As for DUV excimer lasers, 2018 was a strong year overall, and with so many EUV delays, it looks like DUV will be around for many years ahead.

In the macroprocessing segment, sheet-metal cutting grew close to 4%, in spite of turbulence in the low-power end of the business in China brought about by a pricing war among the very large machine suppliers. The predicted rise in welding's share of the market instead remained at 4% as conversion of quotes to sales in key industries such as automotive, specifically electric vehicle battery applications, did not materialize.

Simply put, for the above reasons (plus global manufacturers' tightening of capital investment), the pace of industrial laser sales moderated. The 2018 industrial laser market

was about $5 billion—up 4% from a very healthy $4.9 billion 2017 performance.

For 2019, *ILS* expects mixed, single-digit growth across the board for industrial lasers, with high-power laser applications in the macro sector and a modest rise in marking countering flat growth in the micro sector that will result from the predicted scale-down of installations in faceplate processing. Lest readers disparage a projected low 2% revenue increase, we suggest that a $100 million increase in a slow market year is not to be easily dismissed. Beyond is talk of a paced increase as new applications for UV lasers revive markets for additive manufacturing systems and ultrashort-pulse (USP) laser processing sales expand.

In the lithography light-source sector, we estimate that sales will reach $1.104 billion in 2018 and are forecast to grow reasonably to $1.237 billion in 2019 (roughly 51% DUV and 49% EUV sales). But despite semiconductor capital equipment sales growth[39] of 9.7% to a record $62.1 billion for 2018, SEMI is now forecasting a 4.0% sales drop in 2019 before a return to growth in 2020, and also revised total fab spending downward[40] by 13% in the last half of 2018, citing "trade tensions."

Privately held Gigaphoton (Oyama, Japan) estimates that as of May 2018, its market share in China is 70%,[41] and revealed that its sales of light sources for flat-panel annealing and semiconductor lithography in 2015 and 2016[42] averaged to about $90 million each year. Projecting forward and considering the growth scenario in 2018, Gigaphoton sales for the six months between April and September 2018 were reported at 20 billion yen,[43] or $180 million. Similarly, ASML (Veldhoven, Netherlands), parent company of Cymer (San Diego, CA), says it shipped 18 EUV systems in 2018[44] and expects to ship 30 in 2019. We think a healthy lithography laser segment in 2019 ensures growth overall for the materials processing and lithography laser segment.

Communications and optical storage

Regardless of how the global economy undulates, lasers for telecommunications will be in demand for the foreseeable future. "Global Internet Traffic is set to double in the next 3 years, from around 100 Exabytes per month in 2017 to an estimated 200 Exabytes a month in 2020," said telecommunications expert Michael Lebby in a late 2017 interview by Jonathan Marks,[45] editor at large of PhotonDelta (Eindhoven, Netherlands). "Multiply this by 12 and we are in the 'Zetta-byte' era with the view of 'Yotta-bytes' not that far away," added Lebby.

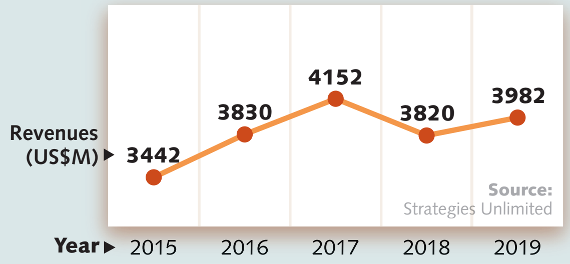
Last year, our forecast discussed a downward trend in the second half of 2017 and into 2018 for communications lasers because of a pause in 4G equipment buildouts before 5G infrastructure investments took hold in 2019. Manufacturers had also cited weakness in China that was expected to be eclipsed by surging datacenter demand in 2019 for high-speed transceivers.

Indeed, Q3 2018 financials (for the three-month period ended September 30th) echoed this forecast: Infinera (Sunnyvale, CA) saw Q3 revenue of $200.4 million—down slightly from $208.2 million in Q2 2018. And although Oclaro (San Jose, CA), which was acquired by Lumentum for $1.8 billion in early 2018, had Q3 revenue of $131.7 million (up from $120.9 million in Q2), revenue was down significantly from the $155.6 million in the same quarter in 2017.

There were some exceptions, however: Finisar, which was acquired by II-VI Incorporated in late 2018 on the strength of its wavelength-selective switch (WSS) and VCSEL portfolio for telecom and 3D sensing applications, respectively, reported revenue of $325.4 million for the three-month period ended October 28, 2018—a 2.5% increase from the previous quarter. Finisar's success continues to be fueled by the surge

Communications & optical storage

Includes all laser diodes used in telecommunications, data communications, and optical storage applications, including pumps for optical amplifiers.



Communications laser revenue was down in 2018, partly from decreased demand and partly from price drops. We expect things to improve in 2019. Communications laser revenue is cyclical in nature, and big new deployments tend to occur in lock-step worldwide. Contributing to the 2018 slowdown is the general slowdown occurring in China that has led to less communications infrastructure investments. Regarding the use of lasers for cellular backbones, most 4G deployments are complete worldwide, with 5G deployments and upgrades yet to occur. In addition, many wireless service providers anticipated 5G needs when they installed their 4G upgrades, reducing the upgrades required when 5G finally materializes. As for optical storage, the future is dimming for lasers: DVD, CD, and Blu-ray media sales continue to decline as more cloud-based solutions eliminate the need for large local storage. Heat-assisted magnetic recording (HAMR), which uses a laser to increase storage capacity of magnetic media, has been pushed back yet again, with Seagate 16 TB 3.5-inch HAMR drives now expected to hit the market in 2020. Western Digital has since moved on to Microwave Assisted Magnetic Recording (MAMR) technology that does not require lasers at all.

in VCSEL sales that we reported in last year's market review and forecast.[46]

Besides the 4G buildout pause and weakness in Chinese purchases, Chinese telecom giant ZTE (Shenzhen, China) was banned in April 2018 from buying U.S. telecom products over sanctions related to Iran and North Korea. Oclaro attributed its Q3 2018 revenue growth to "recovery of shipments to ZTE [Shenzhen, China]" after the ban was lifted[47] in July 2018. The ban, while instituted over sanctions, hurt U.S. companies just as much as it did ZTE. The ban itself serves as a model for how tariffs are broadly anticipated to negatively impact the optical communications sector.

United States FCC Commissioner Jessica Rosenworcel told attendees at a telecom industry event[48] that the new tariffs would be "wildly detrimental" to the U.S. rollout of 5G wireless networks. And because technologists at Corning (Corning, NY),[49] Ciena (Hanover, MD),[50] and L-Com (North Andover, MA)[51] all agree that 5G networks will require lots of optical fiber and, consequently, lots of laser transceivers, so sales of communications lasers will suffer if tariffs continue to be levied.

On the optical storage front, cloud-based solutions continue to outpace CD, DVD, and Blu-ray devices that use optical storage lasers. By early 2017 in the United Kingdom, digital video (film and television streaming and downloads) revenue of $1.66 billion had already surpassed DVD and Blu-ray sales[52] of $1.14 billion. And in Q1 2018, U.S. customers paid nearly $3.0 billion for subscription streaming services (representing 29% growth) compared to only $1.1 billion for physical discs (a 10% decline from the prior year).

Overall, a collision of these negative factors brought sales of lasers for communications and optical storage down in 2018 to $3.82 billion after seeing steady year-over-year growth to a peak of $4.15 billion in 2017. For 2019, we expect modest recovery in this segment to $3.98 billion, assuming the impact of these factors is mitigated, an all-out trade war does not materialize, and new opportunities like quantum communications[53] see further commercialization. The industry also expects consolidation in the optical communications components sector to continue, especially considering the high premiums paid for Finisar and Oclaro.[54]

Scientific research and military

The technology behind lasers for scientific research, which include the most technologically advanced coherent light sources available such as few-cycle ultrafast lasers, optical parametric oscillators and amplifiers (OPOs and OPAs) with expanded wavelength capabilities, supercontinuum sources, frequency combs, and others, are often the prototype for lasers used in industry. Future direction for scientific laser companies comes at least in part from academia and other research institutions that are also fertile ground for commercial startups.

Andreas Tünnermann, director of the Fraunhofer Institute for Applied Optics and Precision Engineering (Jena, Germany), predicts that for 2019, "fiber-laser geometry will continue to increase its market share as new active fibers and technologies such as coherent combining open up new wavelength ranges and allow further scaling of output power in continuous and pulsed operation with excellent beam quality and highest efficiency. Particularly interesting are fiber laser-based secondary sources with emission wavelengths in the extreme ultraviolet (EUV) and terahertz regions, which basically open up new applications."

Optical frequency combs are used in diverse areas of scientific research, including spectroscopy,[55] quantum cryptography,[56] and precision timekeeping,[57] among others. While many of the frequency-comb generators for these projects are custom-made, commercial versions are becoming increasingly available—for example, from TOPTICA Photonics (Munich, Germany), Alpes Lasers,[58] Menlo Systems,[59] and Laser Quantum.[60] Laser Quantum was acquired in 2018 by medical and advanced-manufacturing optical-products company Novanta,[61] illustrating the value that the technology behind scientific lasers holds for commercial use in spectroscopy, metrology, and chemical sensing.

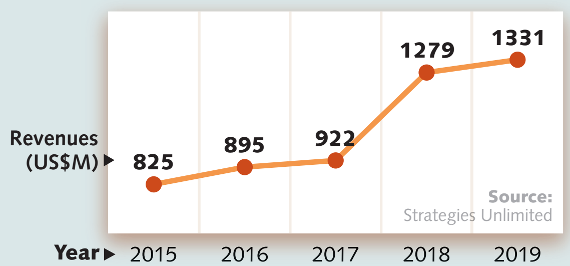
Test and other applications that use high-end lasers in large quantities are of obvious interest to companies that have a strong lineup of lasers for scientific research, such as Coherent, Spectra-Physics (an MKS Instruments brand; Andover, MA), TOPTICA Photonics, the Amplitude Laser Group (which includes Amplitude Systèmes and Continuum), and others.

Wilhelm Kaenders, cofounder and president of TOPTICA Photonics, says, "My prediction is that 3D sensing in all shapes and forms will prevail to be the hottest topic in the industry using pulsed or wide fast-tuning devices [lasers]. Ultimately, for cost reasons, these devices will become diode-laser-based, in particular for consumer and automotive applications. But there are many other smaller markets—still multiple-thousand units—that want to do better in time and spatial resolution and that will continue to feed alternative laser technologies. For TOPTICA, nondestructive testing using laser-based terahertz sources is a big champion that we would like to see grow for testing plastics or carbon-fiber materials, but also for inline production processes [layer thickness, delamination, curing, and so on]."

Years ago, the U.S. Missile Defense Agency's Airborne Laser program's "top-down" attempt at a one-off invention of megawatt-scale military laser technology led to the project's demise.[62] The current

Scientific research & military

Includes lasers used for fundamental research and development, such as by universities and national laboratories, and new and existing military applications, such as rangefinders, illuminators, infrared countermeasures, and directed-energy weapons research.



R&D laser spending saw modest growth in 2018. The U.S. saw a small increase in laser R&D spending, with China maintaining its high laser R&D spending (43% of the worldwide total and growing) as in past years while Europe, despite its economic slowdown, was flat. Military laser revenue had a great year in 2018. After some successful testing in previous years, the U.S. and a few other countries are moving forward with plans for more directed-energy laser weapons. These weapons are not intended to destroy intercontinental ballistic missiles as once hoped, but instead are geared toward defending against drones and other smaller, fast-moving targets.

crop of high-power military lasers, with much of its development taking advantage of well-established industrial laser technology, looks much more promising (although limited to lower maximum output powers in the hundred-kilowatt range).

The U.S. Navy has asked Lockheed Martin Laser and Sensor Systems to develop a 65 kW laser weapon called the High Energy Laser and Integrated Optical-dazzler with Surveillance (HELIOS),[63] with possible increases to 150 kW; the U.S. Army is testing a 50 kW version of its High Energy Mobile Laser Test Truck (HELMTT)[64] at the White Sands Missile Range in New Mexico, with an upgrade to 100 kW planned in 2022; and the U.S. Air Force is working with Ball Aerospace aircraft-mounted laser weapons to disable or destroy enemy aircraft missiles.[65] Based on diode-pumped solid-state (DPSS) or fiber-laser technology aided by techniques such as spectral beam combination,[66] this class of military weapon will become more prominent in the years to come. Benefits to the laser industry include production of laser diodes needed to pump these weapons.[67]

Numerous specific military needs continue to benefit the laser industry, such as lasers for infrared (IR) countermeasures, including further R&D into higher-brightness solutions,[68] as well as for laser-guided missiles.[69] In a look at the future, lidar is being taken up by the U.S. military for uses ranging from aerial infrastructure inspection[70] to detection of biological and chemical agents.[71] In both its remote-sensing and surroundings-sensing incarnations, lidar seems a perfect fit for the military.

Two of the largest laser-related aerospace companies had relatively level 2017/2016 year-over-year income results: Lockheed Martin[72] had net earnings of $1.9 billion in 2017 vs. $3.8 billion in 2016, but it should be noted that the company took a one-time loss of $1.9 billion in the fourth quarter of 2017 because of the impacts of the Tax Cuts and Jobs Act passed on December 2017; and Northrop Grumman[73] reported net earnings of $2.015 billion in 2017, lower than its 2016 net earnings of $2.200 billion—it, too, took a one-time loss because of the Tax Cuts and Jobs Act, including a $300 million tax expense.

II-VI,[74] which is developing high-energy laser systems for the military, had revenues for 2018 of $1.159 billion vs. $972.0 million in 2017 (fiscal year ending June 30). nLight (Vancouver, WA), which launched its initial public offering (IPO) in April 2018,[75] showed, for the three months ended September 30, 2018, revenues of $51.025 million for 2018, compared to $36.547 million in 2017—a growth of almost 40% on the strength of its lasers for industrial, aerospace, and military customers.

The announcements by President Trump in December 2018 that the U.S. will pull all its troops from Syria and 7000 from Afghanistan could possibly have some influence on the military laser market next year. However, it's the technology race between the U.S., Russia, and China that is the wild card. China and Russia have programs to develop hypersonic missiles[76]—could laser antimissile weapons ever enter into the equation? And China is developing space-based lidar with the idea of tracking submarines—is this a threat in any way, and how would the U.S. respond?

As for the numbers, laser revenues for the scientific and military segment grew from $922 million in 2017 to $1.279 billion in 2018, with 2019 revenues forecast to grow modestly to $1.331 billion.

Medical and aesthetic

The sale of lasers for medical applications continued its upward trend in 2018, with cosmetic and dermatology applications leading the sector. In its March 2018 aesthetic laser market forecast, laser components and solutions provider Lasertel (Tucson, AZ) noted[78] that growth in this segment is being driven in large part by the replacement of gas lasers by small, energy-efficient diode lasers. But Lasertel's report also notes that growth because of technological advances and decreased

treatment cost pales in comparison to that arising from consumer demand for laser skin treatment (such as tattoo, wrinkle, hair, and scar removal and skin lightening).

At 20% growth from 2016 to 2017, Asia is at the forefront of aesthetic laser treatments (facilitated by the addition of Taiwan and Korea as medical tourism destinations). In Europe, the Middle East, and portions of Africa (areas that have previously not embraced aesthetics), the laser aesthetics market grew 16%.

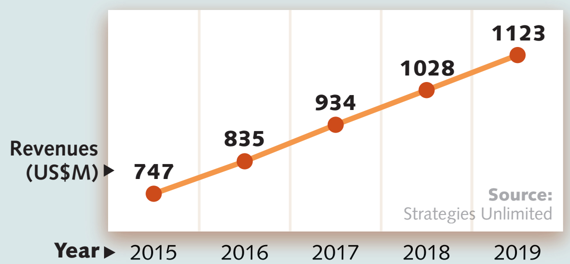
Such growth has attracted the interest of investors, as demonstrated by multiple acquisitions in 2018. In September, Syneron Candela (Wayland, MA) acquired Ellipse (Denmark), a privately held company (financial terms were not disclosed) known for its Intense Pulsed Light (IPL) and laser-based platforms for medical and aesthetic dermatologic applications. The acquisition strengthens Syneron Candela's position in multi-application, multi-technology devices. A key Ellipse product is an IPL-and-Nd:YAG platform targeting vascular and pigmented lesions, hair removal, and (with a fractionated 1550 nm add-on handpiece) skin resurfacing. Incidentally, the provision of systems to address multiple specific applications is a trend in product development—not only in aesthetics, but also in surgical lasers.

In November 2018, private equity firm CVC Capital Partners (Luxembourg) was nearing finalization of its acquisition[79] of medical and aesthetic laser company Lumenis (Yokneam, Israel). The deal is valued at roughly $950 million, compared to the approximately $510 million paid for the company in 2015 by another private equity firm, XIO (London, England). For fiscal year 2014, Lumenis' last as a public company, the firm reported $289 million in revenue. The company's current annual sales are reportedly around $500 million, which represents entry into new medical markets.

Growth in the aesthetic sector was also facilitated by a number of U.S. Food and Drug Administration (FDA) approvals that expand dermatology applications: Alma Lasers (Caesarea, Israel) was approved for its three-wavelengths-in-one compact applicator; Syneron Candela won

Medical & aesthetic

Includes all lasers used for ophthalmology (including refractive surgery and photocoagulation), surgical, dental, therapeutic, skin, hair, and other aesthetic applications.



In 2018, sales of lasers for medical purposes had a great year after a very strong 2017. Cosmetic and dermatology lasers had the strongest showing, driven by positive economic conditions in most regions—and especially in Asia. Applications include tattoo, wrinkle, hair, and scar removal, and skin lightening. Dental laser sales were also up sharply in 2018, but in terms of total revenue, remain a relatively small medical application—only 6% of the total medical laser revenue. After a great 2017, surgical laser revenue had a good showing in 2018. The most exciting part of the surgical laser business is the expansion of its use: a surgeon who uses a laser for one procedure is more likely to feel comfortable with it for other types of surgery, advancing the probability of its purchase by a surgeon for its practice. In addition, laser light, and disposable laser probes, are less likely to carry germs between patients and usually don't require sterilization.

clearance for its 595 nm pulsed dye laser (PDL) cosmetic device that adds a 1064 nm wavelength to treat a broad range of skin conditions; and Lutronic (Korea) was cleared for its device offering pico- and nanosecond modes with precise control over pulsewidth, wavelength, and fluence for cases that have resisted other Nd:YAG treatments. Strata Skin Sciences (Horsham Township, PA), which reported Q3 2018 revenues of $7.9 million (an increase of 8% over 2017), received approval for an excimer laser tip able to custom-filter narrowband UVB light for a maximum non-blistering dose. And Korean developer Hironic got clearance for its hybrid acne treatment device that pairs a 1450 nm diode laser with bipolar radiofrequency and cryogenic cooling.

Hair restoration received a number of FDA approvals in 2018 as well, including the Theradome (Pleasanton, CA) LH80 PRO (now approved for men), the HairMax (Boca Raton, FL) RegrowMD for treatment of androgenetic alopecia in both men and women, and the InMode (Lake Forest, CA) Triton, the only device to provide concurrent emission from the three most-popular hair-removal lasers—alexandrite, diode, and Nd:YAG.

But the FDA's influence on the laser aesthetics market wasn't all rainbows and sunshine. On July 30, 2018, it issued a warning concerning systems it had approved for treatment of "serious conditions like the destruction of abnormal or precancerous cervical or vaginal tissue…" saying that the "FDA has serious concerns about the use of these devices to treat gynecological conditions beyond those for which the devices have been approved or cleared." The agency was targeting the marketing of such products for "vaginal rejuvenation" procedures and stated that adverse event reports and published literature highlighted numerous cases of burns, scarring, and recurring or chronic pain.

The agency notified seven device manufacturers (Alma Lasers, BTL Industries, Cynosure, InMode, Sciton, Thermigen, and Venus Concept) of concerns about inappropriate marketing. The manufacturers—and providers of such services—were quick to respond, and even National Public Radio weighed in,[80] saying that gynecologists have reported good results from CO_2 lasers in particular.

The FDA delivered another wake-up call to manufacturers of laser-based biomedical systems. In April 2018, following Medtronic's (Minneapolis, MN) Class 2 recall of its Visualase Cooled Laser Applicator System (VCLAS) for MRI-guided laser brain surgery, the FDA issued a Class I recall (the most serious type) for Monteris Medical's (also in Minneapolis) NeuroBlate MRI-guided ablation system because of unexpected heating of laser delivery probes. Soon afterward, the FDA issued a general warning about the risk of tissue overheating during use of such systems, owing to inaccurate magnetic resonance thermometry. To address the problem, the manufacturers provided guidance to users, and Monteris obtained 510(k) clearance for a fiber-optic-controlled, cooling-equipped laser probe.

Additional FDA approvals in 2018 included a laser endomicroscopy system for use in neurosurgery from Mauna Kea Technologies (Paris, France); a Lensar (Orlando, FL) laser for presbyopia treatment and another from Carl Zeiss Meditec (Jena, Germany) that extends laser-based myopia treatment to patients with astigmatism; the first 355 nm laser for clearing plaques responsible for peripheral artery disease from Eximo Medical (Rehovot, Israel); and a Multi Radiance Medical (Solon, OH) system for neck and shoulder pain relief that uses advanced laser diodes to "super pulse" up to 50 W of power (more than most Class IV lasers) and aims to maximize treatment by discouraging the body from adapting to its effects.

Acquisitions were also numerous in 2018, demonstrating heightened anticipation of growth in the medical laser industry. In October 2018, Novanta (Bedford, MA) completed its purchase of Laser Quantum (Manchester, England), supplier

of solid-state and ultrafast laser sources to medical OEMs. The $45.7 million deal is a follow-on to Novanta's (formerly GSI Group) January 2017 increase in Laser Quantum's equity stake to 76%.

In a deal valued at $28 million, optics and photonics supplier Gooch & Housego (G&H; London, England) acquired Integrated Technologies (ITL; Ashford, England), maker of medical devices including *in vitro* diagnostic tools. The August purchase helps fulfill some of G&H's strategic goals: ITL business will double G&H's existing life sciences revenues, and the company's system-based products move G&H "up the value chain."

Also in August, fiber and CO_2 laser manufacturer OmniGuide (Cambridge, MA) acquired Lisa Laser (Katlenburg-Lindau, Germany), maker of thulium and holmium lasers for treatment of benign prostatic hyperplasia (BPH)—an application area of growing importance, given that it was also an area of investment for Boston Scientific (Marlborough, MA), provider of the Greenlight XPS Laser Therapy system and holmium platforms.

While dental lasers are still a minor player in the field of laser medicine, their total revenues rose dramatically in 2018. Biolase (Irvine, CA), which calls itself the global leader in dental lasers, reported that U.S. laser revenue for Q3 2018 had increased 22% year-over-year. In its Southern California Model Market, laser revenue increased 127% year-over-year for the quarter and 175% over the last two quarters—growth the company attributed to "early success as we test different go-to-market approaches." Biolase also announced a partnership with the Dallas Mavericks basketball team to raise awareness on the benefits of dental lasers.

Considering the future of the laser market, Praveen Arany, president of the World Association of Laser Therapy (WALT),[81] points to the first-ever congressional briefing on "innovative medical technologies for pain management"[82] and subsequent passage of the Opioid Crisis Response Act (OCRA) of 2018, mandating development and adoption of pain treatment alternatives as an indicator of what's to come for new applications. "There is tremendous excitement about photobiomodulation for pain management and oral mucositis," he said, referencing commercial opportunities for laser treatment of opioid addiction and painful ulcers in chemo-radiation-transplant oncology patients. Indeed, even macroeconomic softening cannot deflate the ever-expanding medical laser markets for 2019 and beyond.

Instrumentation and sensors

Laser-based optical instrumentation for test, measurement, and sensing is a diverse market segment, as it encompasses numerous types of optics and photonics technology. Often, the laser itself is a minor, if essential portion of the instrument or sensing system. This technologically mixed market

also includes a number of billion-dollar companies that "do it all."

MKS Instruments, which throughout its history has been especially known for serving the semiconductor market, strengthened its presence in the optics and photonics arena in 2016 with its acquisition of Newport for about $1 billion, including Newport's own previous acquisitions: Spectra-Physics, Ophir, Femtolasers, and others. In 2018, MKS announced its intent to acquire laser micromachining maker Electro Scientific Industries,[83] also for about $1 billion, in an example of a further diversification of MKS. From 2016 to 2017, MKS' net revenues grew from $1.3 billion to $1.9 billion, while its net income (profit) grew from $105 million to $339 million, indicating that its course of action has been working out well for the company. In 2018, MKS has shown net revenues of $554 million in Q1, $573 million in Q2, and $487 million in Q3.

Although MKS is an optical instrument maker, it is still most influenced by the semiconductor industry. "Despite the recent moderation in the semiconductor market, we are pleased with our strong financial results for the third quarter [of 2018],[84] reflecting our ability to manage through these cycles," says Gerald Colella, CEO of MKS. "Although we foresee the semiconductor market will continue to face headwinds in the near-term, exiting the third quarter we have seen that our semiconductor business has been more steady and consistent. We are very optimistic on the long-term growth drivers within the semiconductor market. Moreover, we have continued to diversify our markets, customers, and product portfolio and are on target to grow our advanced markets more than two times faster than the overall market." It is obvious that diversification is key to MKS' growth.

In 2018, PerkinElmer (Waltham, MA), which makes scientific, medical, and industrial instrumentation including confocal microscopes, many types of spectrometers, and time-resolved fluorescence instruments, brought Shanghai Spectrum Instruments (China) and RHS (Australia) under its wing. In addition, PerkinElmer sold its Phenoptics multispectral imaging portfolio for quantitative pathology portfolio to Akoya Biosciences.[85] PerkinElmer's revenues for 2017 were $2.256 billion, rising from $2.116 billion for 2016.[86] This $140 million boost in 2017 was almost evenly divided between the company's Diagnostics division ($76 million) and its Discovery and Analytical Solutions (DAS) division ($66 million), which produces spectrometers. Prahlad Singh, who becomes PerkinElmer's new president and CEO on January 1, 2019,[87] will likely work at increasing the synergy between the company's DAS and Diagnostics divisions.

From 2016 to 2017, total revenues for Bruker (Billerica, MA) rose from $1.61 billion to $1.77 billion.[88] The Bruker Scientific Instruments segment, which includes all optical instrument production, saw its revenues rise from $562 million to $571 million in the same time period. Bruker was no slouch in acquisitions in 2018: JPK Instruments,[89] which provides microscopy instrumentation for biomolecular and cellular imaging; Anasys,[90] which develops nanoscale infrared spectroscopy and thermal measurement instruments; an 80% majority interest in Hain Diagnostics; and optical metrology products maker Alicona Imaging[91] are now part of Bruker's portfolio.

"While semiconductor metrology markets have slowed, booking rates for the majority of Bruker's portfolio remained quite healthy," said Frank Laukien, CEO and president of Bruker, adding that year-to-date 2018 order bookings were up mid- to high-single digits on an organic basis, including strong growth in North America and China and good results in Europe.

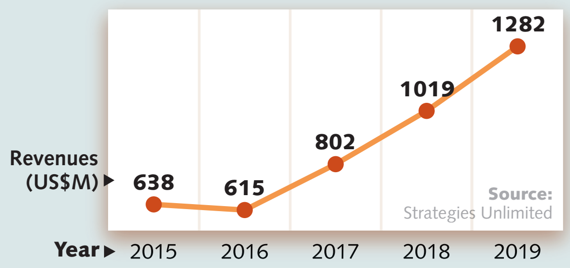
Jenoptik (Jena, Germany), which can count instrumentation—including laser distance sensors, optical shaft metrology, and custom laser-based industrial instrumentation—among its many products and skills, had revenues of $677.5

million for the first nine months of 2018 compared to $601.6 million in the same period of 2017, helped by demand for optical systems for the semiconductor equipment industry, as well as for healthcare instrumentation. Jenoptik CEO and president Stefan Traeger notes that sensor and data fusion are one way to go to boost future growth (see page 120).[92] "As an industry, we are still positioned so that we produce a digital data set and someone else makes money with it," he says. "And we forget that sooner or later, the mere production of the digital data set will no longer bring the money. The sensor becomes a commodity. What's really going to make the money is an integrated solution of sensor and data processing. Within five years, we must have an answer to this question: Do we want to, can we even deal with the Googles of this world? We can't beat them, of course, so how do we deal with them? I think that's a challenge that the whole industry has to face."

Lidar, especially for use in self-driving cars and hazard avoidance, has become a media darling this year and is the focus of much

Instrumentation & sensors

Includes lasers used within biomedical instruments; analytical instruments (such as spectroscopy); wafer and mask inspection, metrology, levelers, optical mice, gesture recognition, lidar, barcode readers, and other sensors.



While many laser sensing applications like computer mice are rather unexciting, numerous sensing applications are very promising indeed. The largest application, which literally just appeared in the last few years, is 3D sensing. This application first appeared in Microsoft's Kinect sensor for the Xbox, and then in the Kinect 2 sensor. After Microsoft sold nearly 35 million of these Kinect sensors, the company killed the product in 2017. But all was not lost. Apple purchased the company that produced the first Kinect, PrimeSense, in 2013, and in 2017 introduced FaceID and included it in the new iPhone X. In 2018, Apple included FaceID in more phones and in the iPad Pro. The success of Apple FaceID led to Samsung and Chinese phone manufacturers needing this new feature. And even though laser 3D sensors are not yet on many phones, they will be by the end of 2019. Add this to the growing number of lidar applications like autonomous vehicles that also use laser sensors, and you have a laser segment with some serious bite going forward. This is certainly one laser area to watch.

2019 – Creating Footprints

We engineered an advanced housing setting a new industrial standard for integrated beam shaping and high power operation. The extremely small form factor still proves a superior heat dissipation. Being hermetically sealed it meets critical reliability requirements of any harsh target application. We solved all the engineering challenges for you. Just mount it on your PCB. Get the future started at 808nm with 20W (pulsed operation) multimode power or at 1060nm with 650mW (cw) single mode power.

commercial development in the optics and photonics community.[93] Practically, though, it has a long way to go: costs are high, many configurations are competing with each other, performance under duress is not proven, and even ethics need to be worked out (should the lidar system try to save the pedestrian, or the driver?). Austin Russell, founder and CEO of lidar developer Luminar Technologies (Portola Valley, CA), predicts that in 2019, "we're going to see fewer companies offering new, hyped-up alternative methods for solving the problem. This year, we saw a lot of new companies coming in with 'groundbreaking, novel solutions' and companies claiming to offer a $100 lidar. We'll be seeing a lot less of that in 2019. Big claims won't cut it anymore; we're getting to the phase in the industry where everyone has to prove themselves through their technology." Russell is expecting that next year will see a lot more lidar units on the road.

For 2018, laser revenues for instrumentation and sensors grew from $802 million in 2017 to $1.019 billion in 2018. The 2019 forecast calls for laser revenues of $1.282 billion—for all these numbers, the projection includes lasers for scientific, industrial, and medical instrumentation, as well as lasers used for sensing in the consumer world (Apple iPhones, computer mice, and so on). According to Allen Nogee of Strategies Unlimited, VCSELs for sensing in consumer items should have another banner year.

Entertainment, displays, and printing

If you're in the market for a projector for home, business, or even full-scale cinema use, look to lasers instead of lamps. The verdict is in: lasers outperform lamps and, increasingly, LEDs at all grades of projection applications, with prices ranging from $2000 to $6000 at home/in the office, and around $100,000 for cinema-scale projectors. Whether high-brightness blue lasers and phosphors in 3LCD technology (from Sony, Epson, and Panasonic), MEMS mirrors and red/green/blue (RGB) lasers or LEDs in DLP technology (from LG, ViewSonic, BenQ, Casio, Optoma, Acer, and Dell), or high-power RGB laser engines in digital cinema designs (from Barco and Christie), lasers continue to penetrate lamp- and LED-based systems.

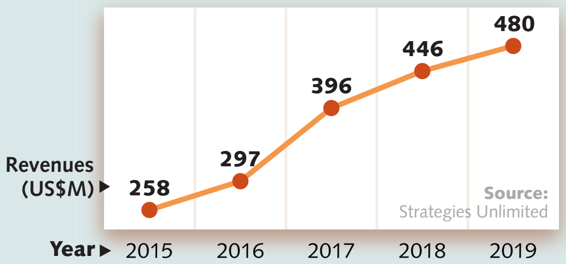
And yet, even in the cinema world, Barco (Kortrijk, Belgium) and Christie (Cypress, CA) suffered some of the same fate befalling consumer electronics, semiconductors, and materials processing markets for lasers in 2018—reduced sales because of trade/currency issues and a slowing in Chinese purchases. For its first half of 2018 (ending June 30, 2018), Barco reported sales[94] of nearly $570 million—down 3.8% from the same period last year on "... lower cinema sales, mainly in China," but actually up 2.7% on a constant currency basis. Ushio, the parent company of Christie, also saw reduced sales[95] of around $730 million for its first fiscal half (ending September 30, 2018) compared to $754 million for the same period in 2017.

Running counter to digital cinema equipment sales is actual box-office revenue worldwide.[96] IHS Markit reported that total box office revenue in North America (U.S. and Canada) reached $6.18 billion in the first half of 2018—a 9.6% increase on the same total in 2017, when North America represented 28% of global box-office sales. And with theater companies like CGR Cinemas (Perigny, France) planning to convert all 700 of its theaters to pure RGB laser projectors from Christie (100 in 2019 and 100 in 2020), and Cineworld (Chiswick, London) planning to add or replace 600 of its 9538 screens with Barco laser projectors in the next three years, we are still in the early stages of growth for laser-based cinema.

Home and office laser printer markets are seeing slow growth, with the overall printer, copier, and multifunction product markets growing only 0.4% in 2018 according to Gartner (Stamford, CT). And on the business image printing side, lasers used in computer-to-plate applications (UV laser diodes, blue diodes) and in flexography applications (CO_2 lasers) will continue to be in demand, but with low-single-digit growth rates of around 2.6% annually at least for flexographic markets,[97] according to Smithers Pira (Leatherhead, England).

Entertainment, displays & printing

Includes lasers used for light shows, games, digital cinema, front and rear projectors, picoprojectors, and laser pointers. Also includes lasers for commercial pre-press systems and photofinishing, as well as conventional laser printers for consumer and commercial applications.



While the laser printer segment is flat at best, and lasers for light shows are slowing a bit after peaking a few years back, lasers used for displays and as a light source are only beginning to hit their stride. Lasers used in projectors of one type or another have been around many years, but their revenue remained relatively small until a few years ago, when lasers were incorporated into commercial cinema projectors. Here, lasers are increasingly being deployed as brighter, more energy-efficient, lower-cost-of-ownership light sources for cinema projectors. The transition from xenon bulbs to lasers came at a perfect time because a movie theater explosion was starting in China, and this technology fit the market perfectly. Today, there are more commercial movie theaters in China than in the U.S. A similar, potentially disruptive technology is using lasers for illumination, such as those being used in the headlights of Audi and BMW automobiles. While a minuscule laser revenue source overall, the potential remains for lasers to replace LEDs in many lighting applications of the future.

Laser light shows for entertainment continue to dazzle audiences, both large and small. "The laser entertainment industry has experienced exponential growth in 2018 due to a couple of key innovations. First, the overall price to purchase a laser projector has come down substantially, thanks to lower costs for the laser diodes themselves. In addition, easier laser controls and user interfaces are helping everyday consumers gain access to the tools they need, allowing them to design, create, and then project their own laser content," says Justin Perry, chief operating officer at Pangolin Laser Systems (Orlando, FL). "As a result, we see lasers being used even more for applications like home entertainment, Christmas and holiday lighting, as well as for classic uses such as nightclubs, tours, and festivals," he adds.

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For the complete list of references, please see https://bit.ly/jan19references.

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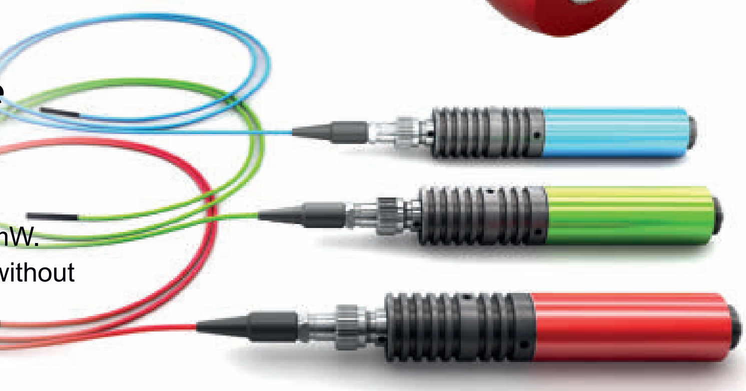

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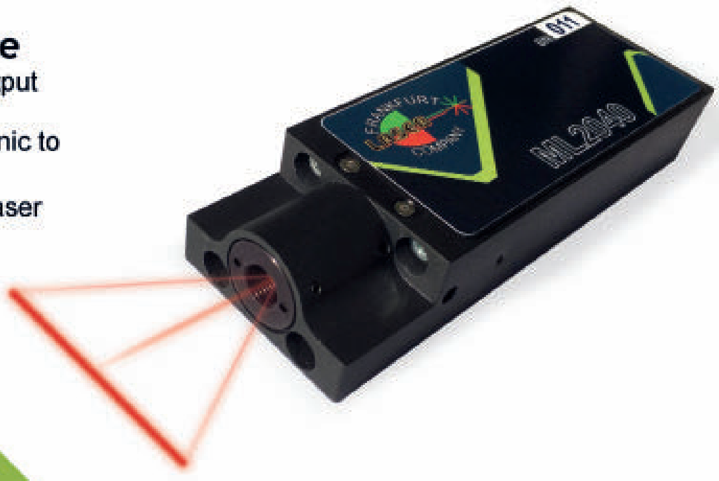

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Lasers for flow cytometry are small, solid, and reliable

JOHN WALLACE, Senior Editor

Single- and multiline lasers with wavelengths across the visible spectrum and beyond allow matching with numerous applications.

In laser-based flow cytometry, biological cells (or sometimes other particles) in fluid are sent through a channel that is arranged so that the cells pass through one by one, allowing a laser, or often multiple lasers, to identify some aspect of the cells or particles. Often, cells in such a setup are labeled with fluorescent dyes. Flow cytometry can be used for science as well as the medical arena, and can enable devices that sort cells.

The technique is incredibly versatile, allowing everything from identifying pathogens, to sorting stem cells from non-stem cells, to diagnosing some forms of cancer. Because each type of detection task is different—for example, requiring a certain chosen fluorescent marker or markers—the required laser wavelengths span a wide range. While laser wavelengths are available in small modules suitable for medical instrumentation at wavelengths ranging from the near-ultraviolet (near-UV) to the near-infrared (near-IR), flow cytometry typically relies on light at visible wavelengths. UV flow cytometry is an area of active interest, with R&D being done on wavelengths into the deep-UV. Here, though, we concentrate on examples of workhorse light sources for flow cytometers: those operating in the visible spectrum.

Multiline lasers

Because flow cytometers often require more than one wavelength, multiline lasers are a natural for this purpose. Cobolt (Solna, Sweden) has provided the flow-cytometry market with standalone high-performance lasers over the visible spectrum for many years, notes Håkan Karlsson, the company's CEO. "Originally, it was our DPSS laser technology with high powers of 532 nm and 561 nm which made Cobolt lasers attractive to the flow community, and in later years our diode-laser portfolio." More recently following the market request for more compact, easy-to-use lasers, the company introduced a multiline laser—the Cobolt Skyra, Karlsson adds.

The Skyra combines up to four individual laser wavelengths, which are permanently aligned using a method that is patent-pending. "The idea was to be able to offer a single compact package that could be used like a single-line laser: that is, an easy-to-use, robust laser with no need for realignment," Karlsson says. He also notes that the lasers are made via the company's HTCure manufacturing method, which he says allows the light sources to meet the beam overlap, power stability, and noise specifications needed for flow cytometers (the HTCure includes matching coefficients of thermal expansion of components so that they are unaffected by the high-temperature baking process. In addition, Cobolt offers customized offset line focus optical designs, which are typically requested from the flow market.

The types of individual lasers available in the Skyra multiline laser include modulated laser diodes (MLDs) at 405, 445, 473, 488, 525, 633, 638, 647, and 660 nm wavelengths, and diode-pumped lasers (DPLs) at 532.1, 552.8, and 561.2 nm wavelengths.

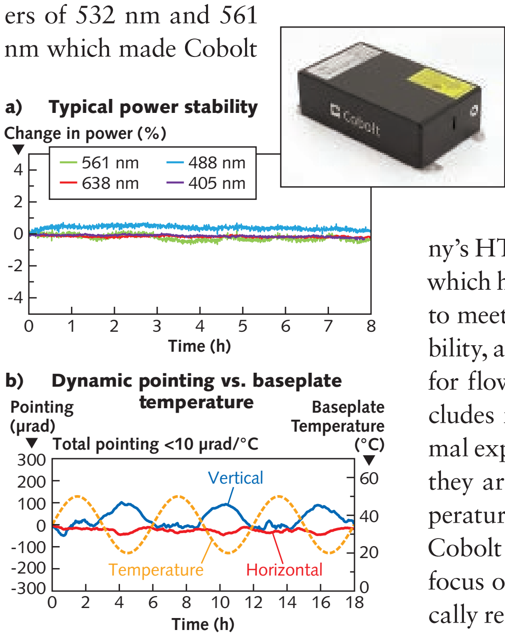

FIGURE 1. The Cobolt Skyra multiline laser for flow cytometry (inset) is stable in both output beam power (a) and in pointing stability under temperature excursions (b).

Optical output stability is better than ±1% over eight hours and pointing stability when cycled over a 30° range is better than ±100 μrad in both vertical and horizontal directions (see Fig. 1). A fiber-coupled option is also available.

"The trend to more compact systems in general in all analytical instrumentation, along with the understanding that by offering more wavelengths the instruments offer additional functionality, means that there is strong market demand for such a compact multiline laser," Karlsson says.

Two trends

Daniel Callen, product line manager at Coherent (Santa Clara, CA), sees two trends in the area of laser-based flow cytometers used for cell sorting. First, he says, expanding the wavelength range supports multiparameter counting.

"Multiparameter methods maximize the data content in both clinical and research settings; that is, the ability to count a larger number of different cell types from the same sample," Callen says. "Increasing the number of counting parameters can be achieved by using wavelength discrimination in both the detection and excitation channels. Specifically, multiparameter instruments measure fluorescence in multiple wavelength bins, and also correlate these signals as a function of several different laser wavelengths. To increase the number of parameters that are simultaneously profiled, instrument builders and users are looking to new laser wavelengths—particularly in the UV, but also in the near-IR and at key visible wavelengths."

Callen explains that the wavelength flexibility of optically pumped semiconductor laser (OPSL) technology, alongside a growing range of available laser diodes, makes these technologies ideal to meet this demand for an expanded palette of wavelengths. At the same time, packaging OPSLs and diode technologies into a common, self-contained smart format such as the Coherent OBIS, has enabled new wavelengths to be added or replaced in a simple plug-and-play fashion.

The second trend mentioned by Callen is the increasing availability and use of integrated light engines with multiple addressable wavelengths.

"Although higher-end research instruments may, for the reasons above, use a large number of lasers with diverse wavelength options, there has been a convergence on a smaller set of standard wavelengths for clinical and related applications, he says. "Specifically, the majority of instruments still use just 405, 488, and 640 nm, with 561 nm sometimes added to the mix. This wavelength standardization has allowed laser manufacturers to take the plug-and-play concept to the next logical stage, with all the lasers and electronics provided in a single module that also includes beam shaping, steering, and focusing optics."

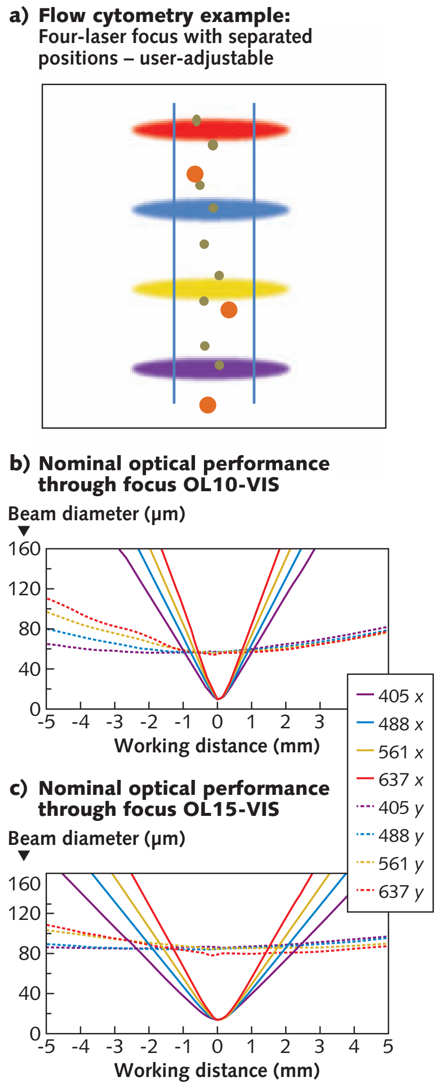

FIGURE 2. Integrated modules are designed to independently adjust each beam with an elliptical focus; the narrow *x* axis provides high (temporal) counting resolution and the long *y* axis accommodates natural deviations in the flow path of cells in the hydrodynamic flow stream (a). In addition to its OBIS lasers for flow cytometry, Coherent produces accessories such as achromatic (400–700 nm) objective lenses producing 10 (OL10-VS) and 15 (OL15-VIS) μm vertical focal spot sizes (b and c).

An example of this approach is the OBIS CellX four-wavelength laser engine that includes lasers along with beam-delivery optics for typical flow cytometry applications, says John Abbott, director of laser measurement and control sales at Coherent. The instrument builder can select from different focus size options and then adjust the position and alignment of each beam by simple internal adjustments, matching the requirements of a particular cytometer design (see Fig. 2). By outsourcing the beam handling and laser integration, the instrument builder cuts development costs and shortens time to market while also minimizing performance risk. Additionally, Abbott says, integrated laser engines such as the CellX allow capital cost reduction by consolidating hardware and electronics, for instance, by shared thermal management and by using a single controller board to drive the lasers, with common power and input/output connectors.

Pulsed as well as continuous-wave

MKS Instruments (Santa Clara, CA), of which Spectra-Physics Lasers is a part, makes a wide range of components for flow cytometry, including motion-control and vibration-isolation systems, optical subassemblies and components, and lasers (by Spectra-Physics). Its laser lineup includes compact lasers (Excelsior One) with wavelengths of 375, 405, 445, 473, 488, 515, 532, 542, 553, 561, 594, 642, 785, or 1064 nm. Herman Chui, senior director of product marketing at Spectra-Physics, notes that the company's Vanguard laser, which is a mode-locked 355 or 532 nm laser producing pulses <13 ps in duration at an 80 MHz rate, is also used for flow cytometry.

"In addition to the usual research and clinical diagnostics applications," Chui adds, "one application of flow cytometry that is a bit less known is gender/trait selection for animal husbandry, such as for cattle breeding. It's an important commercial application that's enabled by lasers."

For More Information

Companies mentioned in this article include:

Cobolt
Solna, Sweden
www.coboltlasers.com

Coherent
Santa Clara, CA
www.coherent.com

Spectra-Physics (MKS Instruments)
Santa Clara, CA
www.spectra-physics.com

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Nanoparticles enhance performance of optical coatings

THERESA HENDRICK

Dispersed nanoparticles provide quantitative and qualitative enhancements to high-refractive-index, antireflective, high-reflection, spectral, and transparent conductive optical coatings.

Evolution of the electronics, display, automotive, medical, and solar industries is a key factor driving advances in optical coating materials. While some industries need coatings for substrates that offer exceptional optical clarity, others require optical coatings that are wavelength-specific and excellent conductors of electricity. Since the demands placed on the optical coatings industry are high and varied, optical coating manufacturers are turning to advanced materials experts for assistance.

Quantitative and qualitative enhancements are possible by incorporating advanced and nanoscale materials into optical coatings. The coatings can be deposited onto a substrate from a dispersion to form a film or can be incorporated into hybrid coating materials. Those who are skilled in the art of nanoparticle engineering can create highly customized and optimized materials for specific (and often proprietary) optical systems by considering particle size, shape, cost, scalability, stability, and compatibility during formulation, thereby allowing companies to introduce novel products to the market.

Based on our extensive market research along with customer interviews, certain stand-out materials have the potential to disrupt the optical coating industry, including silver, titania, and zirconia. Moving forward, it will be critical to further optimize and customize these materials to bring about enhanced performance, as well as to explore other multifunctional nanomaterials that can contribute to further advances in optical coatings.

High-refractive-index coatings

In optical coatings, control of refractive index (RI) is essential to achieve desired performance.[1] Specifically, we have seen demand for high-RI nanoparticles for incorporation into polymer-based optical coatings. By incorporating a high-RI coating on the light-emitting surface of a device, light can travel more productively in or out of the device, leading to improved efficiency and image quality.[2]

High-RI polymers are being developed for advanced optoelectronic applications in display devices, light-emitting diodes (LEDs), and organic LEDs (OLEDs). Typical optical polymers have RIs of 1.30 to 1.70, limiting the range of optical applications.[3]

A promising approach to achieving high-RI (>1.70) coatings is through the incorporation of metal-oxide nanoparticles with organic polymers to create an organic-inorganic hybrid material. The design of nanoparticles is an important consideration in their successful incorporation—specifically, particle size and compatibility with the polymer matrix to avoid aggregation.

Two of the most popular nanoparticles for producing high-RI coatings are titania (titanium dioxide or TiO_2) and zirconia (zirconium dioxide or ZrO_2). Zirconia has shown success in increasing the RI of a coating when it is surface-modified for compatibility with a polymeric system. When incorporated in preliminary polymeric-based formulations, Cerion

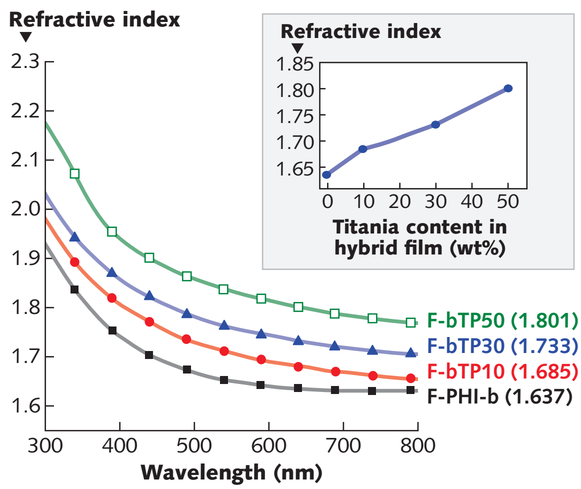


FIGURE 1. Refractive-index variation of polyimide-nanocrystalline-TiO_2 materials with wavelength is shown, where F-PHI-b, F-bTP10, F-bTP30, and F-bTP50 contain 0 wt%, 10 wt%, 30 wt%, and 50 wt% TiO_2, respectively; the inset shows the variation of RI with increasing titania content for these samples at 633 nm. *(Courtesy of National Taiwan University)*

functionalized zirconia nanoparticles showed higher RI with increasing ZrO_2 content, increasing the RI from 1.5 to 1.71 (for 66 wt% ZrO_2) and 1.77 (for 75 wt% ZrO_2).

Using high-RI titania, polyimide-nano-crystalline-TiO_2 coatings with high weight percent (wt%) TiO_2 can form films with high optical transparency. Increasing TiO_2 content enables an RI of more than 1.8 with 50 wt% TiO_2 (see Fig. 1).[4]

High- and low-RI nanoparticles can be used to form adjustable RI coatings. For example, titania and silica (silicon dioxide or SiO_2) can be used to form coatings on substrates with tunable RI, based on the content of SiO_2. Coatings such as these can have other desirable characteristics as well, such as low reflectance and high transmittance.

Antireflective coatings

The surfaces of LEDs and solar cells require antireflective (AR) coatings to provide high transmittance while minimizing reflections of unwanted light.[5] These AR properties result from the destructive interference of light as it travels through thin films of differing RI and thickness.

While obtaining near-perfect AR coatings in a research environment is possible, industrial-scale production has been a challenge because of poor manufacturing robustness and contamination that impacts optical performance. However, two materials that show promise for AR coatings are silica and titania because of their RI difference. A multilayer thin film of alternating titania and silica can improve transmittance for bare glass from 92% to 95% for one coated surface and

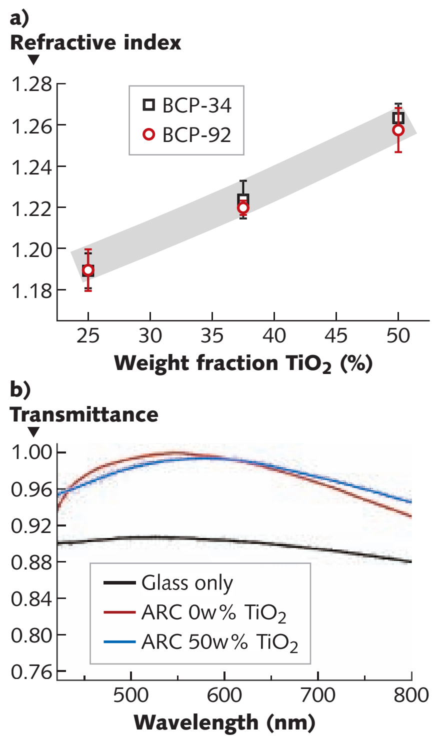
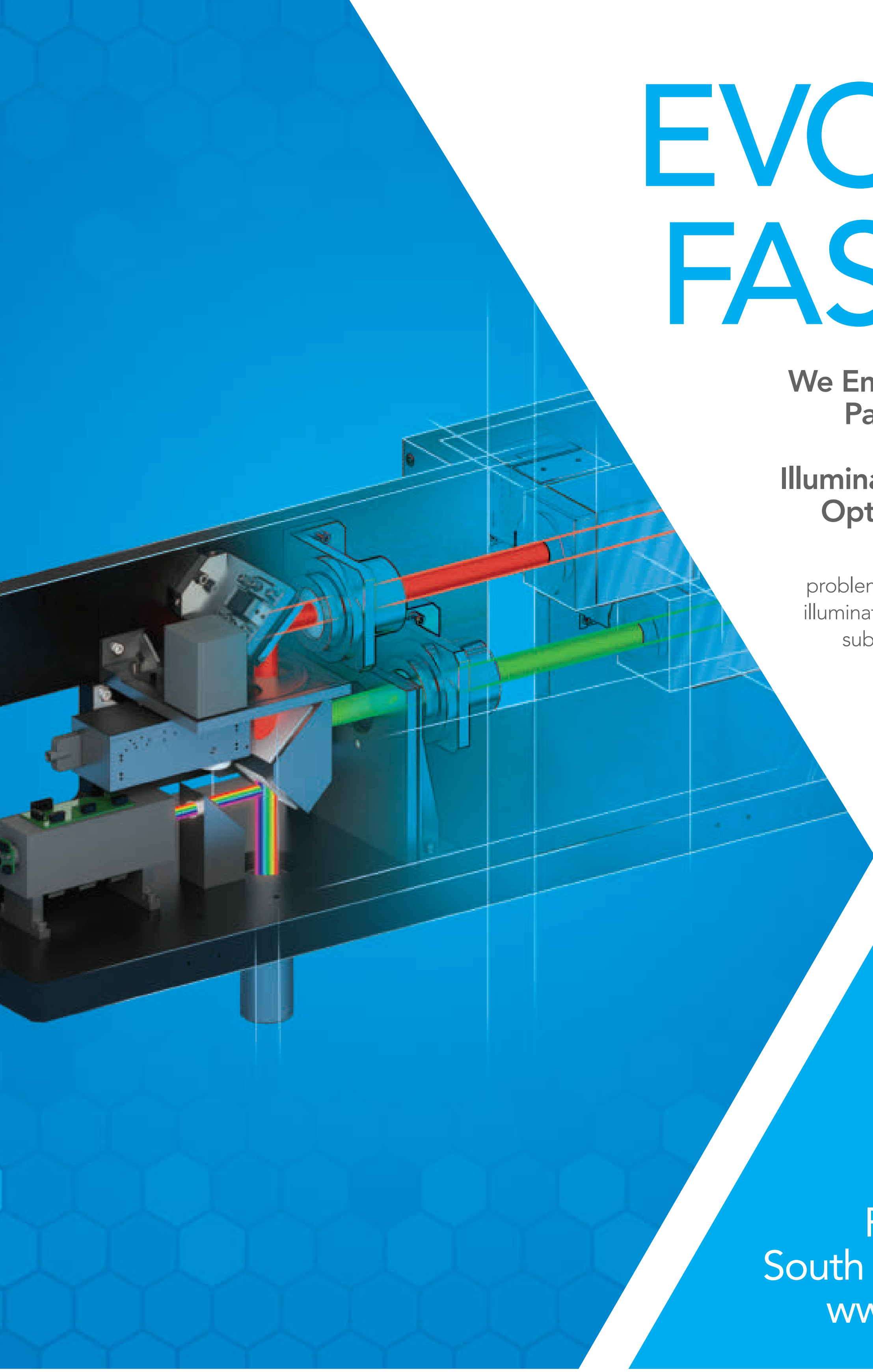


FIGURE 2. Refractive index is shown (a) as a function of TiO_2 wt% for two different block copolymers (BCPs) with molecular weights of 34.4 kg/mol and 91.9 kg/mol; in (b), transmittance of bare glass is compared with glass coated on both sides with an AR coating containing 0 and 50 wt% TiO_2. *(Courtesy of the University of Cambridge)*



more than 97% for glass coated on both sides. This coating also features multifunctional performance as it absorbs ultraviolet (UV) light, is hydrophobic and oleophobic, and has excellent scratch resistance and adhesion.[6]

Because of its photocatalytic properties, TiO_2 is often used for AR coatings with self-cleaning functionality, as titania can degrade organic contaminants. Modified 4 nm anatase TiO_2 nanoparticles incorporated into a block copolymer (BCP) can be processed into a thin film to coat glass or plastic. By incorporating 37.5 wt% TiO_2, an optimal RI of 1.22 is achieved for an AR coating on glass (see Fig. 2a).[7] With 50 wt% TiO_2, the AR coating has a maximum transmittance of about 99.3% with excellent photocatalytic and self-cleaning properties that improve the long-term performance of the substrate used (see Fig. 2b).

Nanoparticles of silica (nano-silica) have also been used to produce AR coatings. Nano-silica thin films can be produced via sol-gel processing and coated on glass to bring about significantly reduced light reflection. Deposition time and cycles impact film morphology, and therefore AR properties as well. For an uncoated glass substrate with a maximum transmittance of 91.5%, one 60 s deposition cycle produced a maximum transmittance of 96%. With two deposition cycles of 30 s each, 97.5% transmittance was reached due to a more homogeneous, dense SiO_2 layer.[8]

High-reflection coatings

Reflective surfaces find applications in heat dissipation for electronics and in solar-cell cooling. Silver-based coatings offer the highest reflectivity from visible (VIS) through infrared (IR) of all metals and, when present in low amounts as silver (Ag) nanoparticles in a polymer matrix, can form metal mirrors with exceptional light reflectivity and electric conductivity.[9] When measured from 250 to 950 nm, Ag polymer coatings have reflectance surpassing 90% (see Fig. 3a). Interestingly, this material has also demonstrated self-healing of surface defects and is easily applied to substrates like textiles, glass, wood, plastic, and steel (see Fig. 3b).

There is also interest in creating coatings with high reflectivity in the solar spectrum and high emissivity in the "sky window" region for radiative cooling and thermal management applications. Two-layer coatings that consist of a top reflective layer containing titania nanoparticles, for instance, and a bottom emissive layer such as silica or silicon carbide nanoparticles, have performed well in this application. Rooftop studies confirm that these coatings can cool an aluminum substrate to ambient temperature when exposed to direct sunlight.[10]

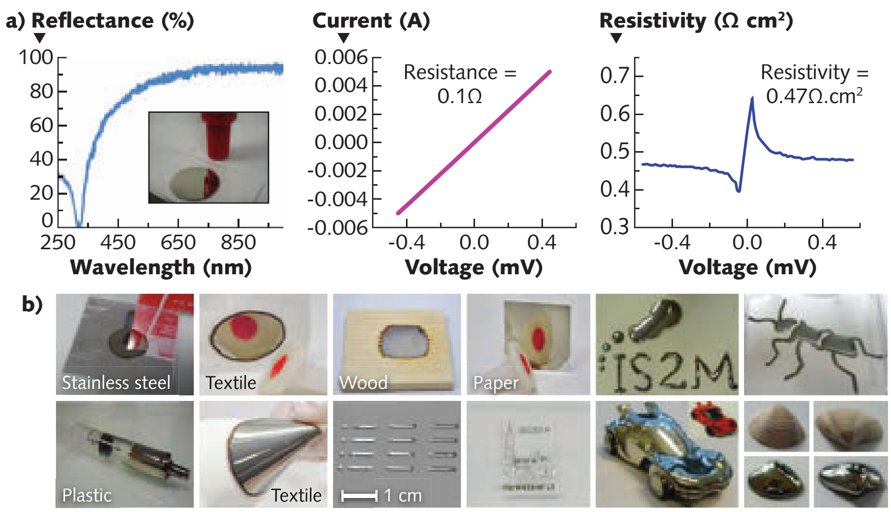


FIGURE 3. High reflectance is shown for a silver polymer coating (a) that can be applied to a range of substrates (b). *(Courtesy of CNRS, Institut de Science des Matériaux de Mulhouse)*

Spectral coatings

Coatings that selectively filter certain wavelengths of light can prevent aging and degradation in certain plastics that are not resistant to UV light, or block near-IR solar energy for solar-driven window cooling.[11] In addition to surface-modification methods, an alternative approach focuses on tuning nanomaterials to selectively absorb damaging or unwanted wavelengths and transmitting those that are preferred.

Titania (TiO_2) nanoparticle coatings can transmit visible light and strongly absorb UV radiation, whereas zinc oxide (ZnO) provides broad-spectrum protection against UV radiation—especially when in nanoparticle form. Incorporating nanoparticles such as these into coatings can improve protection from UV light while remaining transparent.

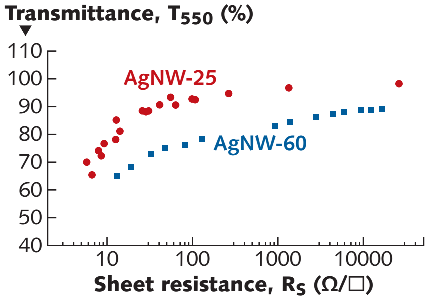


FIGURE 4. Transmittance at 550 nm is plotted against sheet resistance of silver nanowires (AgNWs) with two different sizes, where AgNW-60 has average diameter of 54 nm and average length of 9.4 μm, and AgNW-25 has average diameter of 27 nm and average length of 18 μm. *(Courtesy of the University of Surrey, Guildford)*

TCE	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	eff (%)	R_s (Ω cm⁻²)	R_{sh} (Ω cm⁻²)
AgNWs	0.2	0.54	33	0.05		
ITO	30.7	0.65	65	13.04	0.92	147
AgNW(ZnO)	33.7	0.64	62	13.5	0.65	299

FIGURE 5. Shown are parameters of CIGS solar cells with AgNW, AgNW(ZnO), and ITO as transparent conductive electrodes. *(Courtesy of Incheon National University)*

Transparent conductive coatings

The market for transparent conductive coatings has exploded because of increased demand for touchscreen displays and thin-film solar cells. Indium tin oxide (ITO) is almost exclusively used in transparent conductive coatings—however, its high cost, high film-deposition temperature, brittleness, and yellow tint means that a reliable replacement is being sought.[12]

Because replacement materials like carbon nanotubes, graphene, and conductive polymers cannot match the performance of ITO, silver nanowires (AgNWs) have recently emerged as an exciting substitute because of their high transparency and conductivity, low-cost deposition, and resistance to cracking.

The design of AgNWs is a critical factor in the performance of the resulting coating. Longer nanowires decrease sheet resistance because there are fewer connections between them, and because of this, there is a pressing need for the development of ultralong nanowires. Promisingly, AgNW dispersions with the smallest diameter and longest length have shown results comparable to that of commercially available ITO (see Fig. 4).[12]

Silver nanowires can also be combined with other nanomaterials to improve performance for certain applications. A film of AgNWs with a diameter and length of 60 nm and 30–40 µm, respectively, with a thin overlayer of ZnO (AgNW(ZnO)) offers improved connectivity between nanowires and improved adhesion with low-lying surfaces. A solar cell with AgNW(ZnO) transparent conductive electrodes has 13.50% efficiency compared to 13.04% for ITO. It is thought the improved adhesion contributes to the superior performance (see Fig. 5).[13]

Because of the promise inorganic advanced and nano-sized materials have in optical coatings, many industry leaders are focusing research and development efforts on incorporating these materials into their optical coatings. To overcome hurdles to scalable manufacturing, however, partnerships with inorganic materials experts will be beneficial.

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Research gives high-power diode lasers new capabilities

PAUL CRUMP and ANDREAS THOSS

R&D at Berlin Adlershof has resulted in design improvements for high-power diode lasers that are boosting efficiency, peak power, brilliance, and range of emission spectra.

Many major laser applications in industry and academia are requiring ever-better diode-laser performance. Increasingly complex studies of the device physics are being used to guide developments in epitaxial layer design and device technology, and the resulting improved diode lasers are delivering the higher efficiency, brilliance, and output power that is urgently needed now and in the coming years.

Diode lasers (see Fig. 1) have become the silent heroes of industrial laser technology. They do the tough job of pumping the fiber and disk lasers that have conquered the multibillion-euro (and multibillion-dollar) market of cutting and welding—soon, they will challenge even these systems with direct-diode applications. On the academic side, new ultrashort-pulse high-energy lasers with high repetition rates are projected to open up new horizons in particle acceleration. These lasers will also be diode-pumped.

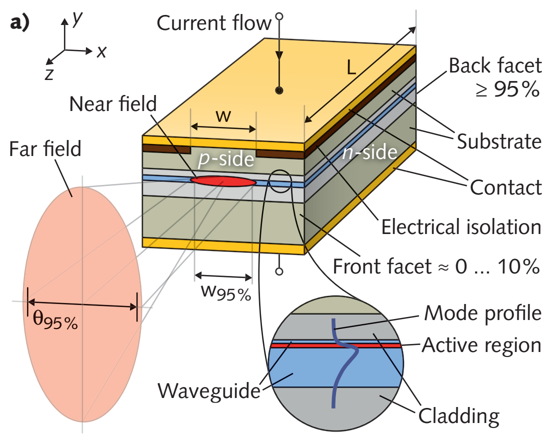
All these developments and more require better diode lasers, and with improved performance and reduced price per watt. While this sounds challenging, the established market for high-power diode lasers is growing fast and diversifying rapidly enough to encourage worldwide development efforts.

One of the hot spots for such R&D activities is Berlin Adlershof, with the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) and other academic institutions located on the same campus in Berlin, Germany. Beside several FBH spinoffs, larger companies such as the Trumpf Group, Jenoptik, II-VI, and Corning have subsidiaries within walking distance of the institute, where they work together on future developments in high-power diode lasers.

How to improve diode laser technology

Diode lasers are well known as the world's most efficient light source, with records of more than 65% wall-plug efficiency at an emitted power of 12 to 15 W from a 100 μm aperture. High-power laser diodes are typically grown using metalorganic vapor-phase epitaxy (MOVPE) on gallium arsenide (GaAs) wafers with typical emission wavelengths between 700 and 1100 nm.

Although the discovery of diode lasers dates back to the early 1960s, diode laser parameters are still rapidly improving—specifically efficiency, peak power, brilliance, and the range of emission spectra. The research team at FBH is playing a key role in advancing this field. Their research in device physics and material technology helps clarify and address performance limits, and design development based on this information maximizes performance of commercially important devices—for example, better pumps to enable higher performance in industrial disk or fiber laser systems. The FBH technology also makes novel devices and modules possible and enables new kinds of applications. Inventions are protected by a broad patent portfolio. Example performance records include the first 1 cm diode



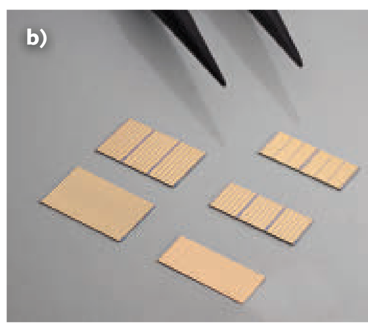


FIGURE 1. Shown is the structure of a typical diode laser (a); the inset shows the triple-asymmetric active region where the laser radiation is generated. The active diode structures of even high-power diode lasers are quite small, as revealed by a close-up photo (b). *(Courtesy of FBH)*

laser bars with 1.5–2 kW output power and bars with >60% conversion efficiency at 1 kW.

Results of the work at FBH are regularly presented at numerous conferences. A plenary talk on the latest progress and prospects in this exciting and industrially critical field will be given by Günther Tränkle, director of the FBH, at SPIE Photonics West 2019 (San Francisco, CA; February 2-7).

Triple asymmetric layer designs

In the best modern high-power diode lasers, peak power and efficiency are not limited by failure, but instead by fundamental loss mechanisms. A deep understanding of the physics within the diode and the device technology is therefore a prerequisite for targeting further improvements.

As an example, based on the results of many years of device research into limits to power and efficiency, the FBH team recently developed the concept of a triple asymmetrical epitaxial layer design. Such a design precisely manipulates the optical field and leads to both higher efficiency and higher output powers.[1] The first asymmetry is within the semiconductor material of the diode structure: The *p*-layer is made as thin as possible, which reduces electrical resistance and optical losses. This is combined with a second asymmetry in the design of the cladding and waveguide inside the diode. The clad/guide asymmetry helps to couple unwanted optical modes into the substrate, preventing them from lasing. Finally, a third asymmetry in the graded profile of the refractive index for the layers on either side of the quantum well is introduced, allowing for fine-tuning of the optical field.

A shift of the optical field towards the quantum well increases optical gain without the need to adjust the *p*-side, which can remain thin for low loss. For the first time, this allows the simultaneous realization of low resistance, low optical loss, low power saturation, and a low threshold current. With this structure, an efficiency record of 66% at 10 W output for continuous-wave (CW) output (940 nm, 25°C) was achieved (69% peak efficiency), 1.05X higher than comparable symmetric designs (see Fig. 2).

Limits to efficiency also lie in the lateral structure, as significant levels of electrical current are lost on either side of the electrical stripe, even in broad-area lasers. A novel current blocking technology eliminates this lost current and is fabricated using a two-step *in situ*-etched MOVPE process. Corresponding prototype buried mesa lasers operated at a 5% higher efficiency (see Fig. 2). Combining both triple asymmetrical designs and lateral current blocking techniques is anticipated to further increase efficiency.

Efficient kilowatt laser bars

These sophisticated epitaxial designs, when fabricated into diode lasers using high-quality low-defect device technology, can be exploited for higher performance in applications. For example, 1 cm laser bars are in wide industrial use, directly and as pump sources, and increased power directly lowers cost per watt, reduces system size, and can also improve performance (via higher-brightness pumping). FBH research has helped address this challenge, enabling a two- to fourfold increase in the peak output power of diode laser bars over the last 10 years (see Fig. 3) in quasi-continuous-wave (QCW) mode for pumping of pulsed solid-state laser systems.

In parallel, efficiency has been increased at 1 kW per bar, from approximately 35% to 63%. Currently, Trumpf and the FBH are collaborating closely, demonstrating kilowatt output in CW mode at the highest reported operating temperature of 298 K, and working to continuously increase efficiency and beam quality. Trumpf will report the latest progress at SPIE Photonics West 2019.

Monolithically wavelength-stabilized diode lasers

For applications such as solid-state laser pumping and sensing, diode lasers with a narrow and stable spectrum are needed. From the viewpoint of production costs, monolithically integrated

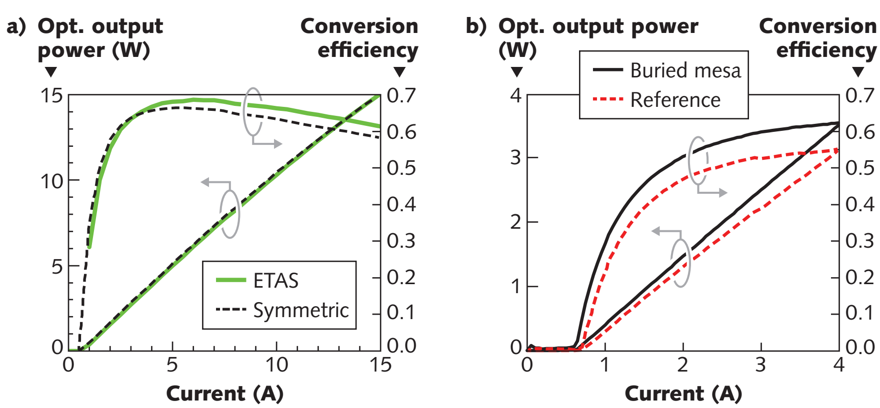


FIGURE 2. The extreme-triple-asymmetric (ETAS) design of a broad-area diode laser (a) shows a superior efficiency (red) of >60% when compared to a regular symmetric design; buried mesa growth technology for GaAs-AlGaAs lasers (b) reduces loss currents and also leads to higher efficiency (CW, 25°C, L = 4 mm, W = 100 µm).

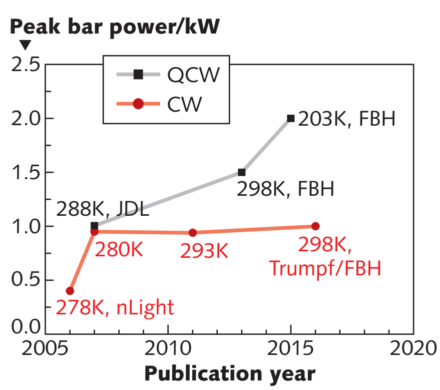


FIGURE 3. Peak optical powers from 1 cm diode laser bars has rapidly increased, both in CW (red) and quasi-CW (black) operation mode; operating temperature, wavelength, and supplier are noted.

gratings are particularly attractive technology for narrowing the spectrum—this approach eliminates the need for external feedback, which leads to lower lifetimes. As a result, FBH scientists have intensively studied design and technology for monolithic grating stabilization for many years, seeking to make this key technology ready for market application.

Again, in the past 10 years, power per emitter has increased around tenfold and efficiency has roughly doubled. The FBH has developed and patented several different approaches that substantially reduce optical losses from the grating. For example, broad-area lasers with uniform monolithically integrated gratings (BA-DFBs) have been developed, in which the feedback is provided by novel apodized surface-etched gratings (see Fig. 4). In these devices, the grating strength is varied along the resonator, thus significantly increasing fabrication yield and performance compared to reference uniform DFBs (see Fig. 5). Corresponding prototype diode lasers have operated failure-free for >10,000 hours, thus promising improved applications in coming years.

Ultrabrilliant beam combining

Industrial systems combine the emission of many diode lasers into a single beam to reach the intensity needed to cut metals such as steel. Current systems use fiber or disk lasers to collect the energy from the diode lasers. Direct-diode laser systems have the potential to be a highly efficient, compact, and reliable competitor to these established solutions—therefore, intensive research is aiming to make this possible.

One important technique to increase the optical intensity from direct-diode sources is wavelength beam combining (WBC), in which light from many diode lasers are brought together into a single beam using, for example, an external grating. In this way, very high combined powers are produced, at the cost of broadening the spectrum. The FBH develops highly efficient ultra-intense arrays of diode lasers specifically for this application. Examples include high-power arrays of single-mode lasers that are tailored for spectral stabilization with an external grating and then wavelength-beam-combined (developed in a collaboration with Trumpf).

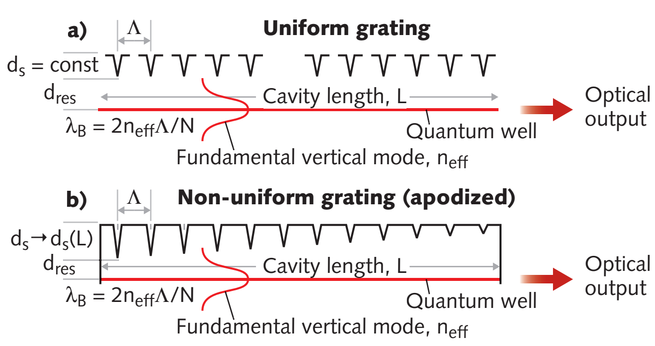


FIGURE 4. Diodes using surface-etched apodized gratings (b) have higher manufacturing yield and efficiency for the same grating depth than those with uniform gratings (a).

If the grating is brought inside the diode laser, the system can potentially be much simpler and more compact—a concept studied in detail in the EU-funded project BRIDLE (developed in a collaboration with DILAS and the Fraunhofer Institute for Laser Technology [Fraunhofer ILT; Aachen, Germany]). An array of five custom diode lasers with monolithically integrated gratings was spectrally combined and coupled into a low-mode optical fiber with 35 μm diameter and a numerical aperture (NA) of 0.2, with a total power from the fiber of 26 W in a single polarization—more than twice the intensity of commercially available unpolarized modules with 105-μm-diameter fibers.

A more advanced approach is coherent beam combination (CBC).

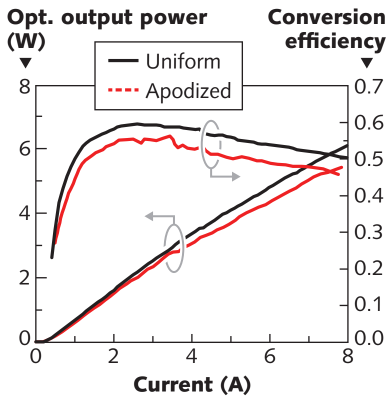


FIGURE 5. Plotted here are the optical power and efficiency of monolithically grating-stabilized diode lasers mounted on submounts and ready for use in a laser system, showing the superior performance of apodized gratings.

Here, the output from one distributed feedback (DFB) seed laser is split into several beams whose powers are boosted via parallel semiconductor amplifier stages. Careful regulation of the amplifier currents hold their output perfectly in phase so that the array of amplifiers acts like a single laser, with a diffraction-limited beam and narrow spectrum. The FBH is studying how best to realize such systems (in a collaboration with the Laboratoire Charles Fabry (Paris, France) and the Technical University of Denmark (Kongens Lyngby, Denmark), and recent studies showed that CBC not only increases power but also improves beam quality, enabling generation of more than 2 W of frequency-converted green light—the highest reported level from a direct diode source.

World's first joule-class mid-infrared laser light source

Advances in high-power diode lasers also open up new applications in solid-state lasers. In August 2018, partners from the German regions of Berlin and Jena joined forces in a new BMBF (German ministry for education and research) project, coordinated by the Berlin-Brandenburg Competence Network for Optical Technologies (OpTecBB). With 1.5 million euros, the team will develop the world's first high-energy class mid-infrared laser (HECMIR), targeting pulse energies of more than 1 J at a wavelength of 1.9 µm. These pulse energies are made possible by highly intense, long-pulse diode laser pump sources, which will be developed and realized for the HECMIR by the FBH, exploiting novel diode laser designs and innovative high duty-cycle stacked array technology.

The short-pulsed MIR sources from HECMIR could enable particle (such as proton) beams from a tabletop device at an energy level that nowadays require basketball-court-sized accelerators. These particle beams would be an ideal non-invasive medical treatment for tumor removal. MIR sources are also projected to play a key role in future very-high-energy pulsed research lasers. A new generation of ultrashort-pulsed high-energy lasers is being installed worldwide, and there is demand for even higher performance. This will only be possible with advanced diode pumping, in both conventional and MIR wavelength bands, as is currently being studied in the EuPRAXIA consortium.[2] ◄

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Paul Crump is the head of the high-power diode lasers laboratory at the Ferdinand-Braun-Institut (FBH), Berlin, Germany; www.fbh-berlin.com/research/photonics/high-power-diode-lasers, while **Andreas Thoss** is founder and managing director of THOSS Media, Berlin, Germany; e-mail: th@thoss-media.de; www.thoss-media.de.

Ensuring quantum-secured communications

CHRISTOPHER CHUNNILALL and TIM SPILLER

Field tests are solving the challenges of counting photons and measuring their quantum states in quantum key distribution (QKD)-based optical transmission networks to ensure communications security.

Quantum key distribution (QKD) is an ultrasecure communication method that uses quantum states of light to communicate between two distant parties ('Alice' and 'Bob'), enabling them to create a secret shared encryption key that can be used to transmit and receive messages (see Fig. 1).

To keep electronic information—such as biometric and financial data—secure, it is encrypted before being transferred between parties. Simply, this involves jumbling it up in a particular way so that it can only be unjumbled by someone who has the key. When Alice sends an encrypted message to Bob, they both need the same key to encrypt and decrypt it. Simply stated, QKD is a unique way of creating and securely sharing a key between Alice and Bob.

Key security

Data encoded using current algorithmic key distribution schemes is vulnerable to being cracked with mathematical insight, powerful computers, or future quantum computers. Work is underway on new mathematical algorithms ("post-quantum" cryptography) that will not be vulnerable. However, it will be very hard to provide security against all possible future quantum computer cryptanalysis.

QKD techniques encode the key using a physical process, not an algorithmic one. As such, key security depends on the physical performance of the QKD system at the time of key creation.

Given a theoretical model for the system, which is built on a set of assumptions about the abilities and performance of the hardware, QKD can be proven unconditionally secure. However, any differences between the actual physical system and the theoretical model could introduce vulnerabilities in the security that could be exploited. Physical characterization is therefore essential to ensure that the hardware is operating as intended. The parameters that go into the theoretical model need to be measured, as well as the effectiveness of measures implemented to nullify hacking attacks.[1]

How does QKD work?

Quantum key distribution takes advantage of a fundamental aspect of quantum mechanics: observing a system changes its quantum state. The key is encoded into the quantum states or pulses of light. If a third party—Eve—tries to copy the quantum state in transit, she cannot avoid introducing changes to the light that can be detected when it is received. But if the stream of quantum light signals has been received unchanged, Bob and Alice know that they—and only they—have the key. They can then begin sending encrypted messages with confidence.

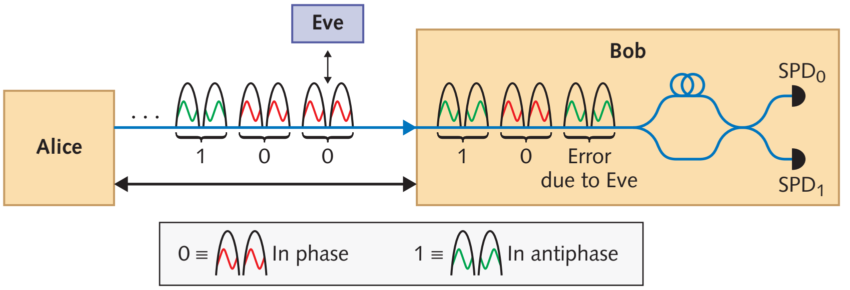

FIGURE 1. In this example of an optical-fiber-based QKD system, the quantum (open) channel is in blue (black). SPD_0 and SPD_1 are single-photon detectors. Each bit is encoded by a pair of pulses—in phase (antiphase) pulses are separated by $n\lambda$ ($[n+½]\lambda$), where n is an integer and λ is the wavelength of the light, and lead to a detection at SPD_0 (SPD_1). If Eve tries to measure this separation and resend a copy, she will sometimes change it (see rightmost pair of pulses) and cause a detection in the 'wrong' detector. (*Image credit: Sophie Albosh/NPL and the University of York*)

In one example of QKD, Alice sends out a string of single photons (elementary particles of light) encoded to represent a bit—a '1' or a '0'. Not all will arrive at Bob. Some will be lost in the optical fiber medium, and some may be stolen. That doesn't matter, however—the key is just created from the photons that are received. Bob uses an open channel to tell Alice that he received the photons in position 1, 5, 7, and so on, and those are used to create the key.

If Eve steals the photons, they won't arrive and won't form part of the key, so are useless to her. If she measures them and tries to send a duplicate, quantum physics guarantees that she will sometimes change the state of the photons, making it clear that they have been tampered with. At this point, a new key is created. So, it is physically impossible for Eve to steal the key.

Alice's transmitter is a pulsed photon source (the highly attenuated output from a laser) that modulates the encoding property of the photons. For optical fiber communications, this may typically be the phase of the photons, or the time slot in which they are transmitted. A random number generator selects the state to be encoded at random.

At Bob's end, there are single-photon detectors. For example, if phase-encoding is used, an interference measurement is performed, with detectors at each output port of the interferometer. The phase is determined from knowing which detector receives the photon.

The evolution of QKD

Commercially viable QKD transmitters and receivers are available—however, they are physically large and expensive, and only suitable for very high-value security applications. The aspiration of the industry is to address these size, weight, and power (SWaP) limitations, to deliver practical quantum-secured communications that will open broader markets for consumers, commerce, and government. This has been one of the driving goals of the Quantum Communications Hub (www.quantumcommshub.net) since it was established by the UK government in 2014 as part of the UK National Quantum Technologies Programme (http://uknqt.epsrc.ac.uk). The Hub is led by the University of York (York, England), and is a collaboration of eight universities, the UK National Physical Laboratory (NPL; Teddington, England), and numerous industrial partners.

A major step towards SWaP-saving is to engineer QKD on affordable chips, such as those that will fit into a smartphone. The physics is proven, but the challenge is developing small-enough devices.

For transmitters, photon sources at chip-scale have been successfully developed using light sources with filters to control production of single photons. These provide workable devices for current commercial QKD. However, further photonics challenges remain, particularly around chip-scale entangled photon generation for alternative approaches to QKD.

Detectors are more challenging since materials sensitive enough to detect single photons are bulky. The best current detector materials are superconducting—requiring significant cooling apparatus. However, detector size is less of an immediate problem since early QKD would likely involve a secure end-user location—such as a bank or government department—that could accommodate a bulkier detector. But the long-term goal is smaller detectors so that laptops can communicate directly with each other, pointing towards semiconductor devices.

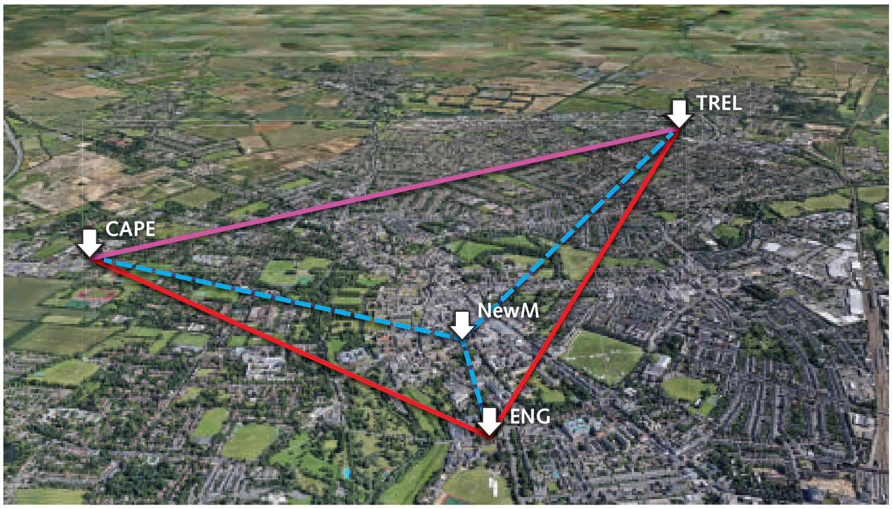

FIGURE 2. The Quantum Communications Hub is creating the UK's first quantum network—a place to test and demonstrate new technologies and highlight useful applications of QKD. (*Image credit: Dan Tsantilis/EPSRC*)

Developing and testing QKD

QKD systems are being developed in many countries, most notably in Austria, Canada, China, Japan, South Korea, Switzerland, the U.S., as well as the UK.

A driving goal of the Quantum Communications Hub creating the UK's first quantum network, the UKQN, is providing a place to test and demonstrate new technologies and highlight useful applications of QKD. The UKQN comprises multinode fiber-optic networks in Bristol and Cambridge, with connections being established between them, and also from Cambridge to BT Labs at Adastral Park near Ipswich, England (see Fig. 2).

In recent years, Hub industrial partners ADVA, BT, and Toshiba demonstrated that 200 gigabit-per-second (Gbit/s) data, encrypted with quantum keys, can be sent over 100 km of fiber—with one channel in the same fiber being used to establish the quantum keys. This is progressing well towards the first high-speed real-world deployment of quantum-based network security in the UK.

Meanwhile, NPL is working with the Hub, industrial developers, and other national measurement institutes to establish accurate, robust measurements to verify the security of QKD keys.[2] Measurements must be performed at the single-photon level and with low jitter, since QKD systems can operate at clock rates above 1 GHz. Single-photon detectors and sources used to respectively characterize QKD transmitters and receivers must be calibrated to the International System of Units (SI).

Even though quantum communications products are now available, the lack of agreed-upon standards for testing device performance is limiting end-user confidence and slowing potential industry uptake of these systems. The European Telecommunications Standards Institute (ETSI; Sophia-Antipolis, France) Industry Specification Group on QKD (ETSI ISG-QKD) is working to provide the documented standards and procedures that are required for the development of an assurance framework for these technologies.[3] NPL led the drafting of the first ETSI Group Specification to document measurement protocols for testing QKD components.

The future of QKD

Currently the most practical and commercially advanced QKD systems use single photons that are created by attenuating laser pulses. Originally developed as modules fitting into 19-in. racks, chip-scale prototypes have been recently developed, offering low SWaP consumption and the potential for integration into consumer electronics (see Fig. 3).[4]

Other methods of implementing QKD are being rapidly developed, including those based on encoding information into the phase of multiphoton pulses, as well as systems based on entangled photons. These approaches have advantages and disadvantages with respect to the current approach, and it is anticipated that they will all find their role in a future quantum-enabled security network.

Considerable research is also going into extending the range over which QKD can be used. Fiber links limit the point-to-point range of QKD to a few hundred kilometers because of the attenuation loss as photons propagate through optical fiber. And while performing QKD over 'lit' fiber carrying standard communications traffic further reduces the transmission distance due to increased noise, distances around 100 km have been demonstrated under these conditions.

Setting up trusted nodes is the short-term answer to long-distance secure communication. This involves detecting keys and then re-encoding quantum states, meaning that the nodes must be completely secure to maintain QKD's guarantee that no one has eavesdropped. A longer-term solution is quantum repeater technology that involves stretching out high-quality quantum entanglement over very long distances. However, this technology is still a way off, as quantum processing and quantum memories are required. Nonetheless, it is hoped that significant headway will be made towards

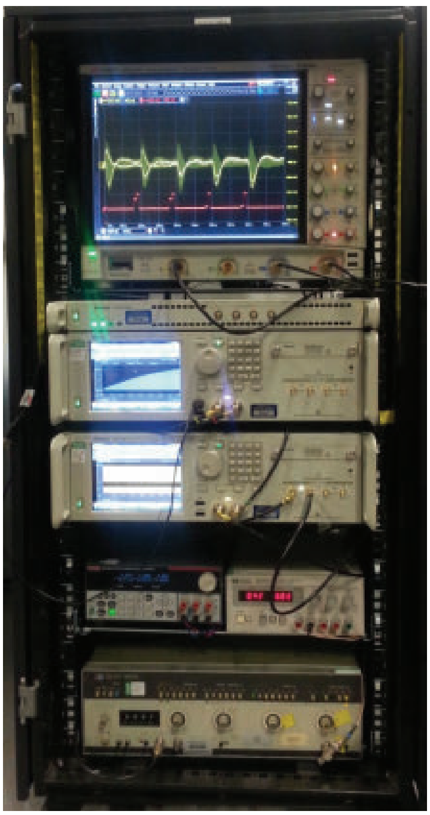

FIGURE 3. Current QKD systems use bulky rack-mounted equipment as shown, but smaller and even chip-based systems are envisioned and in development. (*Image credit: Rupesh Kumar/University of York*)

entanglement distribution and quantum repeater stations during Phase 2 of the UK National Quantum Technologies Programme, which starts in 2019 and runs for five years.

Global QKD could ultimately be achieved by distributing keys via satellites, as there is less photon loss and decoherence experienced in the clear atmosphere and in space. This can also bring QKD to locations where it would be costly, unfeasible, or not secure enough to create fiber links. This field has been stimulated by a recent demonstrator system, and various test missions are in the planning stage.[5] Satellite QKD is another priority area for the UK's quantum program over the next five years.

These new approaches will also require a calibration and assurance process, and the ETSI ISG-QKD recently prepared a report surveying some of the new protocols and the physical parameters that will need to be characterized.[3]

Technology push, industry pull

Although QKD is a proven technology, the next steps involve further SWaP-saving improvements and demonstrating network scalability. Only by engaging with industry and demonstrating successful applications of QKD using test facilities such as the UKQN and working with technical and cyber security standards bodies such as ETSI and the UK's National Cyber Security Centre (London, England) will the physical specifications and security protocols be established to encourage end-user investment and allow QKD systems to proliferate.

Early adopters are likely to be government and financial institutions, whose high-value communications and trading habits can be lucrative targets for sophisticated hackers. But in the end, necessity may drive uptake of QKD. The advent of quantum computing—another technology that uses information encoded into the states of quantum devices and systems—will lead to the ability to quickly crack current algorithmic encryption codes. Post-quantum algorithms are being actively researched. However, as proof that these codes will always be uncrackable is likely to be very difficult, "future-proof" secure systems may need to combine both QKD and post-quantum algorithms.

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A deconvolution revolution for confocal image enhancement

JAMES LOPEZ, SHINTARO FUJII, ATSUSHI DOI, and HIROMI UTSUNOMIYA

A combination of advanced algorithms and improved hardware is driving the popularity of deconvolution for optical confocal microscopy.

Image deconvolution is an image-processing technique designed to remove blur or enhance contrast and resolution. Historically, its application was limited to the enhancement of widefield images and it was considered unnecessary in confocal microscopy. Data provided by deconvolution was considered difficult to interpret and sometimes untrustworthy—however, deconvolution is now considered a powerful and versatile research tool and is often part of a confocal protocol. Now, every major microscope manufacturer promotes the use of deconvolution for enhancing confocal image resolution.

Making effective use of deconvolution, however, requires careful attention to methods and associated artifacts.

Deconvolution and resolution

In microscopy, deconvolution refers to the use of algorithms to enhance the signal-to-noise ratio (SNR) and resolution, typically by reassigning out-of-focus light back to its original position. (The term "resolution" in this context relates to the minimum distance that two objects can be from one another and still be optically distinguishable as individual entities.)

Microscopic image resolution is usually measured as the full-width at half-maximum (FWHM) of the point spread function (PSF), which is a three-dimensional intensity measurement of a small object (such as a 50–100 nm fluorescent bead). It is possible to use the FWHM measurements of PSFs on raw and deconvolved images to measure the effect of the deconvolution processing. Objects are mathematically determined to be separated based on the Rayleigh criterion, the classic method for determining resolution changes. However, the FWHM measurement on a PSF is not the full story for measuring the effect of deconvolution.

Although resolution of a confocal microscopy system is often defined by FWHM, FWHM is different than resolution, especially in relation to processed images. Blur can often be reduced in the observable image as defined by FWHM, but while deconvolution reduces FWHM, improved resolution may not result. The specific method applied for deconvolution and the parameters used for the algorithms greatly impact both measurable FWHMs and total image resolution. And it is worth noting that some methods perform better on small, clearly defined objects such as beads rather than the tangled filaments commonly depicted in cellular images.

In research settings, deconvolution is used for two purposes—to improve image quality and to resolve underlying

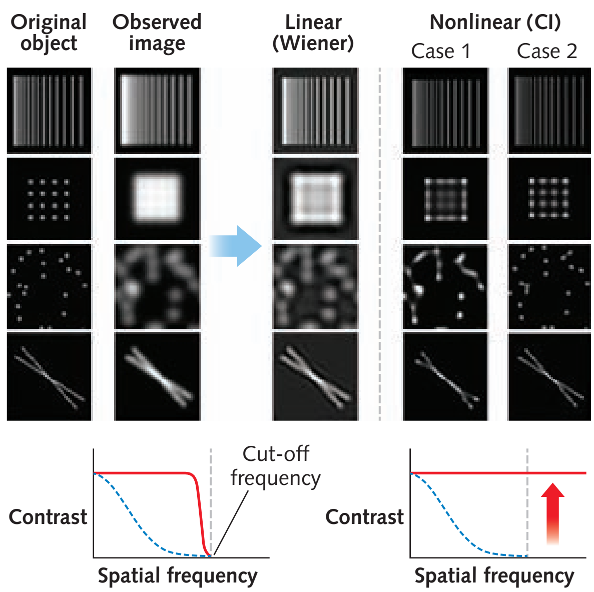

FIGURE 1. Results from linear and nonlinear deconvolution are shown in these images depicting original objects before image acquisition, observed confocal image through microscope, and following deconvolution (left). The center panel depicts linear deconvolution with a Wiener filter, resulting in ringing artifacts observable in the beads and crossed filaments. Nonlinear deconvolution results (right) improve image quality, but may create data beyond the cut-off spatial frequency. Case 1 results show artifacting in connections between adjacent beads. When deconvolution parameters are carefully adjusted (as depicted in Case 2 column), good results can be achieved.

data obscured by blur. But if deconvolution does not always improve resolution, do we need it?

Because the image produced by a microscopy system represents both the object being imaged and the imaging PSF, it will depict blur around the object. Optical and electronic system noise contributes to the blur, further reducing contrast. Deconvolution mathematically reverses "convolution"—that is, the mixing of PSF and real object with system noise. Thus, it restores to original the objects depicted.

A fundamental question of image processing has emerged: is the raw image real? Or does the deconvolved image better represent the sample? Given the reality of convolution, one could argue that a processed image more closely represents real objects than does a raw image. The addition of detail and improvement in image quality is the reason deconvolution is now commonly used in many imaging modalities.

Through advancing deconvolution algorithms and improved sensitivity in modern imaging systems, scientists are able to produce better microscopy images than ever before. In recent years, deconvolution has overcome barriers associated with long image processing times. Olympus cellSens software implements GPU-based deconvolution, resulting in up to 7X faster processing. Image-restorative algorithms also now produce fewer artifacts, allowing deconvolved images to be far more reliable and representative of samples than they were a decade ago. The results not only look better, they more accurately depict events and structures.

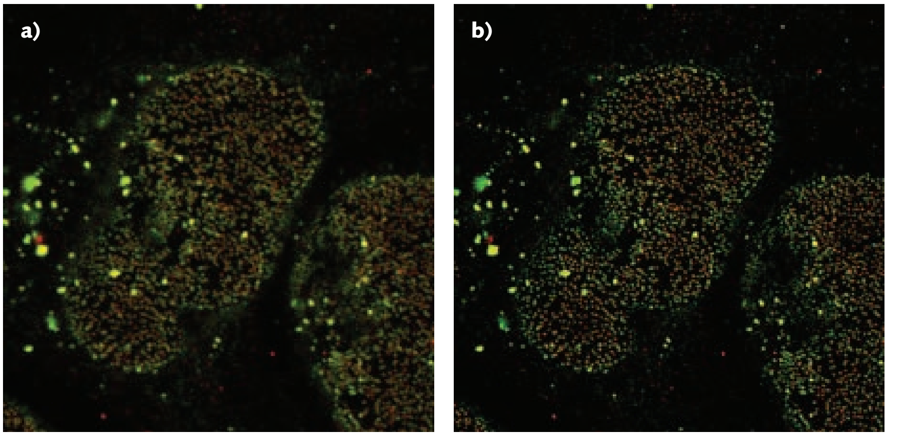

FIGURE 2. Images of a nuclear pore acquired with the Olympus FV3000 confocal system before (a) and after (b) nonlinear deconvolution using an advanced maximum likelihood estimation (AdvMLE) deconvolution algorithm. *(Courtesy of Dr. Hidetaka Kosako, Fujii Memorial Institute of Medical Sciences at Tokushima University)*

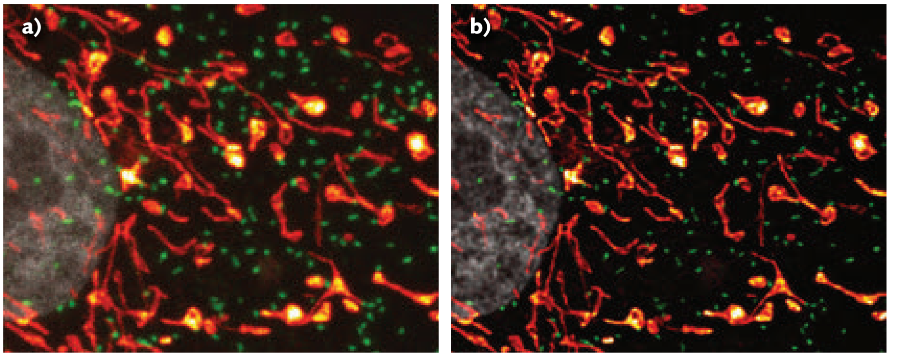

FIGURE 3. Confocal data depicted with maximum projection of 0.5 airy unit (a) and with high-resolution nonlinear deconvolution using an advanced maximum likelihood estimation (AdvMLE) deconvolution algorithm (b); images were acquired using an Olympus FV3000 confocal laser scanning microscopy system and a 100x TIRF 1.49NA Olympus objective.

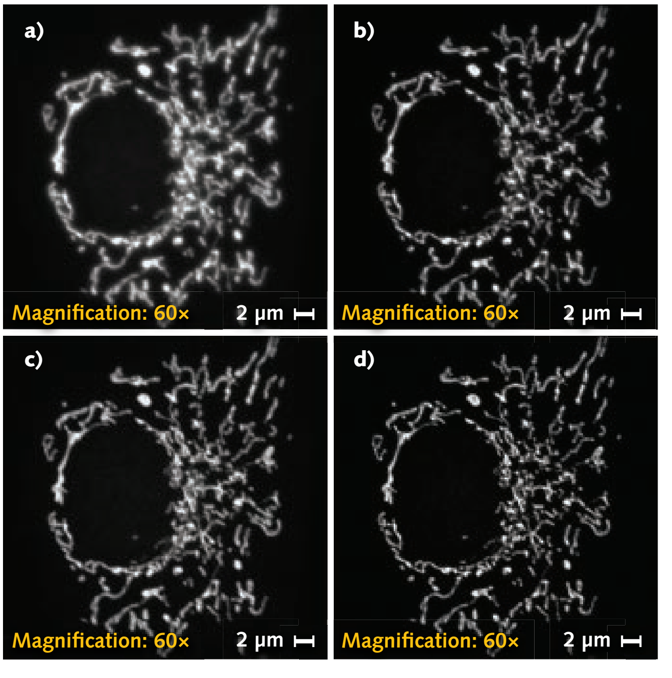

FIGURE 4. Deconvolution allows balancing brightness with resolution, as shown in this image of a fibroblast cell labeled with Mitotracker Red using the 60x UPlanSApo 1.35 oil objective and imaged with the Olympus FV3000 confocal system: confocal aperture of 4 airy units, raw (a); confocal aperture of 4 airy units, nonlinear AdvMLE deconvolution (b), confocal aperture of 0.5 airy units, raw (c). and confocal aperture of 0.5 airy units, nonlinear AdvMLE deconvolution (d). Maximum intensity projections and laser powers were adjusted to maintain image brightness.

Deconvolution methods

Types of deconvolution include linear, nonlinear, and a combination of the two. Deconvolution methods enhance contrast from small objects detected by the optical system. It is possible to convert an image from the spatial domain to the frequency domain (or spatial frequency) by applying a Fourier transformation. Large objects, which are low-frequency and high-contrast, are easily detected by an optical system, while small objects increase in the frequency domain and typically have reduced contrast. Reducing contrast with increasing spatial frequency, at some point the "cut-off frequency" is met in the frequency domain and the optical system collects no information above this spatial frequency point. In the frequency domain, linear deconvolution involves amplification of contrast only within the cut-off frequency; it will not create higher frequency components above that spatial threshold, and thus is considered reliable.

Linear deconvolution may have very positive effects on image quality if artifacts are minimized. However, linear deconvolution can impart a ringing artifact, meaning that positive and negative intensity oscillations appear outside the imaged object. Ringing can reduce overall image resolution, while individual measurable objects may exhibit reduced FWHM measurements.

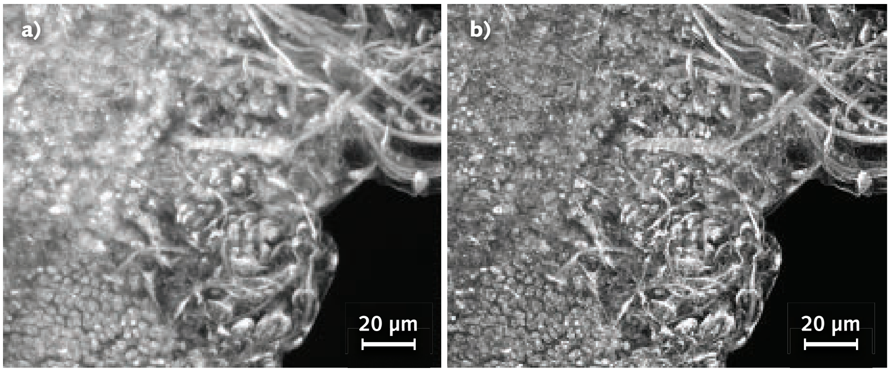

FIGURE 5. This image of an eosin-labeled brine shrimp, acquired with two-photon excitation at 960 nm using an Olympus FVMPE-RS system, is shown at maximum intensity projection (a) and with nonlinear AdvMLE (b).

The major method of nonlinear deconvolution is an approach that estimates the object by revisiting the result over multiple iterations. This estimate is created by establishing convolution and creating a blur image, and then comparing this to the original. Estimated images with fine structures are produced in a gradual process. Various algorithms (MLE, Fast MLE, Gold, etc.) are available for creating estimated images.

As more iterations are applied, nonlinear deconvolution gradually shrinks the object size by comparing the calculated blur image to the original. For this reason, it is more effective to improve an image's appearance with nonlinear deconvolution than with linear deconvolution—but image enhancement results depend on structures in the image. And the effect of nonlinear deconvolution cannot be described as a simple reduction in PSF or amplification in spatial frequency, because the original image impacts the resulting deconvolution image.

In nonlinear deconvolution, estimation accuracy depends on object structure. A point can be easy to estimate, but with denser structures, estimation becomes more difficult: Structures will shrink, but resolution may not improve. Components above the cut-off frequency can be created by estimation, and data not captured by the optical system can produce artifacts. With too many estimation iterations, a 100 nm bead can be reduced to 80 nm, resulting in a loss of data.

Besides object density, estimation results can also be impacted by factors such as imaging condition and processing parameters such as PSF shape, iteration number, and nonlinear deconvolution mode. Thus, careful consideration is necessary and various values should be tested. The validity of estimation can be judged only by the appearance of the image (see Fig. 1).

Putting knowledge into practice

To summarize, then, linear methods can produce ringing effects that reduce FWHM without improving resolution. And only the components within the cut-off frequency are enhanced. With nonlinear deconvolution methods, image quality improves, but the results are difficult to evaluate. Nonlinear methods may also offer lower reliability because of potential amplification above the cut-off frequency.

In practice, nonlinear methods that dominate the market are great tools for reducing blur in three dimensions as well as reducing noise. Various microscope modalities (including widefield, confocal, spinning disk, superresolution, and two-photon) with corresponding PSFs are also supported (see Figs. 2-5).

A few tips to keep in mind:

- Weigh the pros and cons of the various deconvolution modes—linear, nonlinear, and combination;
- Deconvolution can be overdone—seek a balance between artifacts and restored resolution;
- FWHM does not equal resolution—it is possible to reduce FWHM and not improve resolution;
- While artifacts occur with all deconvolution methods, they can be minimized; and
- Deconvolution is an excellent tool for improving image quality, as long as the factors above are adequately considered.

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Spectrally tunable light sources allow advanced sensor characterization

TREVOR D. VOGT

LED-based tunable light source (TLS) technology enables modern sensors to be tested with higher precision, accuracy, and speed.

The need for precision light sources to test image sensors and detectors has existed for decades, but as sensor technologies advance and evolve, requirements for these test sources have intensified. To handle these needs, LED-based tunable light source (TLS) technology has been developed that enables modern sensors to be tested with higher precision, accuracy, and speed than when relying on pre-existing sources.

Here, a few different characterization techniques will be outlined, including color accuracy and Bayer filter spectral mismatch, image-sensor linearity, and frame rate/readout time. The fundamental limits of halogen sources for characterizing silicon charge-coupled device (CCD) and complementary metal-oxide semiconductor (CMOS) sensors will also be outlined.

Traditionally, image sensors need to be characterized for overall performance in some key areas. Determining how the sensor responds to different light stimuli is important to optimize the image captured, whether it be for scientific or consumer applications. In science or machine vision applications, understanding the linearity or timing characteristics can mean the difference between a valid or meaningless result. For consumer applications, color accuracy can be absolutely critical for photography—whether the subject is a human skin tone or vibrant landscape, users will expect the color captured to represent their physical experience.

In all cases, the sensor must be characterized at multiple phases in the production process to ensure a quality end result. Using a stable and precise reference light source is a critical part of those tests, but having tunability in the output intensity or color is also highly desirable. Modern TLS light sources can use LEDs in ways that are more flexible than traditional halogen sources, resulting in higher stability without the drawbacks and problems that were present with early LED reference light sources.

Sensor linearity characterization

One key sensor performance criterion is linearity. Many applications benefit from high linearity, both regarding actual photon-to-electron conversion happening within the chip and the variations in electrical readout relative to exposure time.

To test linearity, a precision light source is swept through a range of different output intensities and the sensor response measured at each power level. The calculated linearity is only as good as the linearity of the light source itself—therefore, the absolute intensity of the light source must be known with high precision and repeatability with low uncertainty. Traditionally, this would be done using a halogen lamp coupled into an integrating sphere, with an iris in between to control intensity.

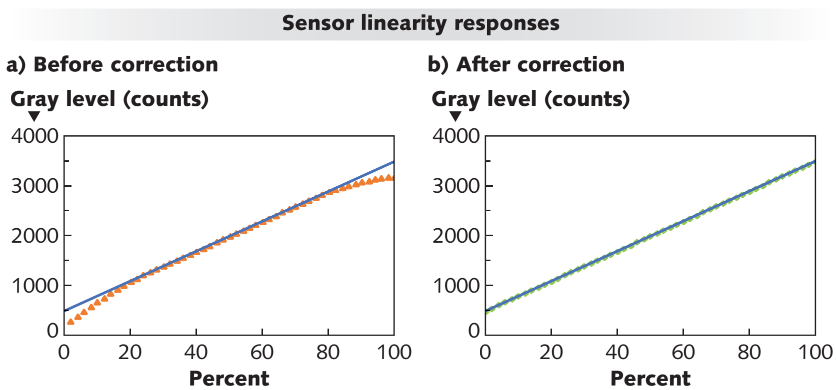

FIGURE 1. Linearity is compared between a traditional source (a) and a TLS source (b); linearity of the traditional source suffers at both the low and high ends of the range.

However, a halogen source itself is only stable over short time periods of less than 100 hours, and the iris has mechanical sources of uncertainty as well. In addition, the test time is limited by how quickly the iris can be adjusted and other things like lamp warm-up after collecting a dark background.

Using an LED-based TLS can overcome these limitations and provide better linearity accuracy than traditional methods. Built-in optical feedback can be used to regulate the LED constant-current drive circuit. Using this closed-loop system with optical feedback adjusting the drive current allows the LED output to be accurately controlled with linearity better than 0.1% of full scale. Feedback also ensures that the absolute output intensity is stable over thousands of hours of operation. Fully solid-state operation means that there are no moving parts to fail and no inaccuracies because of iris mispositioning. The spectrum used for linearity testing can also be tuned, allowing for linearity to be tested with different broadband spectra (such as Illuminant A or D50), or with saturated colors such as red-green-blue (RGB) wavelengths. Figure 1 shows the difference in linearity between a traditional source and the TLS method—note specifically the low-power regions and regions near saturation.

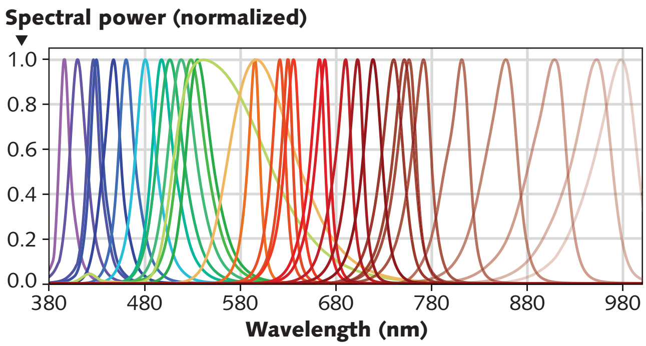

FIGURE 2. Modern LEDs span the near-UV, visible, and near-infrared in their output wavelengths and spectral profiles.

Sensor color accuracy: Bayer filters and spectral mismatch

For some applications, the most important aspect of performance is color accuracy. In those cases, the spectral transmission of the Bayer filter (the color filter array covering the sensor) needs to be carefully determined. There is also much that goes into "demosaicing" algorithms to transform the filtered color channels into what human eyes perceive. Understanding the raw sensor performance is key to proper correction being applied during demosaicing.

Traditionally, the spectral responsivity or quantum efficiency (QE) of the bare silicon would be measured using a scanning monochromator with a halogen illumination source. The response of the 2D sensor would then be measured again with the Bayer color filters in place. Using the bare sensor response, the actual transmission of the Bayer filters themselves could then be determined. Both tests would be done using a scanning monochromator—however, these scans are quite slow and the output signal is limited because the throughput from the monochromator is low. LEDs can provide similar narrowband emission wavelengths—Figure 2 shows just how diverse modern LEDs have become in their output color and spectral profiles.

Using LED-based TLS technology, an alternate method for determining QE can be realized. By sweeping through each LED channel one at a time, the sensor response relative to wavelength can be characterized. There are some minor resolution limits compared to the scanning monochromator system, but the signal strength can be orders of magnitude higher because of the high efficiency of LEDs. The light output area of an LED TLS is also much larger than for a monochromator—the latter typically provides only an approximately 5 mm area of illumination, whereas an LED source can provide a highly uniform 25- to 300-mm-diameter area. Having these higher power levels and large spot sizes enable QE characterization over an entire large-area sensor, rather than only over a small subset of pixels in the center of the 2D array. There are also power advantages, which will be discussed further below.

Halogen light source vs. LEDs in the blue and UV region

A fundamental disadvantage exists with using halogen sources to test silicon sensors—that is, the spectral power distribution of a halogen source is quite low in the UV and deep blue region. Coincidentally, that is also where the sensitivity curve of silicon is lowest. These two factors combine in any application where halogen sources are used to characterize silicon CCD and CMOS sensors, and lead to a poor signal-to-noise ratio (SNR). On the other hand, blue LED emitters are among the most efficient of any LED color.

To get around the low amount of energy in the blue, conventional optical filtering techniques may be used. However, filtering light or using monochromators is a subtractive method, meaning that it will never produce more energy out than is put in. Therefore, even if the relative blue content of a halogen lamp is increased using a "daylight" filter, the overall power will be limited. In comparison, the TLS approach uses different color LEDs in an additive method, combining different LEDs and adding power just where it is needed for a given spectral output.

Figure 3 illustrates this point in greater detail. A blackbody curve and silicon response curve are shown, and the resulting raw signal is indicated. The same comparison is done with a LED source generating a high correlated color temperature (CCT) output—in this case, the result is flat across the spectrum. In this fashion, the SNR across the entire wavelength range can be made essentially flat. The result is a more accurate representation of the true SNR across all wavelengths, without a bias towards the near-infrared. In general, this means any type of test that may be performance-limited will have better signal fidelity in the blue region.

Sensor frame rate and readout time

One major area of advancement in sensor development is in readout speed and overall frame rate. High-speed cameras are becoming more popular in a variety of applications, but maintaining speed as pixel counts skyrocket can be challenging. Main drivers for overall frame drive rate start at a purely electrical level with the serial conversion time (the time required to digitize a single pixel), the overall number of pixel rows and columns, and the time required to clear the charge from registers. However, in full camera assemblies, other factors exist such as the exposure time required for a given capture and the delay from mechanical shutters opening and closing.

Taking all those factors into account gives a close estimate of the theoretical frame rate, but actual performance needs to be verified using a physical standard. This often requires a light source to be modulated with frequencies on the same order of magnitude as the frame rate. High-quality TLS devices provide pure DC current drivers that avoid high-frequency pulse-width modulation flicker that can create undesirable effects in the measurement. However, the ability to modulate the drive current on millisecond timescales can be useful to fully characterize the electronic readout time or the overall frame rate.

Just as the majority of commercial, residential, and automotive lighting has moved to solid-state LEDs, so too will LEDs eventually surpass traditional lighting for scientific and industrial applications. While there have been some technological roadblocks with stability and repeatability of early LED sources, new advancements have allowed LED performance to be refined so that it is suitable for scientific measurements. These advances have allowed LED-based tunable sources to be used for nearly any image sensor characterization method.

In many areas, TLS capabilities surpass traditional halogen-based methods for these measurements in terms of stability, performance, and speed. New TLS devices can also replace multiple pieces of legacy equipment, as there is much more versatility and flexibility in how the output can be tuned and adapted for a variety of tests. In addition, overall operational lifetime of the LEDs is more than 100X longer than halogen lamps, with high stability and faster switching time. Nearly any image sensor test procedure can be improved and optimized using new LED tunable light source technology.

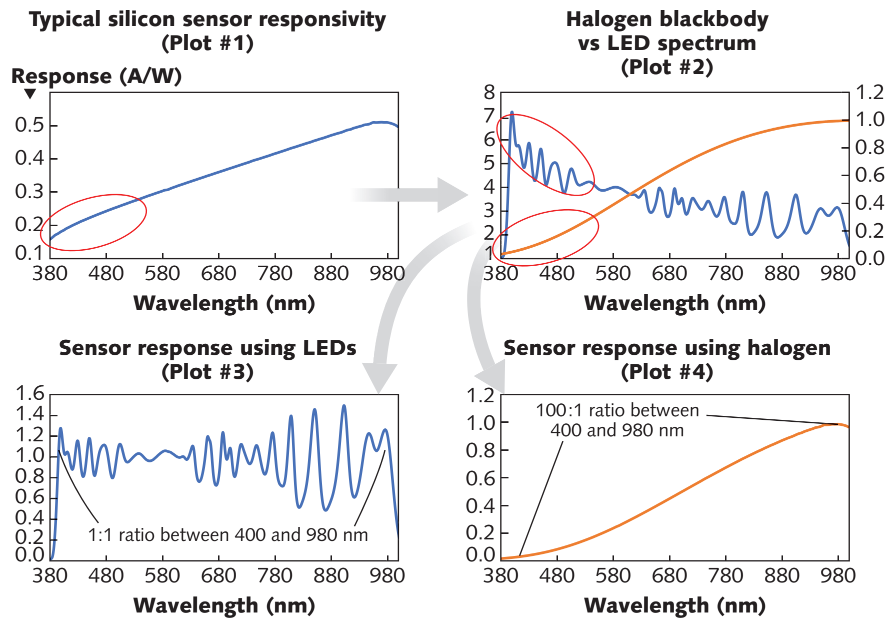

FIGURE 3. Both the typical silicon sensor sensitivity (upper) and halogen-lamp output spectrum (upper right) are low in the blue and near-UV; as a result, the sensor response using a halogen lamp is 100X lower at 400 nm than at 980 nm (lower right). In contrast, the output of a TLS source, which uses different-color LEDs in an additive method, is high in this region (lower left), allowing for high sensor response for short wavelengths.

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Gravity-free optical fiber manufacturing breaks Earthly limitations

HARRISON PITMAN

Alternatives to relatively high loss silica optical fibers like ZBLAN have historically been limited by the confines of gravity-fed manufacturing processes. However, this could change through zero-gravity manufacturing beyond Earth.

The optical fiber used to connect continents is made from silica glass. Though silica fibers are the industry standard for telecommunications cables, the material is limited by its narrow transmission window and the need for repeaters to amplify the light source. Other fibers such as ZBLAN have been theorized to perform better than silica, but terrestrial manufacturing challenges have historically made these fibers infeasible for telecommunications applications.

With the limitations of silica fiber being well understood, improvements are continually being made to the fiber available for underwater cables. However, to address the increasing global demand for Internet usage, which is approaching the upper limit of what the current infrastructure can support, other materials are being considered for subsea telecommunication lines. These alternatives may not be subject to the same limitations as silica fibers, especially if the confines of standard draw-tower manufacturing are removed.[1]

Silica fiber alternatives

Rare-earth-doped zirconium fluoride/barium fluoride/lanthanum fluoride/aluminum fluoride/sodium fluoride (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) or ZBLAN optical fiber has a broad transmission window, optimally transmitting at 2200 nm, and significantly lower attenuation than silica fiber at standard 1310 and 1550 nm telecommunications wavelengths (see Fig. 1).

The compounds which comprise ZBLAN vary greatly in density, giving the material attractive properties across the near-to-mid infrared spectrum. Because of its unique composition of heavy metal fluoride compounds, ZBLAN is formed as a crystalline lattice. This lattice, however, cannot form properly in Earth's gravity, creating significant barriers to its potential as a commercial telecommunications fiber and limiting production to small quantities for specialty applications. Despite these barriers, ZBLAN fiber is still used in lasers, endoscopy and spectroscopy equipment, supercontinuum light sources, and advanced optics and sensors.

There are two types of losses that restrict ZBLAN from more closely approaching its theoretical potential: absorption losses caused by impurities in the glass as a preform, and scattering losses caused by small microcrystals that form when the glass is manufactured in a gravity-rich environment. While ZBLAN experts Thorlabs (Newton, NJ) have addressed absorption losses through the creation of ultra-pure preforms, scattering losses can only be addressed by pulling the fiber in microgravity.

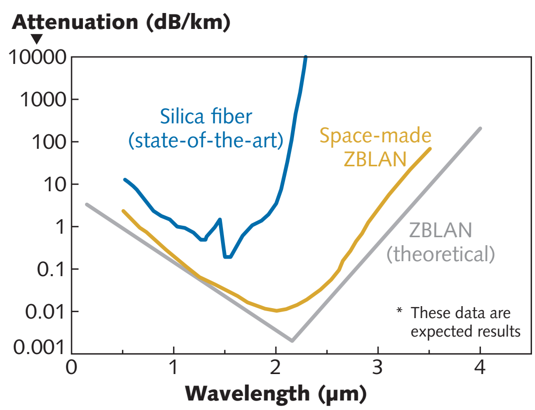

FIGURE 1. The attenuation curve of state-of-the-art, telecommunications-grade silica fiber is contrasted with space-produced ZBLAN and the theoretical ZBLAN attenuation.

If ZBLAN could be manufactured to perform better than silica fiber, the planet's available data-throughput infrastructure could grow at a faster pace, ensuring that the world stay connected as the number of Internet users and Internet-enabled devices continues to grow exponentially.

Microgravity manufacturing

Made In Space (MIS) is a manufacturing company with the goal of enabling people to live and work in space. By developing and deploying space-ready manufacturing systems, we are developing solutions for industry and government to meet the manufacturing needs of the future.

In 2010, MIS began developing zero-gravity 3D printers for the International Space Station (ISS). In developing manufacturing hardware for space, MIS is constantly making new discoveries about how materials behave in the microgravity environment. Microgravity, high radiation, extreme temperature, and extreme pressure environments are normal challenges that we face when designing systems for space. Despite these challenges, space is actually the optimal environment for processing certain materials.

MIS owns and operates the world's only commercial manufacturing facility off Earth—the Additive Manufacturing Facility (AMF). The first space-ready 3D printing facility, AMF is changing the paradigm of delivering assets to space, as it has been used by doctors, researchers, universities, and space explorers to further mission lifecycles, evaluate the feasibility of 3D printing medical devices in remote areas, and create satellites in space (see Fig. 2).

Since development of its first 3D printers, MIS has also advanced several other technologies from space robots to material recyclers, enabling the future of deep-space missions and supporting the development of a Low Earth Orbit economy.

FIGURE 2. A finger splint designed by Dr. Julielynn Wong was manufactured by the Additive Manufacturing Facility (AMF) onboard the International Space Station. (*Image credit: NASA*)

FIGURE 3. The microwave-sized instrument shown was the first Made In Space Fiber Optics payload to go to the International Space Station.

Building on its experience with developing AMF and other systems for the space environment, MIS is now manufacturing ZBLAN optical fiber in space. Leveraging the microgravity environment, the fiber is produced in a relatively small, efficient machine that is about the size of a microwave (see Fig. 3). This machine allows us to create ZBLAN in space with minimal losses from scattering and microcrystal formation, increasing the fiber's performance towards approaching its theoretical limitations.

Extensive research has been performed on the effects of ZBLAN when processed in a microgravity environment. Interested in ZBLAN's benefits, the National Aeronautics and Space Administration (NASA; Washington, DC) carried out a series of experiments in the 1990s that sought to better understand the role that gravity plays in the composition of the material. In 1994, NASA researchers heated terrestrially produced ZBLAN onboard a KC-135 flying microgravity parabolas. It was observed that none of the noncontaminated samples that were processed in microgravity showed signs of new crystal formations.[2]

In 1996, NASA attempted again to test the effects of microgravity on ZBLAN processing, but poor design of the experiment allowed the fiber to be exposed to water, effectively destroying the material used in the experiment. Three samples remained intact, none of which had gravity-induced crystallization present.[3] Together, these experiments demonstrated that crystallization is suppressed in ZBLAN when processed in microgravity (see Fig. 4).

Although the experiments did provide conclusive evidence of crystal suppression in microgravity, the very limited duration of microgravity on these test flights did not allow researchers to quantify the performance improvements. Additional experiments need be done on a persistent microgravity platform that will allow researchers to produce longer, quantitatively testable lengths of fiber.

On Earth, ZBLAN is made in tall draw towers that can range from 3 m to three stories tall. The process involves using gravity to begin to pull a section of the heated preform until it achieves the correct diameter of drawn fiber. Several components contribute to a successful fiber pull, such as the temperature of the furnace, the uniformity of heating, the angle of the preform as it heats, and the speed at which the fiber is pulled. Sensors, motors, and actuators ensure that every aspect of the system is functioning correctly, from first heating up the preform to spooling the fiber.

To begin adapting the manufacturing process for space, MIS sought a partnership with Thorlabs. Thorlabs showed MIS the intricacies of drop tower manufacturing, and the companies began work on shrinking the process down to work in a microwave oven-sized device, as space is limited on the ISS. In addition to significantly reducing the size of the entire system, the MIS Fiber Optics payload needed to be completely autonomous, as devices on the ISS cannot viably rely on seldom and expensive astronaut labor. When the device leaves Earth on a rocket, it is sealed, not to be opened again until it returns to Earth.

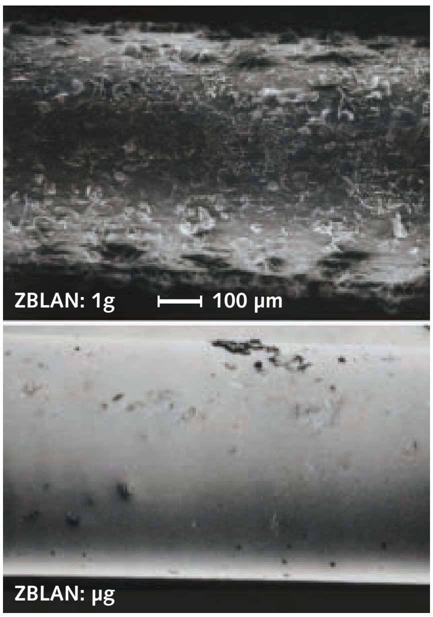

FIGURE 4. Images show ZBLAN optical fiber processed in 1g (Earth's gravity) and ZBLAN processed in approximately 0g (microgravity). (*Image credit: NASA*)

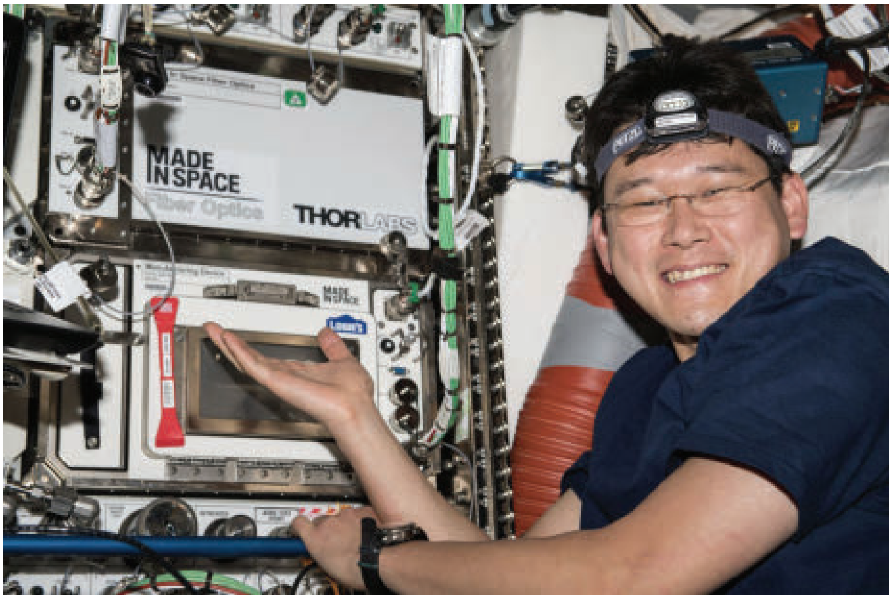

FIGURE 5. Japan Aerospace Exploration Agency (JAXA) astronaut Norishige Kanai presents two MIS payloads onboard the International Space Station: the Additive Manufacturing Facility (AMF) and Made In Space Fiber Optics. (*Image credit: JAXA*)

Because the fiber will be ruined if it contacts any amount of water, MIS developed a completely enclosed system with a custom environmental control unit that maintains an optimal manufacturing environment within the payload. Once the unit arrives to the ISS, the astronauts unstow the device, attach its power and data connections, and it is then commanded from the MIS Mission Control Center in Moffett Field, CA.

The device stows ultra-pure Thorlabs preforms inside, relying on internal robotics to correctly position the preforms and spool the fiber. After all preforms have been processed into space-enabled fiber, the device is disconnected from power and data and re-stowed on an entry capsule before returning to Earth.

Space-enabled fiber

Made In Space has two core objectives in manufacturing space-enabled fiber. The first is to demonstrate that space-enabled fiber can be efficiently manufactured on the ISS. Crewtime is limited and many experiments are being conducted simultaneously, so it is pivotal for the MIS Fiber Optics payload to not rely on active human involvement. The second is to produce long-enough quantities of ZBLAN that the material improvements can be quantitatively characterized.

The first fiber-optic manufacturing device from MIS was sent to the ISS in December 2017. Since then, there have been three additional fiber-optics missions to the ISS, each sending a unit after the preceding unit returns. The most recent launch took place in November 2018, with several more launches manifested in 2019. The company is actively working with Thorlabs and other partners to understand the full material benefits and advantages of space-produced ZBLAN. ◂

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High-power diode lasers focus on improved utility

HEIKO RIEDELSBERGER

Recent advances in diode packaging and implementation are transforming the utility and economics of applications for high-power diode lasers.

Diode lasers offer unmatched electrical-to-optical efficiency, a higher power/size ratio than any other industrial laser technology, and solid-state stability and reliability (see Fig. 1). For many years, development work primarily focused on improving the performance of the core technology: achieving higher power and longer lifetimes with ever-brighter output. However, many other factors must be addressed to successfully develop new applications and to improve the economics of existing ones. Here, we examine representative advances in three different practical areas that improve the utility of diode lasers and see how they positively impact real-world applications.

Beam delivery: new zoom optics, new applications

Constructing multikilowatt diode laser systems entails combining the output of multiple bars, each having multiple single-emitting output facets. The emitting area is effectively much larger than many other laser types and whether fiber-delivered or free-space, the power at the workpiece cannot be efficiently focused to micron-level spots. For this reason, most applications for high-power diode lasers involve irradiating a defined area typically measured in millimeters. The size and shape of this area vary greatly even in similar applications. For example, Figure 2 shows how a line profile is used in two orthogonal directions to support either wire- or powder-feed cladding processes.

Several applications need the ability to change the shape and/or size of the irradiated area (see Fig. 3). This can be required to heat-treat (case-harden) a mold for automotive add-on parts with a complex shape, for example. Other applications need the flexibility to produce variable shapes to handle job-to-job variety and hence maximize the productivity of a laser-based system. Some obvious examples are fast-growing applications in the furniture and cabinet industries, such as laser edging and laser heat treatment of molds.

Even premium-brand furniture makes common use of laminates and veneers to minimize costs, maximize strength, and simplify production. Each time a panel is cut, an edge is left that must be concealed by carefully applying a tape of a matching material. Traditionally,

FIGURE 1. High-power diode laser systems for industry are being augmented with improved beam-delivery optics, compact rack-mounted configurations, and simplified cooling.

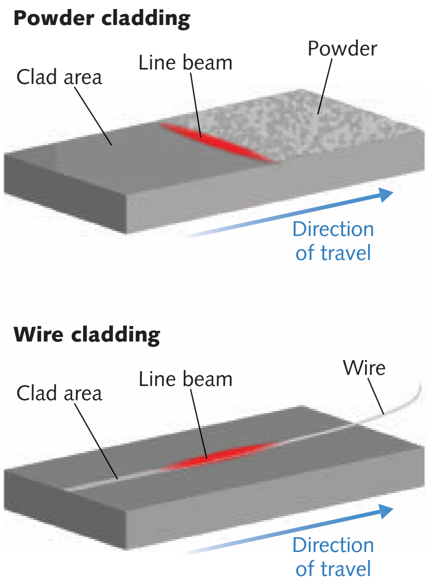

FIGURE 2. In cladding applications, different orientations of a line beam geometry are used for powder-based or wire-feed methods.

this was performed using thermal adhesives, but now, many manufacturers are switching to laser edging. Here, one side of the edge tape is heated to melting and is then mechanically pressed against the substrate, which produces a strong direct bond with no need for gluing. This has been proven to produce closer edges than with adhesives, eliminating postprocessing such as removing excess glue with solvents. Different laser spot shapes and sizes are needed to process different tape widths as well as a range of plastic materials.

Another growing application for multikilowatt diode lasers is laser softening in the automotive industry. This is used to prepare the edges of high-strength steel panels for car bodies and acts as a form of stress relief. Without presoftening, the joints between panels would otherwise have an increased probability of cracking during the subsequent joining process.

The need for laser spot adjustment is met by motorized zoom optics. These use specially designed optics so that the *x* and *y* axes can be independently changed in real time. Weight is an important consideration here, as it may preclude the use of lower-inertia robots and their associated lower costs. The glass lenses, mechanical mounts, and drive motors all contribute to the weight of this type of zoom beam-delivery module. And the lenses require a minimum size (and mass) to deliver a wide range of zoom. However, the latest zoom module from Coherent uses a novel optical design specifically designed to minimize the mass of the lenses. Together with the use of low-cost rigid alloys, that means a module with a mass of only 9 kg can now deliver a focused irradiation area ranging from a 4 × 4 mm line to a 45 × 45 mm rectangle or square.

Compact systems: rack mounting

Size and weight also matter in manufacturing environments, where costs tend to scale with footprint. This is particularly true in semiconductor fab and electronics packaging, which are performed in cleanrooms or under other tightly controlled ambient conditions. It is also a concern in highly automated, high-throughput manufacturing situations such as in the automotive industry, where high density implementation of sensors, vision systems, robotics, lasers, and other technology puts space at a premium.

The multikilowatt diode lasers needed for many of these applications have traditionally been bulky, floor-standing units. However, laser manufacturers have responded to the increasing emphasis on space saving with compact systems that fully exploit the inherent miniaturization of diode lasers. For example, Coherent recently released a system (the HighLight DL4000HPR) with an optical output of up to 4 kW in a 19 in. rack-mounted package. This is a self-contained system where the power supply, control electronics, and diodes are all housed in a single compact enclosure.

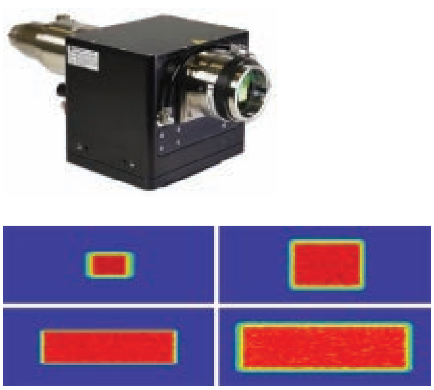

FIGURE 3. This zoom module enables independent adjustment of *x* and *y* axes with no change in the beam uniformity; the two axes have continuously adjustable spot size in *x* and *y* from 4 × 4 mm up to 35 × 35 mm.

Simplified cooling requirements: eliminating deionized water

In terms of market growth, one of the developments with potentially huge impact is the elimination of the requirement for deionized (DI) cooling water. With diode laser lifetimes nominally in the tens of thousands of hours, the lifetime of the cooling technology can sometimes be shorter than that of the lasers. Depending on the semiconductor type and junction architecture, electrical efficiencies are typically in the 45–70% range—even with these high efficiencies, with (for example) 10 kW of output power, up to 12 kW of heat must be dissipated. If the heat is not efficiently removed, the increased temperature can change the optical properties of the output in the short term and shorten device lifetime in the long term.

A commonly used approach is to use microchannel cooling, where water flows through tiny channels in a copper heatsink soldered to the diode laser bar. To minimize current leakage and electrochemical corrosion, deionized water, which has low electrical conductivity, is typically used. The requirement for DI water or DI water cartridges increases operating costs and is a significant drawback for manufacturing in some remote or otherwise infrastructure-challenged world locations.

In response, laser manufacturers have developed cooling schemes based on the use of conductive cooling, eliminating the need for flowing water directly next to the bars and current contacts. As a result, newer systems (such as the rack-mounted HighLight DL4000HPR) can be cooled with plain filtered tap water, reducing operating costs and simplifying their use.

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CLAMIR precisely controls advanced laser manufacturing processes

ARTURO BALDASANO RAMÍREZ

A high-speed mid-infrared camera and software system monitors melt pools more accurately than visible CMOS cameras.

Industry 4.0 is pushing the industrial world to adopt new technology for introducing automation, along with specialized and sophisticated tools, in production lines. At the same time, other concepts such as "factories of the future" and "zero defects" force the implementation of new methods of fabrication, including faster, cleaner, more efficient, and reliable processes fully monitored and, when possible, controlled in real time. As an example of this industrial transformation and the implementation of these concepts, laser technology is being adopted as a replacement for traditional tools, with manufacturing processes being converted in this way for a wide range of industrial applications.

One of these laser techniques is direct energy deposition (DED). Among the different applications of DED, two are becoming widespread in the industry: laser metal deposition (LMD) and laser cladding, both of which are mainly used for additive manufacturing, coating, and repairing. Frequently, these processes require very long manufacturing times during which the initial conditions change dynamically while the process is running. This increases the need to integrate sensors and actuators into the production equipment that are capable of monitoring and controlling the key parameters of the process and adapting them dynamically to variations occurring during the manufacturing time.

Monitoring the melt pool

One of the process features that is most subject to change is the melt pool, or the area in which the light power is suddenly transformed into heat via an interaction between incident photons and matter. As a result, it makes sense to monitor and control the parameters affecting the melt pool: geometry, heat distribution, dynamics, temperature, and so on.

Control for Laser Additive Manufacturing with Infrared (CLAMIR) is a solution developed and commercialized by New Infrared Technologies that continuously monitors the melt pool and performs closed-loop feedback control of the laser power to maintain its properties at a constant throughout the process. CLAMIR uses a high-speed uncooled infrared (IR) camera as a main sensor, which is coupled coaxially into the laser optics, allowing the camera to obtain IR images of the melt pool at a 1 kHz frame rate. Based on real-time processing of the images performed internally by the camera, the system continuously extracts key parameters of the melt pool such as temperature gradients, geometry, area, and width. Using advanced algorithms for analysis and control, CLAMIR controls, in real time, the power of the incident laser with the objective of keeping the deposition process within the range of tolerances defined by the user (see Fig. 1). The capability of installing CLAMIR in an existing optical port makes it possible to be retrofitted into existing machines.

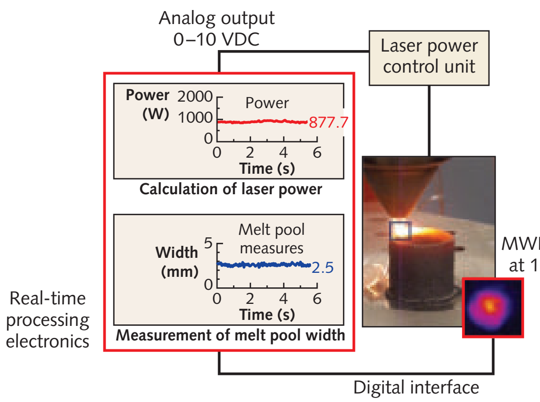

FIGURE 1. Control for Laser Additive Manufacturing with Infrared (CLAMIR) is a process control system that is based on monitoring via midwave infrared (MWIR) rather than near-IR and visible light. Software operations provide feedback for control of laser power. *(Courtesy of NIT)*

CLAMIR is a compact and rugged device that is compliant with robustness requirements demanded by the industry. The embedded system consists of three main subsystems: 1) the sensor, a high-speed IR camera sensitive in the 1–5 μm range and uncooled operation at room temperature (very important as regular maintenance of the camera is not necessary); 2) electronics for real-time image processing; and 3) electronics for process control.

MWIR has advantages

The use of a midwave-infrared (MWIR) camera results in exceptional performance compared with other vision technologies

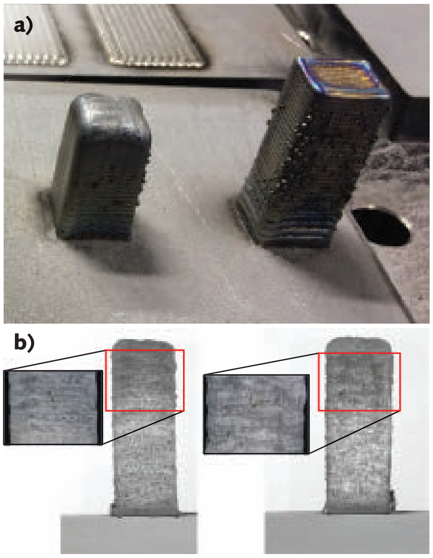

FIGURE 2. Two LMD cuboids fabricated without CLAMIR control (a), resulting in an unwanted process halt; and with CLAMIR control, the process completed, creating crack-free parts (b). *(Courtesy of NIT)*

at other wavelengths such as traditional high-speed visible (VIS)-range cameras. A study carried out by the Spanish Center of Excellence (AIMEN; Galicia, Spain) and the research center Fraunhofer ILT (Aachen, Germany) concludes that high-speed MWIR imagers provide more valuable information than traditional high-speed VIS-CMOS cameras for monitoring laser welding and LMD processes. The advantage comes from the ability of MWIR cameras to observe wider temperature gradients with much more contrast before reaching saturation.[1] The benchmarking analysis presented in this work showed that the most important features were extracted from MWIR imagers. In a list of the top-performing features, the first representative VIS feature was in the 34th position, giving an idea of the advantages of using the MWIR spectral band for monitoring and controlling laser welding processes.

CLAMIR includes a software tool that configures the system for a chosen production machine and process, logging of the process data (including the IR images), and visualization of the logged data.

CLAMIR has been designed for real-time control of LMD and cladding processes using multiple process speeds and materials, and can be used with most of the existing laser optics in the market. The mechanical integration of CLAMIR in the laser optics is done by coupling the camera (via a C-mount) into an existing optical port, which needs to be capable of transmitting the process' reflected light at wavelengths above 1.1 μm, as this is the wavelength range used by the IR camera to monitor the melt pool. Most current laser optics already have dichroic mirrors to bring this radiation into the optical port for observation purposes, making this integration quite straightforward.

CLAMIR allows continuous control of laser power, avoiding overheating the manufactured part because of an excess of power, reducing the rates of defective parts, the amount of materials and the wasted energy improving productivity. Figure 2 shows the differences between two LMD cuboids fabricated without (a) and with (b) CLAMIR control. The melting effect can be seen in the top part of the left cuboid, which has caused an unpredicted stop of the machine because of the inability to continue growing the part normally. On the other hand, the cuboid of the right shows clear and defined edges on the top part. In addition, a metallographic analysis showed the absence of cracks in the cuboid fabricated with CLAMIR control.

CLAMIR is currently a versatile tool for real-time control and monitoring of most existing LMD and cladding processes used in the industry (see Fig. 3). However, new applications are regularly arising that require the use of new materials, and more-complex and sophisticated new deposition processes are emerging. Different materials and structures will require modified process conditions. The CLAMIR concept was envisioned as an adaptable system able to suit new manufacturing methods, adding new control functionalities in a feasible way.

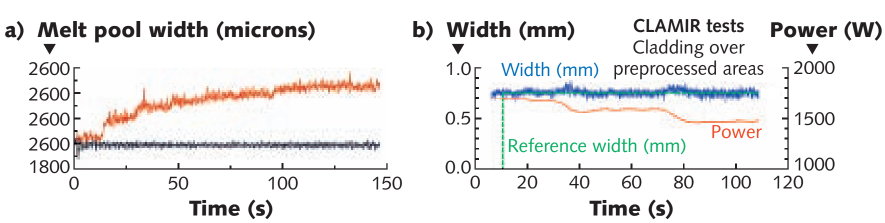

FIGURE 3. The evolution of the width of a melt pool (a) during the LMD process is plotted without control (orange) and with CLAMIR control (dark blue). In the case of cladding processes, CLAMIR prevents the damage of the substrate material and allows, for example, a smooth transition when entering into preprocessed areas, as shown in the lower plot, where CLAMIR controlled the laser power (orange line) during cladding of Inconel 718 on a steel tube, then on a section where one layer had been already deposited, and then on a section where two layers were present. The green line shows the reference width and the blue line shows the real width measured during the process.

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Novel tunable lasers enable new nanoimaging techniques

JAROSLAW SPERLING, PATRYK KUSCH, and **KORBINIAN HENS**

State-of-the-art OPO technology delivers laser light for excitation-tunable tip-enhanced Raman spectroscopy.

Driven by the desire to characterize the electronic and vibronic properties of new materials with nanometer resolution, photonics researchers go through considerable effort to continuously refine nanoimaging techniques. Tip-enhanced Raman spectroscopy (TERS) is an approach that has been well recognized and relies on strongly localized enhancement of Raman scattering of laser light at the point of a near-atomically sharp tip. However, not least due to the lack of sources that would deliver laser light conveniently tunable throughout the visible spectral range, the vast majority of TERS experiments so far has been limited to single excitation wavelengths.

A recent study now demonstrates excitation-dependent hyperspectral imaging, exemplified on carbon nanotubes, by implementing a tunable continuous-wave optical parametric oscillator into a TERS setup. We take a closer look at the laser technology behind the experiment and illustrate the vast potential of the method.

Principles of optical parametric oscillators

Optical parametric oscillators (OPOs) might be considered as light sources that deliver coherent radiation very similar to lasers, but with two main differences between the devices.[1] First, the OPO principle relies on a process referred to as parametric amplification in a nonlinear optical material, rather than on stimulated emission in a laser gain medium. Second, OPOs require a coherent source of radiation as a pump source, unlike lasers, which can be pumped with either incoherent light sources or sources other than light.

Figure 1 illustrates the basic scheme common to OPOs and other optical parametric devices. The process can be perceived as splitting of an incoming pump photon of high energy into two photons of lower energy, the latter usually referred to as signal and idler photons, respectively. It is essential to note that the overall process is subject to the conservation principles of photon energy and photon momentum (phase-matching condition), but otherwise does not have further fundamental restrictions, at least in theory. The huge potential of OPOs thus derives from their exceptional wavelength versatility, as they are in principle not limited by the wavelength coverage dictated by the energy levels and suitable transitions in a laser gain medium.

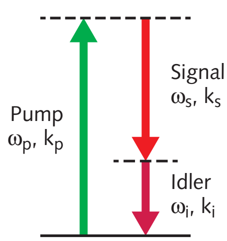

FIGURE 1. The parametric process in optical parametric oscillators (OPOs) can be perceived as splitting of an incoming pump photon of high energy into two photons of lower energy (usually denoted as signal and idler) and is subject to the conservation principles of photon energy and photon momentum.

In practice, the OPO concept was experimentally demonstrated already more than half a century ago,[2] but the progress in development and commercialization of turnkey devices has been substantially stalled by several technical obstacles.[3] These obstacles have been easier to overcome at the high peak powers of pulsed devices, so that tunable OPOs operating in pulsed mode have become readily available from a variety of suppliers. Only relatively recently have there been comparable advances in continuous-wave (CW) OPO technology, which have spurred the development of commercial systems.

This progress has been mainly driven, on the one hand, by the increasing availability of cost-effective high-performance CW pump lasers and, on the other hand, by the advent and increasingly sophisticated design of new nonlinear crystals. As to pump lasers, the operation of CW OPOs puts stringent requirements on potential light sources in terms of preferential single-mode operation, noise characteristics, beam quality, and beam pointing stability.

Depending on power requirements of the end user, either high-performance diode-pumped solid-state (DPSS) lasers (for lower powers) or fiber-laser-based solutions (for higher powers) are typically used. As for nonlinear materials and novel crystal design techniques, it should be noted that the emergence of so-called quasi-phase-matched nonlinear materials like periodically poled lithium niobate (PPLN), whose crystal structure alternates with a certain periodicity, has been of great utility for the design of practical optical parametric devices.

Practical design considerations

While OPO technology appears to be ideally suited for generating tunable CW laser light across arbitrary wavelength ranges, one must keep in mind that the OPO process itself will always generate output at wavelengths that are longer than those used for pumping. Consequently, OPO devices operating across the visible spectral range either require UV pump sources or, alternatively, need to employ additional frequency conversion stages. As of now, only the latter approach has been proven to be technically practicable and operationally stable in commercial turnkey systems.

The essential building blocks of a tunable CW OPO designed to cover the visible range are shown in Figure 2.[4] The operational principle relies on a cascaded sequence of nonlinear optical processes within two cavities, referred to as OPO and SHG cavities, respectively. As outlined above, pump laser photons are first split into pairs of photons of lower energy (signal and idler). The particular OPO scheme used is commonly referred to as singly resonant OPO cavity design: For a certain operational wavelength of the entire system, the cavity is operated on resonance at either a particular signal wavelength or a particular idler wavelength. Therefore, a precisely movable stack of periodically poled nonlinear crystals allows for broad wavelength coverage. At a particular wavelength selection, a crystal layer with a suitable poling is automatically selected and its poling period fine-adjusted through a temperature-control loop. At the same time, the effective OPO cavity length is actively stabilized to a multiple integer of the selected operational wavelength. While circulating one of the generated (signal or idler) waves resonantly inside the OPO cavity, its counterpart can be extracted for wavelength conversion into the visible spectral range by another nonlinear process.

As shown in Figure 2, this wavelength conversion takes place in a second, separate cavity by frequency doubling of the primary OPO cavity output, a process widely known as second-harmonic generation (SHG). Though this configuration is technically practicable and provides favorable operational stability, it should be mentioned that alternative designs, like intracavity frequency-doubling, have been successfully demonstrated in the lab.

Raman spectroscopy of carbon nanotubes

How does widely tunable laser light, as can be provided by the sources described

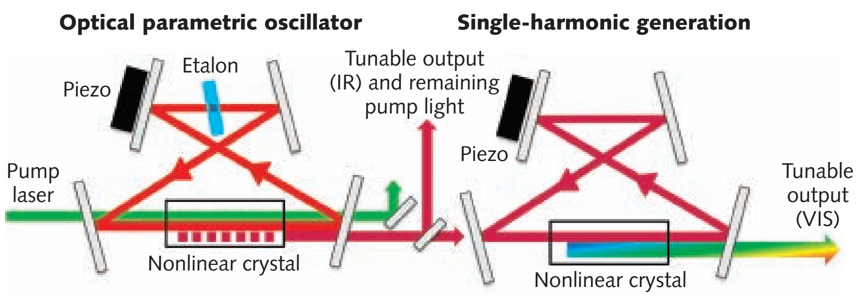

FIGURE 2. The beam path inside a commercial CW OPO system[4] is shown here in a schematic. In the first step, a 532 nm laser pumps a nonlinear crystal to generate signal and idler photons (in a 900–1300 nm range). Wavelength selection and subsequent second-harmonic generation (SHG) converts either signal or idler photons into the visible range of the spectrum (450–650 nm). The green arrow depicts the pump laser beam; dark red and light red arrows depict the signal and the idler beam (arbitrary assignment).

above, advance nanoimaging techniques? To answer this question, carbon nanotubes (CNTs) have been selected in a recent study as a testbed for proof of principle of a novel experimental approach based on TERS.[5] We recall that a CNT is essentially a strip of graphene (a one-atom-thick sheet of carbon) rolled up into a cylinder along a so-called chiral vector with two indices (n,m). It is this chiral vector that completely determines the CNT microscopic structure—that is, its tube diameter and the chiral angle along the tube axis.

Raman scattering has been well established as one of the main techniques to identify the chiral vectors of CNTs experimentally.[6] So-called radial breathing modes (RBMs) that correspond to collective movements of carbon atoms in the radial direction serve as fingerprints of particular (n,m) configurations in the Raman spectrum.

The usual CNT Raman scattering signals are typically very weak, and therefore of little practical relevance. However, the Raman scattering efficiency is significantly enlarged if the laser energy matches the energy of an optically allowed electronic transition—an enhancement process referred to as resonance Raman scattering.[6] In other words, for a particular laser excitation wavelength, the observed Raman signals (respective radial breathing modes) from a mixture of CNTs will derive only from those CNTs that are in electronic resonance with the laser excitation (see Fig. 3). Note that the Raman data, recorded for a mixture of CNTs in solution, is to be perceived as a compositional analysis, but does not contain any spatial information whatsoever.

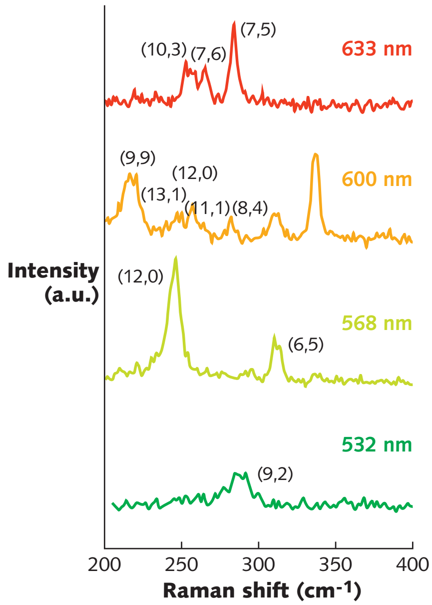

FIGURE 3. Resonance Raman scattering spectra are shown of a mixture of single-wall carbon nanotubes (CNTs) in ethanol solution. The spectra are recorded for excitation wavelengths of 633, 600, 568, and 532 nm (from top to bottom). The peak captions indicate the peak assignment to signals of CNTs of a particular chirality (n,m). *(Courtesy of Patryk Kusch from the group of Stephanie Reich at the Freie Universität Berlin)*

Excitation-tunable tip-enhanced Raman spectroscopy

The three main components of a TERS setup include: A laser light source for excitation, an atomic-force microscope (AFM) equipped with a sharp metallic tip, and a Raman spectrometer recording the inelastically scattered radiation.[5] The basic physical principle behind TERS relies on so-called localized surface plasmons that are excited by the laser light in the microscope tip. These plasmons generate a strongly localized electromagnetic field, which not only enhances the incoming and Raman-scattered radiation by orders of magnitude, but also ensures a highly localized excitation of the sample under study. Thus, by recording tip-enhanced Raman spectra intensities as a function of the tip position, TERS allows for nanoimaging with a spatial resolution down to below 10 nm.

Figure 4 illustrates the sequence of events and results of a TERS experiment carried out at a single laser excitation wavelength (633 nm) on a film of a CNT mixture.[5] In a first step, a so-called composed Raman spectrum is recorded by placing the microscope tip at a particular *x*, *y* position in close proximity to the CNT film. The resulting composed Raman spectrum encompasses the radial breathing mode peaks of several CNTs (all of them in electronic resonance to the excitation wavelength). In a second step, the microscope tip is retracted and the far-field spectrum recorded without the tip-enhanced Raman contribution to the signal. By subtracting the far-field spectrum from the composed spectrum, the pure tip-enhanced Raman spectrum is obtained. Eventually, from the pure tip-enhanced Raman spectrum, the tube species underneath the tip position can be unambiguously identified—a CNT with (7,5) chirality in the example shown in Figure 4a.

For a spatial image of the particular CNT, the outlined procedure is repeated: The tip position is scanned stepwise over the sample surface and at each point the intensity of the pure tip-enhanced Raman peak determined. Figure 4b shows the result of such a scan and images the position of a (7,5) CNT in a 550 × 140 nm^2 area. As can be seen, the CNT is around 800 nm long and bent in a steplike shape.

The full beauty of the experimental

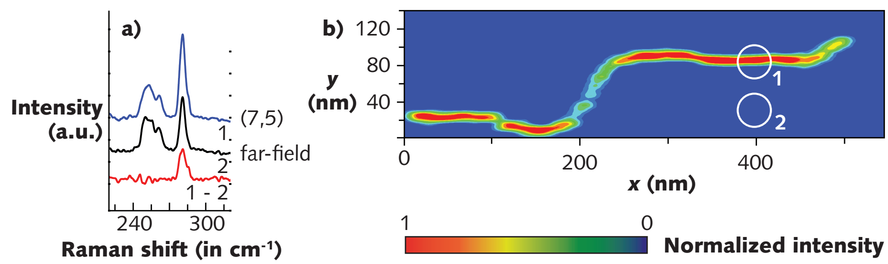

FIGURE 4. Shown are composed (blue line), far-field (black line), and tip-enhanced Raman spectra (red line) of the radial breathing modes (RBMs) of several carbon nanotube species (a). The tip-enhanced Raman spectrum can be unambiguously assigned to a nanotube of (7,5) chirality. A nanoimage of the (7,5) carbon nanotube, obtained by plotting the tip enhanced RBM intensity as a function of tip position, is also shown (b). *(Courtesy of Patryk Kusch from the group of Stephanie Reich at the Freie Universität Berlin; adapted from N. S. Mueller, S. Juergensen, K. Höflich, S. Reich, and P. Kusch[5])*

approach now unfolds when realizing that the imaging capability of the setup is no longer limited to a subset of CNTs that happen to be in electronic resonance to a particular excitation wavelength, as has been the case for the vast majority of TERS experiments. On the contrary, the examination of the sample under study can be in principle performed for a quasi-continuum of wavelengths that is covered by the tunable laser light source.

In the present example, this allows unprecedented access to a broad variety of CNT species—Figure 5 shows excitation-tunable tip-enhanced Raman spectroscopy (e-TERS) methodology recently reported.[5] By using four different excitation wavelengths, it becomes possible to identify and image a total of nine different CNT species within one and the same sample area. We point out that the e-TERS nanoimages in Figure 5 visualize, for the first time, the shape and orientation of different CNT species in spatially overlapping arrangements. And they are no longer limited to an observation window that is dictated by a narrow band of electronic transitions that fall to be in resonance with a single excitation wavelength.

Outlook

The experimental demonstration of excitation-tunable tip-enhanced Raman spectroscopy comes in tandem with the availability of novel tunable laser light sources based on OPO technology. From the general laser technology point of view, the performance characteristics of OPOs make them competitive alternatives to conventional lasers and related technologies for the generation of widely tunable CW radiation. From the experimental methodology point of view, we expect e-TERS to open new experimental horizons for studying the electronic and vibronic properties of matter on the nanometer scale—it is tantalizing to envision the application of this method to the existing broad variety of 1D and 2D materials. ◀

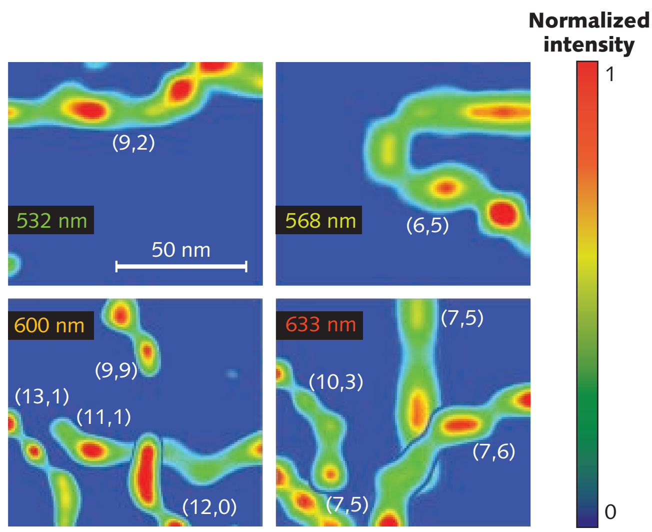

FIGURE 5. Nanoimages of carbon nanotubes are recorded with four different excitation wavelengths.[5] The different tube species are labeled by their chiral indices in the nanoimages. *(Courtesy of Patryk Kusch from the group of Stephanie Reich at the Freie Universität Berlin; adapted from N. S. Mueller, S. Juergensen, K. Höflich, S. Reich, and P. Kusch[5])*

ACKNOWLEDGEMENTS

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Aurea Technology
Besançon, France
www.aureatechnology.com

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AdlOptica
Berlin, Germany
www.adloptica.com

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NKT Photonics
Birkerød, Denmark
www.nktphotonics.com

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Hübner Photonics
Kassel, Germany
www.hubner-photonics.com

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The SMD type spectral sensor head with flex C14384MA series uses an active pixel sensor (APS) to enhance sensitivity in the near-infrared. It features a spectral response range of 640 to 1050 nm, spectral resolution of 20 nm maximum (17 nm typical), optical numerical aperture of 0.22, slit size of 15 × 300 μm, and spectral stray light of <-23 dB.

Hamamatsu
Bridgewater, NJ
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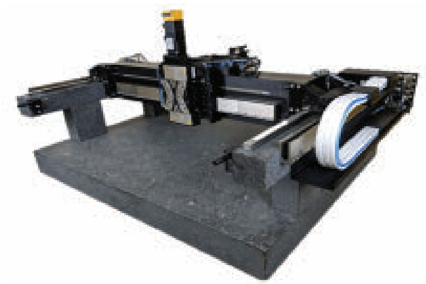
The A-341 hybrid gantry positioning stage provides precision XY/XYZ motion with linear motors, air bearings, and ball bearings. It features 300 × 300 to 500 × 1000 mm XY travel, absolute encoders



from 1 nm resolution, 2 m/sec maximum velocity (cross axis), and dynamic error mapping.

PI (Physik Instrumente)
Auburn, MA
www.pi-usa.us

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TECHSPEC λ/10 laser-line-coated windows are designed to protect sensitive optical and electronic components in high-power industrial laser applications. They have λ/10 surface flatness, 10-5

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Edmund Optics
Barrington, NJ
www.edmundoptics.com

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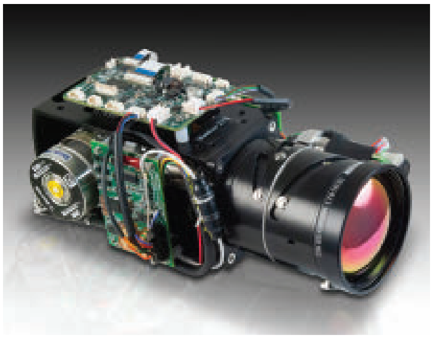

ous-zoom optic. The compact thermal camera core is specially designed for OEM integrators of surveillance system enclosures and other imaging gimbals.

Sierra-Olympic Technologies
Hood River, OR
www.sierraolympic.com

Tunable IR laser

The Carmina automated, tunable infrared (IR) laser features a wavelength range from 2.15 to 15 μm. It has two operating modes—in narrowband

mode, it has a narrow bandwidth of 20 wavenumbers and a broadband mode of >300 wavenumbers. It is suited for both spectroscopic experiments in narrowband and chemical imaging in broadband.

APE (Angewandte Physik & Elektronik)
Berlin, Germany
www.ape-berlin.de

Objective lenses

The Optem LWD M-Plan APO objective lens series is optimized to meet the apochromatic flat-field demands of next-generation, large-format sensors and digital image processing techniques. Its flat-field correction delivers high image quality across the entire sensor field-of-view to support advanced digital image processing algorithms and larger-format image sensors.

Excelitas Technologies
Waltham, MA
www.excelitas.com

Optical thickness gauge

The 137LS optical thickness gauge can measure the thickness of materials up to

28 mm for products such as multi-element optical lens systems. The measurements have an accuracy of ±1 μm and a repeatability of ±0.05 μm. The gauge measures all layers simultaneously in both hard and soft materials.

Bristol Instruments
Victor, NY
https://bristol-inst.com

Motion controller

The MC2010 motion controller system includes LabView control, a simplified interface, and the ability to automatically create scripts. It enables operation

of up to 10 linear and/or rotary actuators based on DC servo technology. This

closed-loop system delivers unidirectional linear motion down to 0.1 μm, with a bidirectional accuracy of ±2 μm.
Siskiyou
Grants Pass, OR
www.siskiyou.com

Simulation software tutorials

A series of tutorial videos guides users through Multiphysics simulation software. The COMSOL Learning Center takes users through each step of the modeling workflow, explaining the purpose and use of each aspect, including building the geometry and definitions, adding materials, defining the physics, meshing, performing a study, and post-processing the results.
COMSOL
Burlington, MA
https://comsol.com

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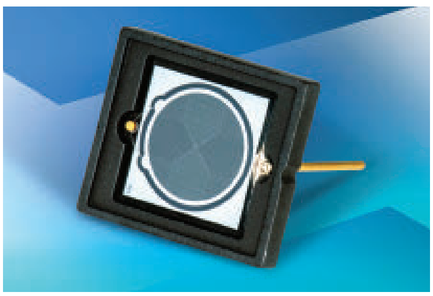
The AXUV20HS1 high-speed photodetector has a 5-mm-diameter circular active area (typically 20 mm^2). It



is suited for detection of low-energy electrons or x-rays and features electron detection to 200 eV with a typical rise time of 3.5 ns.
Opto Diode
Camarillo, CA
www.optodiode.com

Microscope

The HT-2 microscope combines both holotomography and 3D fluorescence imaging into one unit. It provides morphological, chemical, and mechanical properties of cells through the 3D refractive index (RI) tomograms and

adds molecular specificity information with a fluorescence imaging capability.
Tomocube
Daejeon, South Korea
www.tomocube.com

Lidar sensor

A 1550 nm lidar sensor is based on germanium-on-silicon avalanche photodetector array (APD) technology. A single APD pixel provides responsivity of ~3.2 A/W at typical 90% breakdown voltage, dark current of ~2.2 mA, and a 3 dB bandwidth of ~9.0 GHz. The 25 pixels on a 5 × 5 APD array show a responsivity variation of <5%, with a bandwidth of up to 1 GHz.
Advanced Micro Foundry
Singapore
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Diamond-turned optics can be supplied in complex geometries with nanometer tolerances in a wide range of materials and substrates. Configurations include freeform, polygonal, aspheric, biconic, toric, off-axis, Fresnel, and rotationally

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NiPro Optics
Irvine, CA
www.niprooptics.com

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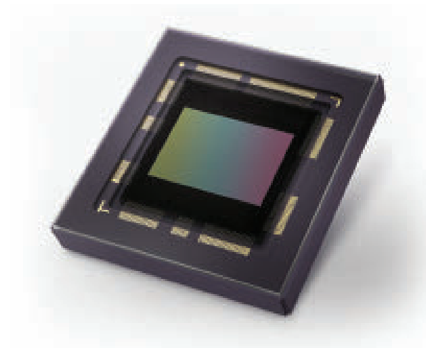
Coherent
Santa Clara, CA
www.coherent.com

CMOS image sensor

The Emerald 5M CMOS image sensor is designed for machine vision, automated optical inspection (AOI), and fac-



tory automation applications. Available in both monochrome and color, it has a 1/1.8 in. optical format, containing a 2.8 μm, low-noise, global pixel shutter, arranged in a 2560 × 1936 array.
Teledyne e2V
Grenoble, France
www.teledyne-e2v.com

Scan head

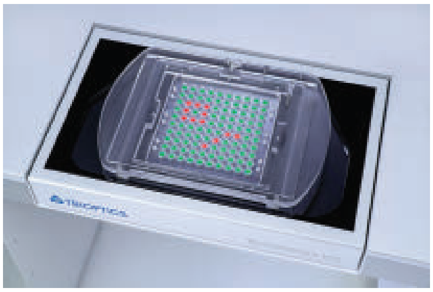
The basiCube scan head's SL2-100 interface allows direct control by RTC5 boards, making possible execution of

elaborate laser jobs and complex graphics for laser marking, subsurface glass engraving, or similar applications. RTC5 boards let laserDESK professional laser processing software use these scan heads, serving both as a controller and a graphical user interface.

Scanlab
Puchheim, Germany
www.scanlab.de

Lens-sorting station

The WorkstationIOL lens-sorting station is designed to complement the company's OptiSpheric IOL PRO 2 automated test system for intraocular lenses. The workstation features a display indicating whether each lens has passed quality inspection, with green and red to indicate "pass" or "fail." A barcode scanner identifies sample trays.



Trioptics
Wedel, Germany
www.trioptics.com

Liquid flow sensor

The SLF3S-1300F liquid flow sensor is designed for diagnostics, analytical instruments, and life sciences. Based on proprietary CMOSens technology, it features flow rates up to 40 ml/min. and bidirectionality. The sensor allows monitoring of entire systems operation and detects common failure modes.

Sensirion
Staefa, Switzerland
www.sensirion.com

Brushless linear motor

The BLSM-1F compact brushless linear motor can generate 300 lbs at a 10% duty cycle and 100 lbs at a 100% duty cycle and when used with a matching BLST-FSX magnet track. The motor can be driven using either a trapezoidal or digital standard three-phase brushless amplifier.

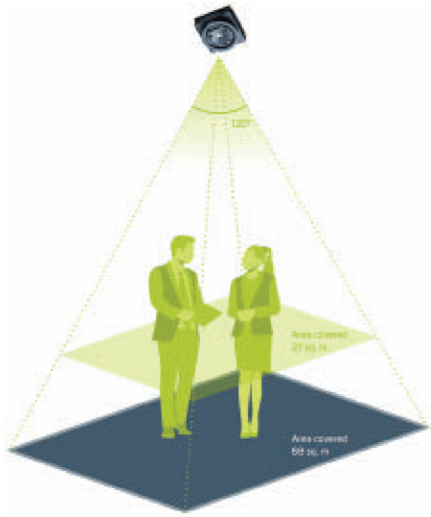
H2W Technologies
Santa Clarita, CA
www.h2wtech.com

USB cameras

Two USB 3.0 industrial cameras, in color or monochrome, for high-dynamic-range imaging applications are based on Sony's CMOS global shutter sensor. The PL-D757, based on IMX420, provides 60 frames/s at 3208 × 2200 pixels on a 1.1-in. sensor. The PL-D753, based on IMX421, captures 143 frames/s at 1936 × 1464 on a 2/3-in. sensor.

Pixelink
Ottawa, ON, Canada
https://pixelink.com

Building thermal sensor



The ThermEye Building thermal sensor line is designed for system integrators of detection and people counting equipment for connected buildings. It includes two new products: ThermEye-b90 and ThermEye-b120. These 80 × 80 thermal sensors are

coupled with a 90° or 120° field-of-view lens to cover a zone of 30 m^2.
ULIS
Grenoble, France
www.ulis-ir.com

DPSS green laser

The UL532HRR DPSS green laser operates at 532 nm with an average output power of 25 W and runs at a pulse repetition rate of 500 kHz. It is suited for processing of battery terminals, PCB cutting, and glass processing.
Unilase
London, England
www.unilase.com

1750 nm LED

The SLC1750-1100-GF high-power 1750 nm LED features a glass lens and ceramic package with 10 mW radiated

power at 500 mA. It is suited for plastic detection for sorting in recycling applications and alcohol detection.
Marubeni
Santa Clara, CA
www.tech-led.com

Tunable laser lens

A tunable laser lens enables 3D lens processing using continuous-wave or pulsed lasers from 950 to 1100 nm by shifting the laser spot in the *z* axis. This lens is installed ahead of the galvo and *f*-theta lens. It has a clear aperture of 10 mm and is suited for 30 W average power.
Optotune
Dietikon, Switzerland
www.optotune.com

Optical detergents

Valtron formulated detergents are designed for use in the precision optics industry. These concentrated detergents include both alkaline and neutral pH formulations, and are available as low foam or low surface tension. They contain no nonyl- or octyl-ethoxylated-based surfactants, hazardous solvents, or EDTA chelating agents.
Universal Photonics
Central Islip, NY
www.universalphotonics.com

Broadband PIN photodiodes

The Model MTPD1346D-xx series InGaAs/InP broadband PIN photodiodes convert broadband light into photocurrents within the visible to shortwave-infrared range. They feature standard

spectral ranges of 0.6 to 1.7 µm, low dark current, typical efficiency of 0.6 A/W, and active area sizes from 0.1 to 3.0 mm.
Marktech Optoelectronics
Latham, NY
www.marktechopto.com

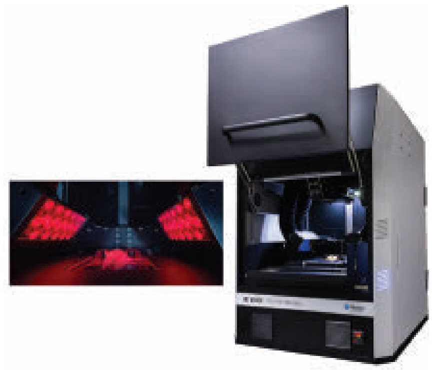
Alignment laser system

This alignment laser system features variable laser light output that is suitable for short distances. A dimming feature provides flexibility for object alignment against different backgrounds, such

as dark, light, chrome, or other shiny surfaces. Lasers are available in red or green, and each with a line or dot optic.
BEA Lasers
Elk Grove Village, IL
www.bealasers.com

Preclinical imager

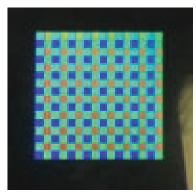
Using the first (NIR) and second biological window (NIR-II) from 900 to 1620 nm, the IR VIVO preclinical imager provides multispectral or hyperspectral infrared (IR) imaging capabilities for *in vivo* studies on small animals or living



organisms. Emission of several fluorophores can be isolated with a tunable filter and a low-noise, scientific-grade InGaAs camera.
Photon Etc.
Montréal, QC, Canada
www.photonetc.com

Nanoscale optical arrays

Nanoscale optical arrays using MagAssemble technology are suited for both point detection sensors and hyperspectral imaging systems. Multivariate Optical Computing (MOC) allows design and manufacture of patented optical filters and Pattern Transfer



Nanomanufacturing (PTMN) allows the design and manufacture of shapes and structures on the nanometer scale.
Cirtemo
Columbia, SC
www.cirtemo.com

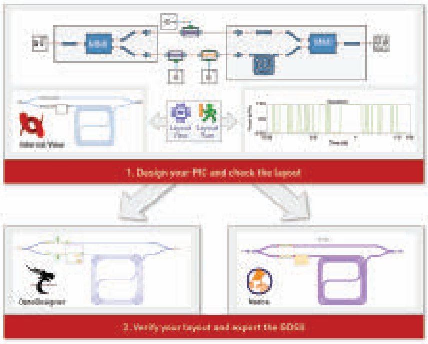
Hall sensors

The HAL 39xy Hall sensors feature stray-field compensation capability and build-on architecture for multidimensional magnetic fields measurements. Using 3D HAL pixel technology, they provide linear position detection, rotary 360°

angle detection, and rotary 180° angle detection with stray field compensation, including gradient fields.
TDK
Freiburg, Germany
www.micronas.com

Photonic circuit design tools

Version 1.4 of VPItoolkit supports the SMART Photonics Process Design Kit for simulation of photonic integrated circuits and automated extraction of mask layouts. The new tool kit supports the Nazca Design open-source framework. It has a broad set of designs and layouts,



defined via Python-enabled scripting. Instrumentation tools provide automated data analysis.
VPIphotonics
Berlin, Germany
www.vpiphotonics.com

Terahertz spectrometer

The Newport Terahertz Time-Domain Spectrometer is designed to work with amplified, femtosecond laser sources. Researchers can use it to study carrier dynamics in semiconductors on a very

short time scale. A two-color, laser-induced plasma generates terahertz radiation that passes through a sample and is detected by a timed gate pulse in a zinc telluride crystal.
Newport (MKS Instruments)
Irvine, CA
www.newport.com

Yellow laser

A yellow laser emits 1 W of power at 577 nm. It is designed mainly for medi-

cal and bioscience applications, including treatment for borreliosis, multiple sclerosis, and depression.
Necsel
Milpitas, CA
https://necsel.com

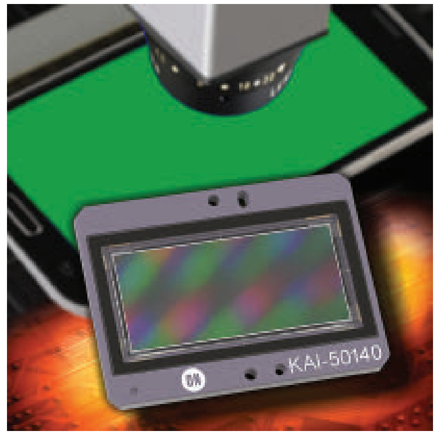
Digital borescope

The SV-1000 digital video borescope with illumination is a water-resistant

chip-on-tip inspection camera 1.6 mm in diameter. An integrated LED illuminates the 1.9-m flexible shaft. The 1 × 1 mm CMOS sensor provides 400 × 400 pixel resolution with a 120° field-of-view lens. A separate control unit includes electrical connections, video outputs, and LED control.
Toshiba America Imaging Systems Division
Irvine, CA
www.toshibacameras.com

CCD image sensor

The KAI-50140 CCD image sensor has 50 Mpixel resolution and a 2.18-to-1 aspect ratio for inspection of smart-



phone displays. Its 4.5-μm Interline Transfer CCD pixel provides high resolution with a true electronic (global) shutter. It supports rates of 4 frames/s with a 1-, 2-, or 4-output readout architecture.
ON Semiconductor
Phoenix, AZ
www.onsemi.com

Rotation stage

The RTHM-16 Rotation Mount is a compact stage designed to rotate polarized optical components with diameters of

25.4 mm. It offers continuous rotation with a speed of 10°/s, a unidirectional repeatability of ±60 μrad, and resolution of 0.25 arcs. It is thin at 17 mm, with an aperture of 27 mm, and is USB 2.0- and 3.0-compatible.
Intellidrives
Philadelphia, PA
www.intellidrives.com

Chromatic sensor

The confocalDT IFS2404-2 confocal chromatic sensor provides a measurement range of 2 mm with a resolution of 40 mm and a light spot of 10 μm in diameter. The OEM performs displace-

ment and distance measurements with a linearity of ≤ ±1 μm and thickness with a linearity of ≤ ±2 μm.

Micro-Epsilon
Raleigh, NC
www.micro-epsilon.us

Lattice light-sheet microscope

The Luxendo InVi SPIM AIM lattice light-sheet microscope features an advanced illumination module (AIM) for low-phototoxicity light-sheet fluorescence microscopy of live samples. A variety of illumination patterns, including single or multiple variable Bessel beams, lattice light sheets, and structured illumination, are possible. The microscope uses

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Bruker
Billerica, MA
www.bruker.com

Machine vision cameras

The Phantom S210 and S200 machine vision cameras reach 1730 frame/s at full 1.3 Mpixel resolution and 7000 frames/s at full 0.3 Mpixel VGA resolution, respectively. Both cameras use up to four CoaXPress (CXP6) channels to

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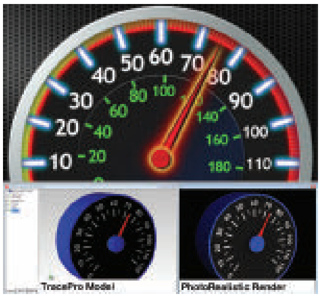
Vision Research
Wayne, NJ
www.phantomhighspeed.com

Manufacturers' Product Showcase

Manufacturers' Product Showcase

Do you want to be a light pipe design expert?



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TracePro, from Lambda Research Corporation, provides the tools to investigate and design better light pipes. Unlike other programs that fall short in the design process with limited design tools, TracePro delivers exceptional results using innovative new tools.

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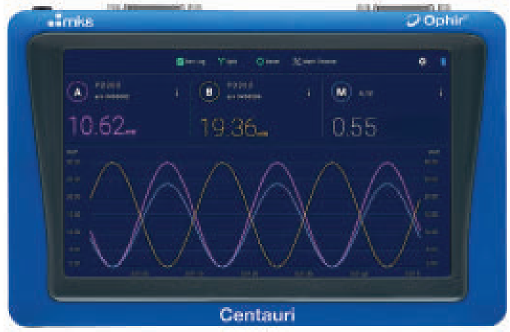

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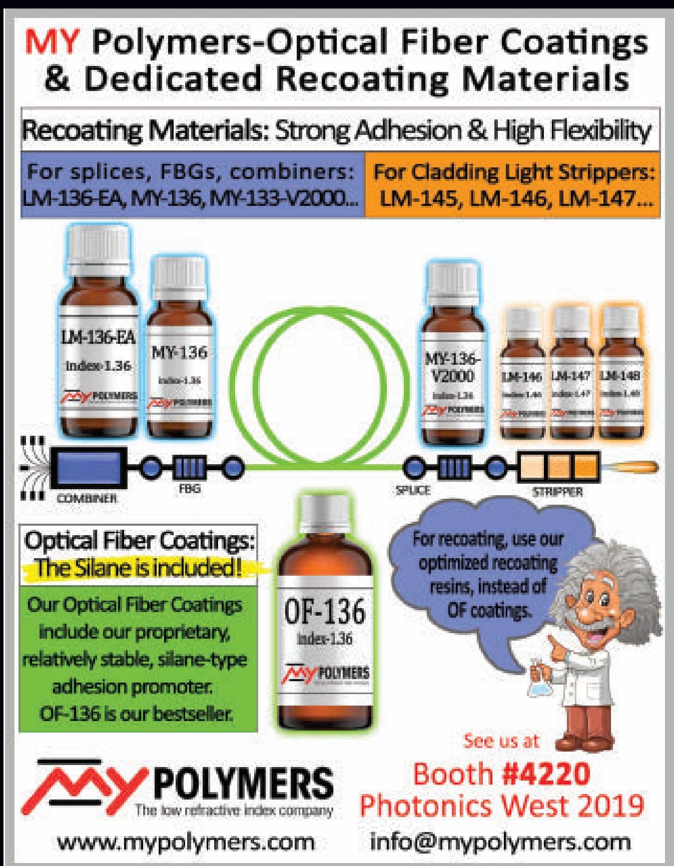

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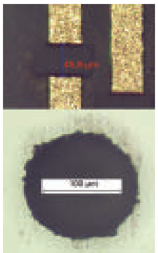

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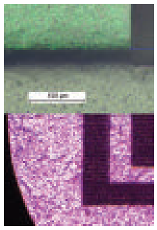

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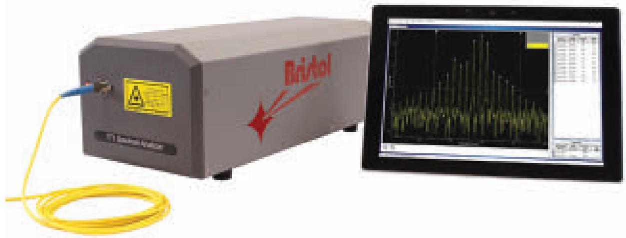

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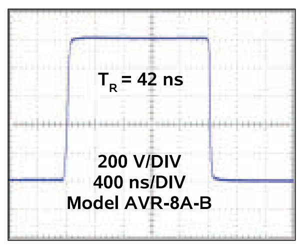

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Manufacturers' Product Showcase

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AT: *If we look at the photonics part, which markets do you want to focus on in the near future and how?*

ST: In our OEM business, which we are going to call Light and Optics, we are going to focus even more on customers in the semiconductor manufacturing equipment, biophotonics, industrial, and data and communication environments.

In our new Light and Production division, we will continue to focus on the automotive sector. But in the future, we also want to expand our activities to adjacent segments for this business. And of course, in our Light and Safety business, we will focus on making roads and communities safer, together with our customers.

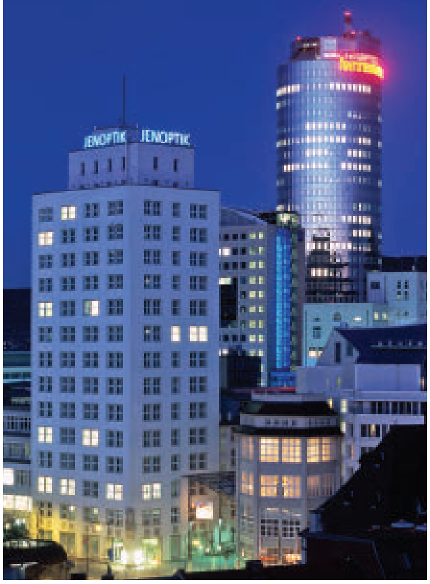

FIGURE 2. When the (former) East German part of Zeiss was split off in the early 1990s, the historical Ernst-Abbe Building went to Jenoptik; today, it hosts their executive board. *(Photo credit: Günther Prätor)*

AT: *Does that mean you would form new research groups, or do you put additional freedom on the existing teams?*

ST: Definitely the latter one. We are trying to create more room for creativity within our existing organization. Whether we will add incubators or additional groups, we don't know yet. But that's certainly something we're thinking about at the moment, and we will focus on that even more in 2019.

AT: *Have you already determined fields where you want to focus your R&D?*

ST: We're certainly continuing to focus on classical optical technologies such as microstructured optics, nano-optics, and the like. However, the future lies in the application. Just producing the most sophisticated piece of glass or the best polished surface will not be good enough.

In my opinion, we can become stronger in the data-driven environment. Our sensors and our cameras are actually right on the interface between analog information and the digital dataset. Because what's a camera doing? Essentially, it provides a digital dataset.

As an industry, we are still positioned so that we produce a digital dataset and someone else makes money with it. And we forget that the most important resource of the future will be the data itself—the sensor becomes a commodity. What's really going to make the money is an integrated solution of sensor and data processing.

Within the next five years, we must have an answer to the question: How do we address the changes in our ever-more digitized world? How do we work with the Googles of this world? I think that's a challenge that the whole industry has to face.

AT: *Is there a common strategy you follow?*

ST: Optics and photonics is a fairly broad sector with lots of different verticals and lots of different subsegments. I, for one, believe that for Jenoptik, it's best to focus on sectors in which technological differentiation enables premium prices. We're not at our best when it comes to commoditized products.

AT: *Can you give me one example where you can really stand out with products that you do with the excellent staff here in Jena or other places in Germany? Because I think one should mention that while Jena is a classical hotspot of optical sciences, Jenoptik has acquired, I think, almost a dozen factories all across Germany and around the world with extremely talented people. And those are the right people to stand out, to develop technological advances that are not commodities, right?*

ST: Sure. Just think about our contribution to the semiconductor industry, for example. The sensors and the devices that we develop and build in Jena, in Dresden, and in a couple of other places for the semiconductor manufacturing space are outstanding. There are only a few companies that I know of that have the technological competences required at this level.

AT: *How do you want to change your strategy on R&D?*

ST: Considering the balance between R and D, we want to invest a bit more into the R part of R&D. We did a lot of contract development, which is in a way great since we have built a lot of customer intimacy. However, if we only develop what our customers tell us, we may risk losing our competitive edge.

Thus, I believe that we need to invest a bit more into advanced research. We now have enough financial firepower to be able to face risky endeavors at times. We won't just do blue sky research, but I think we can afford to take more calculated risks. This, in turn, will be the basis for securing a competitive edge in the future.

AT: *Jenoptik is making a big strategic change to adapt to the 21st century. What are you doing to take your people with you?*

ST: This is probably our biggest challenge. We must make sure that we're not losing our strengths in German engineering. This has made us strong in the past, but we want to add a more-international appeal and more intercultural competencies. In the end, it is all about communication.

AT: *What do you do to attract new talents?*

ST: Talents are much more mobile these days than in the past. To have a nice working environment in Jena is just not good enough. We have to be able to provide international experiences to our people. We can offer secondments to our sites and application labs in Silicon Valley, for example, or in Shanghai. For our engineers, that's quite an interesting prospect. ◄

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'Jenoptik is at a decisive moment in its history'—An interview with Stefan Traeger

ANDREAS THOSS

Jenoptik has just raised its 2018 revenue forecast for the second time, so the company is doing very well in its core markets of photonic and mechatronic solutions. Contributing Editor Andreas Thoss spoke with Jenoptik's CEO, Dr. Stefan Traeger, about Jenoptik's Strategy 2022 and what is in the strategy beyond structural changes.

Andreas Thoss: ***How was the year for Jenoptik? And what are your prospects for 2019?***

Stefan Traeger: To us, 2018 has been driven by strong markets in all segments. We're still having a lot of tailwind from the semiconductor industry and the demand in areas of biophotonics, healthcare, and life sciences is growing fast as well.

Business in 2019 is a bit harder to predict. In our own funnels, we don't see a downturn at the moment. Our business is strong and when I talk with customers, most of them are still quite optimistic. However, if discussions around tariffs and trade protectionism intensify, then we might actually see a problem. We do believe in free trade and we depend on free trade.

FIGURE 1. Jenoptik's president and CEO Stefan Traeger worked for ZEISS and Leica Microsystems (Danaher group) before taking the lead in Jena in December 2016. *(Photo credit: Walter Oppel, Fraunhofer IOF)*

AT: ***Earlier this year, you announced a substantial strategic change for Jenoptik. Could you tell me more about this change and why you think it is necessary?***

ST: We have summarized our strategy under the headline "More Light." It basically calls for three major building blocks: We're talking about "more focus" for the company as a whole; we're talking about "more innovation," and we're talking about becoming "more international."

Jenoptik today is a relatively diversified industrial conglomerate. What we want to do is to transform this diversified industrial conglomerate into a focused technology group. We will focus on optics and photonics, which is our core competence at the end of the day.

Why are we doing this? We have a lot of success in the marketplace at the moment. However, if you look back, things haven't always been easy for Jenoptik. The company went through quite some challenging times in the last decade. It wasn't always clear whether or not Jenoptik really survives. Those days are over. We now have a strong balance sheet—we have the financial means and certainly the willingness to invest into growth. From my point of view, Jenoptik is at a decisive moment in its history.

And given that change and that we are now coming from a pretty-strong position, we do want to invest in growth and we do want to take the company to the next level. I don't think that we can do everything at the same time with the same rigor, though. Thus, we've got to focus actually on something that we're really good at—on our core competencies in optics and photonics.

AT: ***You have split the company in two branches. The one that is optics and the other one that is not optics. Could you say a few words more about that?***

ST: Sure. We have just recently established the new brand Vincorion for our mechatronic business. We had to look for synergies between our mechatronic businesses, which cater predominantly to defense and aerospace customers, and our optics business. Those businesses are very different. They act in different marketplaces, they follow different rules and different regulations, and they have a different mindset.

AT: ***Do you want to sell it?***

ST: We do not have an active process to dispose that business. However, we explicitly don't want to exclude that for the future.

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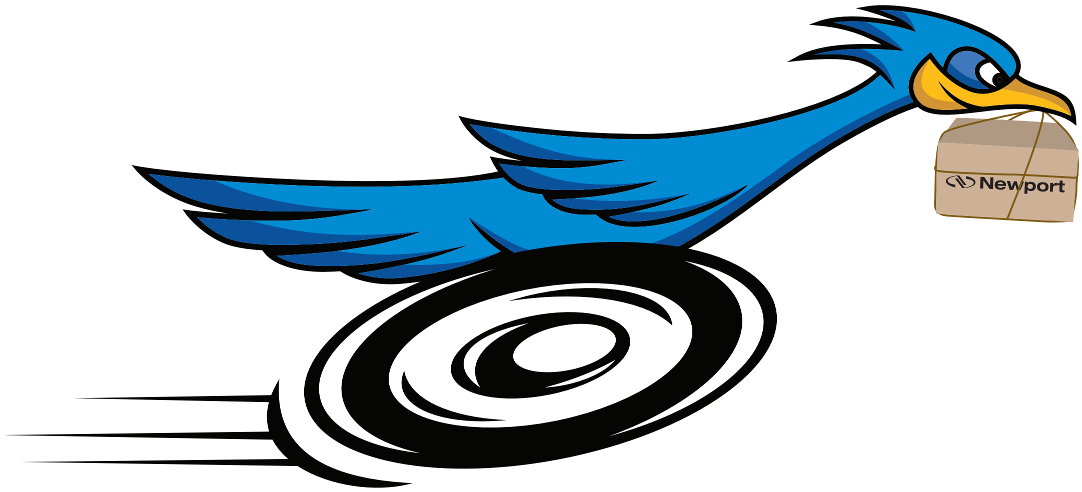

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