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AFM teams with optical imaging

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Laser projection displays find new life

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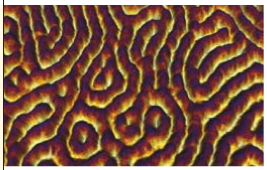
features



25 COVER STORY
An atomic-force microscopy (AFM) quantitative imaging (QI) mode enables more precise control over the probe force for nanometrology, imaging delicate or difficult-to-handle samples—such as sticky polymers like the one shown here—and obtaining mechanical, chemical, and electrical data—especially useful in the life sciences. (*3D and 2D views; Courtesy of H. Haschke, JPK Instruments*)

Coming in April

Special Feature!
How to begin a career in photonics
Many say that the secret to a successful career in photonics is knowing which undergraduate institution to attend. This article provides an overview of the programs at several major and minor post-high-school educational institutions worldwide and offers some useful resources for the aspiring optics/photonics student.

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Exclusive Feature: Optical Design

Free-form optics enable lightweight, high-performance head-mounted displays

Free-form optics tiling can potentially overcome the invariant on the field of view and the resolution in a head-mounted display, and enable the design and development of lightweight and high-performance head-mounted displays. *Dewen Cheng, Yongtian Wang, Hong Hua, and José Sasián*

http://bit.ly/y9Rxlq

News: **Sandia's laser-guided bullet prototype can hit small targets a mile away**

Sandia National Laboratories researchers Red Jones, Brian Kast, and their colleagues have invented a finned self-guided bullet for small-caliber, smooth-bore firearms that could accurately hit laser-designated targets at distances of more than a mile. *John Wallace*

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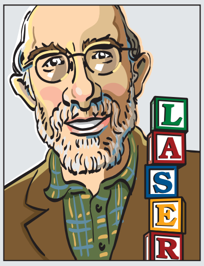
New on OptoIQ!

Our latest addition, "Photonics Building Blocks," is where contributing editor Jeff Hecht decodes and explains the fundamentals of photonics. It's a blog that educates and amuses, and tries to make the world of photonics just a little bit easier to understand.

http://bit.ly/w0HN4P



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The OSA Foundation has announced the finalists for the Corning Outstanding Student Paper Competition, a highly competitive program that provides the field's most promising young researchers the opportunity to present and be recognized for their groundbreaking work.

http://bit.ly/ykQDI1

Blog: Opto Insider

On photonics executives, complexity, and margins

Photonics West went well again. People were in a good mood, including the executives at SPIE's forum, where I moderated. One topic was "managing complexity." It sounds like a buzzword, until you think about it. There can be great advantages to complexity. Clayton Christiansen, the Harvard business guru, says that the margin in the supply chain goes to where there is the greatest complexity.

http://bit.ly/xwCVdE

Blog: Larry's VC View

Aussie 'Gold Rush' in SV?

Aussies have been coming to the States for 30 years—actually, longer if you think about Ugg and others, but for sure Peter Farel founding Resmed. There's a misconception that if you come here, everything is solved and the streets are paved with gold. It's a little like the scientist I started out to be saying naively it's such great technology; build it and they will come. http://bit.ly/yfjbUO

editor's desk

Acronym World

W. Conard Holton
Associate Publisher/ Editor in Chief
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Acronyms have been used to simplify communications for thousands of years—the official name for the Roman Republic, and then Empire, was SPQR (*Senatus Populusque Romanus*). Today, a technology-based profession like photonics is rife with critical and confusing acronyms, as any engineer or journalist in the field can tell you.

For anyone in the industry, the simple act of reading a table of contents in our magazine can be daunting (and we strive for clarity!). For example, our cover story describes how QI (quantitative imaging) adds the advantage of optics to AFM (atomic force microscopy). An article on SC (supercontinuum) lasers shows how an all-fiber design extends the application window into the mid-IR (infrared). And an article on laser projection displays describes a recent design based on 2D (two-dimensional) SLMs (spatial light modulators) that improves upon previous designs, which used a GLV (grating light valve) or GEMS (grating electromechanical systems) and an OPO (optical parametric oscillator).

I could go on with many more examples, but instead I would like to introduce an antidote to acronym confusion. First, we have redesigned OptoIQ.com, which is one of the web sites in our online network that includes LFW (*Laser Focus World*), ILS (*Industrial Laser Solutions*), and BOW (*BioOptics World*). The OptoIQ site is now focused on photonics business and education (EDU).

The EDU side of the site features links and news from and about universities, community colleges, company-sponsored training courses, grants, and awards. It also has regular blogs from our editors and guests, including the weekly blog "Photonics Building Blocks." In it, contributing editor Jeff Hecht not only defines common acronyms, but provides an explanation of the terms along with some amusing insights. A blog is not a cure for all acronyms, but it can be a good guide to translation.

LaserFocusWorld

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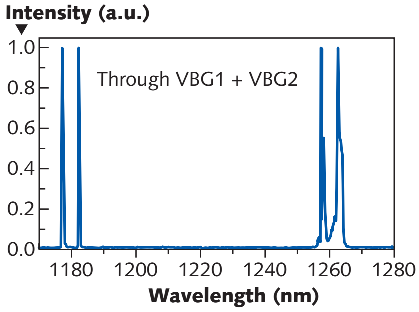
newsbreaks

Quantum-dot laser produces multiple wavelengths for terahertz generation

A single quantum-dot (QD) laser diode developed by a group at the University of Dundee (Dundee, Scotland) generates stable dual and/or multiple longitudinal modes in the near-infrared. The device has potential for production of terahertz radiation via optical difference-frequency generation.

Temperature-stabilized at 20°C, the laser diode is situated in an external-cavity setup containing two volume Bragg gratings (VBGs): one that selectively returns 1177 ±0.5 nm and 1182 ±0.5 nm wavelengths, and the other that selectively returns 1257 ±0.5 nm and 1262 ±0.5 nm wavelengths. The glass VBGs have an efficiency of about 15% and grating tilts of 1° to prevent backreflections. The difference frequencies for the two gratings are 0.946 ±0.019 THz and 1.078 ±0.021 THz, respectively.

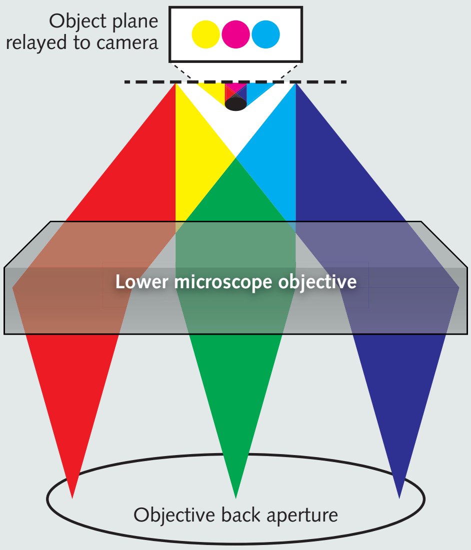
When driven at a current of 70 mA, the laser emitted from the ground state (GS; matching VBG2); at 210 mA, excited-state (ES; matching VBG1) emission dominated the output. Intermediate currents produced a mix of GS and ES emission. Because each VBG is multiplexed (containing two gratings), a total of four wavelengths can be produced by the laser, with the relative output of each of two pairs adjustable by varying the current (the figure shows the output for a 150 mA current). In addition to photomixing for terahertz generation (and potentially two-color terahertz imaging), the laser is useful for spectroscopy. *Contact Ross Leyman at* r.r.leyman@dundee.ac.uk.



Three-color optical system measures 3D positions of many trapped microparticles

Using three colors of light projected through a microscope objective in different patterns, researchers at the Technical University of Denmark (Roskilde, Denmark) simultaneously and unambiguously find the 3D coordinates of multiple microparticles. The scheme can be used while optically trapping and manipulating the particles, whether by holographic trapping or counterpropagating-beam trapping.

Red, blue, and green (RBG) light patterns are created by an LED-based digital-light-processing (DLP) projector (which actually projects yellow, cyan, and magenta hues that mix to form RBG) and projected into a microscope to the back aperture of the lower objective, with the green projected on-axis. An optically trapped particle casts shadows that are missing one or more of the three colors; from these shadows, the 3D information on the particles is obtained. Because there is some "bleeding" between the colors (for example, both the red and blue illumination patterns produce a detectable signal in the green color plane), the researchers measure the background signal (offset and color-plane bleed ratios) and compensate using a deconvolution algorithm. In one experiment using a 50X objective with a numerical aperture of 0.55, 6 μm particles were accurately tracked over a 180 μm vertical distance. A video of seven optically trapped microparticles being manipulated while their coordinates are being measured can be seen at http://www.jeos.org/suppfiles/304/304-1729-1-SP.avi. *Contact Jesper Glückstad at* jesper.gluckstad@fotonik.dtu.dk.



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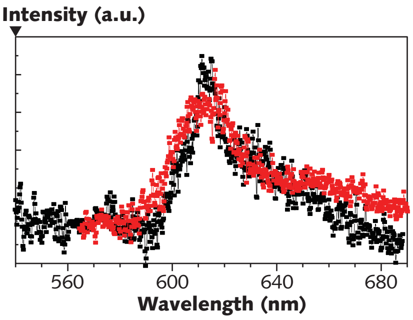
OLED-style emitter has single-photon 'pixels'

Unlike the broadband, diffuse emission from organic light-emitting diode (OLED) displays, a new type of emitter made using standard OLED manufacturing processes and materials releases only distributed single photons upon electrical excitation of the active layer.[1] Designed by researchers at the University of Stuttgart (Stuttgart, Germany), the University of Ulm (Ulm, Germany), and the University of Würzburg and ZAE Bayern (both in Würzburg, Germany), the single-photon emitter also operates at room temperature (unlike semiconductor quantum dots), offering numerous opportunities for applications in secure communications and cryptography.



Because fluorescent molecules embedded in polymer or photonic-crystal matrices have inefficient electroluminescent properties, the researchers chose an iridium (Ir)-based organometallic complex—specifically, $Ir(piq)_3$ (tris(1-phenylisoquinoline)iridium) molecules—that emits single photons at 613 nm with almost 100% internal quantum efficiency via phosphorescence in a polymer matrix.

The emission is successful based on two key fabrication steps: First, the red-light-emitting molecules are dispersed evenly in a blue-light-emitting host polymer; and second, a low-work-function barium metal is used as the cathode to ensure adequate charge-carrier densities suitable for electron injection and, hence, electrically driven single-photon emission at room temperature. Photon-correlation measurements confirm single-photon emission from the distributed Ir-based molecules with lifetime values ranging from 1.0 to 1.4 μs using a 12 V input. *Contact Maximilian Nothaft at* m.nothaft@physik.uni-stuttgart.de.

Programmable optical processor achieves multichannel OTDM-to-WDM conversion

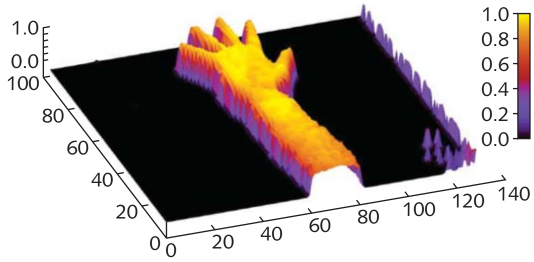
Scientists at the Universidade de Aveiro (Aveiro, Portugal) and Nokia Siemens Networks Portugal (Amadora, Portugal) have created an optical time-division multiplexing (OTDM) to wavelength-division multiplexing (WDM) converter that handles multichannel conversion with flexibility in both time and wavelength domains, thus opening up the possibility of getting OTDM and WDM systems to work together in a straightforward manner. The converter relies on a so-called programmable optical processor (POP) to do its work.

Part of a 160 Gbit/s input data signal from an OTDM with *N* different signal "tributaries," or channels, feeds a clock-recovery system, which provides a clean optical clock signal that is then split into *N* different wavelengths, with the resulting signal pulses (SPs) processed by the POP to suppress amplified-spontaneous-emission and other noise. Via four-wave mixing in a highly nonlinear optical fiber, the rest of the OTDM signal interacts with the multiwavelength sampling pulse train. The time delays and shapes of the SPs are controlled through adjusting the POP's phase and amplitude function, respectively. An output tunable optical filter filters the resulting signals, producing a 4 × 40 Gbit/s WDM output. Error-free performance was achieved for all signals, with a maximum power penalty of 6.3 dB. Tweaking of the system parameters can further reduce the power penalty. *Contact Miguel Drummond at* mvt@av.it.pt.

3D CMOS time-of-flight imager uses new photodiode design

Three-dimensional CMOS time-of-flight sensors operate by determining the distance of different portions of a scene based on the delay recorded by individual pixels in a sensor co-located with a modulated, diffuse illumination source. To operate at distances of several meters, short nanosecond-scale pulse lengths are needed with short integration times for the photogenerated charges, presenting such challenges as short transit time, low noise, and fast readout for each pixel. To address these challenges, researchers at the Fraunhofer Institute for Microelectronic Circuits and Systems (IMS; Duiburg, Germany) developed a new intrinsic lateral-drift-field photodiode (LDPD) that achieves a 30 ns complete charge transfer from the pixels into the readout node and accumulates charge over many readout cycles to lower the signal-to-noise ratio.

The LDPD is fabricated in a 0.35 μm CMOS process, and owes its functionality to a surface-pinned, nonuniformly *n*-doped well that induces an intrinsic lateral-drift field parallel to the detector surface in the direction of the pixel-readout node, effectively funneling the photogenerated charges to a specified node for almost noiseless reset and readout. The 40 μm^2 pixels (38% fill factor) were assembled into a 128 × 96 pixel sensor and a human arm was easily imaged in 3D using the sensor within a standard camera setup in conjunction with a 905 nm pulsed source (with a pulse duration of 30 ns) operated at 10 kHz. Responsivity of the LDPD was 230 $\mu V/W/m^2$ and dynamic range was about 60 dB. *Contact Werner Brockherde at* werner.brockherde@ims.fraunhofer.de.



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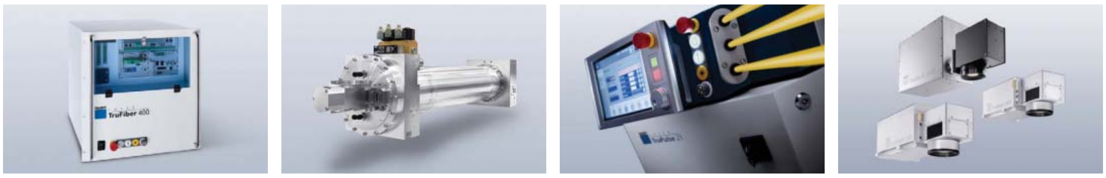

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world news

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DIODE-PUMPED SOLID-STATE LASERS

Laser dazzlers are deployed

Nonlethal laser weapons are going big time. After testing green laser "dazzlers" at checkpoints in Afghanistan and Iraq, the US Army in November 2011 ordered thousands more "Green Laser Interdiction Systems" for deployment, with plans to buy more in the next two years. The technology is likely to gain users in law enforcement, after the Food and Drug Administration (FDA) in August 2011 issued a waiver allowing sale of a civilian laser dazzler with a sophisticated safety system. Similar green solid-state CW lasers, emitting up to 1 W, are offered openly on the Internet, although some vendors claim to limit sales to law-enforcement agencies.

Emitting at green wavelengths where the eye is most sensitive, dazzlers are intended for a range of military and law-enforcement uses, from nonverbal warnings to people approaching checkpoints to emitting blindingly intense glare to stop hostile forces from seeing the target they want to attack (see figure). Typical operating ranges are 300–500 m during the day, and up to a few kilometers at night. Class IIIB lasers are needed to reach those distances, but the power is limited to around 200 mW to limit the chance of permanent eye damage. (Deployment of lasers designed specifically to blind is banned by the Protocol on Blinding Laser Weapons, adopted by the United Nations in 1995.)

The Joint Non-Lethal Weapons Directorate (JNLWD; Quantico, VA) leads the Pentagon's development of laser dazzlers. "Optical distracters, like many nonlethal weapons, are part of an escalation-of-force option for warfighters, assisting in minimizing civilian casualties and limiting collateral damage," explains JNLWD spokeswoman Kelley Hughes. So far, several types of dazzlers have been used at checkpoints, during urban patrols, on convoys, and for perimeter security. Field reports indicate the dazzlers have been extremely effective in engaging unauthorized people at safe standoff distances, according to JNLWD director Col. Tracy Tafolla. This both protects soldiers from would-be attackers and keeps noncombatants out of harm's way.

That experience convinced the Army to buy 12,542 Glare Mout Plus lasers from B. E. Meyers Electro-Optics (Redmond, WA). That system is rated to emit 200 mW at 532 nm, either pulsed at a few hertz or continuous, with operating range of 20–500 m. Closeup operation is limited by the ocular hazard distance of 20 m; the beam diverges so it covers a person's head and shoulders at 100 m and an entire vehicle at 500 m. The laser module weighs just 10 oz and can be mounted on a gun or held separately. The system was kept small and simple so soldiers will use it, says Jeff Bradbury of B. E. Meyers. The company expects additional orders this year and next.

Long-range ocular interrupter

In December 2011, the US Navy requested proposals to develop a "long-range ocular interrupter" that could switch between warning and visual suppression modes and provide warnings up to 3 km from a ship, even in hazy conditions. The

A laser dazzler is used from a Humvee. (*Courtesy of the Joint Non-Lethal Weapons Program*)

Navy's big concern is preventing small-boat attacks. Private shipping companies are considering dazzlers for nonlethal defense against pirate attacks. "If you can't look at something, you can't attack it," says Paul Kerr of Photonic Security Systems (Dunoon, Scotland), which has developed a green dazzler that is being tested by maritime security firms. Lasersec Systems (Jorvis, Finland) offers a 10 W dazzler that may be the most powerful nonlethal maritime laser.

The US Army relies on soldier training to assure safe use of dazzlers, as it does for guns, but the FDA requires a safety system on dazzlers for civilian use. In August, the FDA granted its first waiver for nonlethal lasers to B. E. Meyers for a law-enforcement system called Glare Enforcer that it introduced in January at the SHOT Show in Las Vegas. It fires a 200 mW, 532 nm green laser in one of four modes: Continuous, slow pulses at 4 Hz; fast pulses at 8 Hz; or random pulses at 4–12 Hz. Potential users include the Coast Guard and border patrol.

Glare Enforcer's safety system is based on an eye-safe laser ranger that checks for objects in or near the nominal eye-hazard zone, where intensity is high enough to cause eye damage. If a person is near or in the eye-hazard zone, the system reduces laser power to levels safe at that distance. Monitoring the surrounding area extends protection to people who might move into the hazard zone, or who might be hit when the laser is moved. The system also looks for reflective objects near the beam field to protect the laser operator from dangerous reflections. That makes Glare Enforcer more complex and—at 21 oz—heavier and larger than the military system. It is effective to 500 m during the day and beyond 1 km at night.

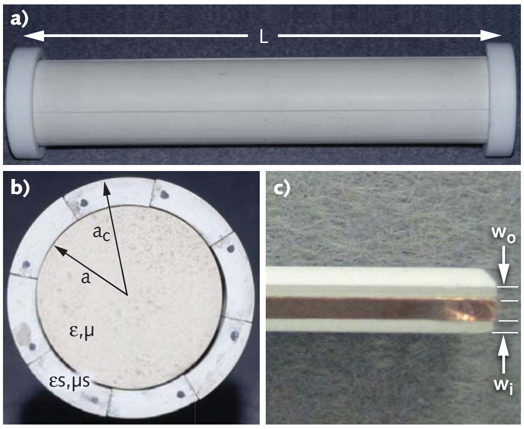
Such safety features are not standard in green lasers emitting 200 mW to 1 W available on the Internet, a few of which are described as pointers. A company called "GreenLaserPointer.org" offers 500 mW lasers claimed to be "FDA-compliant"—some of which are called pointers—for $500 to $600. —*Jeff Hecht*

PLASMONICS

Metamaterial cloaking approach goes 3D

Researchers at the University of Texas at Austin have "cloaked" a macroscopic object in free space from detection in three dimensions at all viewing angles for the first time. The approach works in the microwave region of the electromagnetic spectrum, but is in principle applicable to much shorter wavelengths. Work on metamaterials for cloaking applications has been going on at a feverish pace in recent years with some successes, each with its own limitations. Very few approaches have worked for more than a single incidence angle and viewing angle.

The demonstration is a long-awaited proof of principle for Andrea Alu, who has been championing the use of plasmonic metamaterials for a number of years. He has been watching with interest what has been going on in the field of "transformation optics" in metamaterials. In this most common cloaking approach, nanoscale structures in manufactured materials carefully guide lightwaves in prescribed ways around an object, coming together on the viewing side of the object as if the object were not there. But he says the approach is fundamentally limited to two dimensions.



The cloaked cylinder is seen from its side (a) and end (b), along with a cross-section of the plasmonic material jacket (c). (*Courtesy of A. Alu*)

"More recently, there has been a lot of work on this 'carpet cloaking,' like hiding a bump on a mirror or reflector, but this is still not really what we're looking for," he explains. "Our goal for this new paper was to prove that we could build a cloak that can work in 3D."

Rather than simply guiding light and reconstructing an image on different sides of a cloaked object, plasmonic

metamaterials aim to effectively "undo" the optical effects of the object—a kind of photonegative wrapped around it. The materials are made of metal and dielectric stacks that absorb incoming light and rechannel it in a different form: Surface plasmons, which are traveling excitations that can move around the object and then exit as light.

Alu and his team aimed to cloak an 18-cm-long cylinder from incoming microwaves in a custom-made jacket of plasmonic metamaterial (see figure). To prove that it worked, they used a microwave horn and imaging detector, which could be moved to a variety of viewing angles both above and below and on either side of the cylinder. The result, Alu says, stands in marked contrast to previous works.

"It's a real object standing in our lab, and it basically disappears," he says. "We proved this theoretically seven years ago, but this month we were able to prove it experimentally in a robust way."

Custom-fit jacket

One notable difference between the plasmonic and more standard transformation optics approaches is that the jacket is a custom fit. A different set of stacks would be needed to hide anything other than the dielectric cylinder they cloaked. And the approach works best only for objects with a size not too much greater than the wavelength of light. However, it puts comparatively few constraints on the materials, or requirements to make precise, nanoscale structures that—for an object the size of the cloaked cylinder—would present significant manufacturing hurdles. For that reason, Alu says that plasmonic materials are a significant, novel way forward. "If I had to bet in five years what kind of cloaking technique might be used for applications for practical purposes, then I would say plasmonic cloaking is a good bet."

Alu says the most straightforward applications of the approach may be in noninvasive sensing or near-field imaging. "Plasmonic cloaking has limits, so I wouldn't try to cloak an airplane or a tank," he says. "But if I know I have a 'hotspot,' I can cloak that part, and that may already help a lot." Harry Potter-style cloaks they are not, but Alu says the current work serves as an indication that plasmonic metamaterials are worth pursuing. "There is still a lot of work to be done," he notes. "Our goal was just to show that this plasmonic technique can reduce scattering from an object in free space." —*Jason Palmer*

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X-RAY LASERS

8.8 nm tabletop x-ray laser operates at 1 Hz

Demonstration of a 13 nm tabletop x-ray source that could achieve 25-nm-resolution imaging in only 30 s (compared to 30–50 nm resolution in 80 min from prior sources), as reported in *Laser Focus World*'s July 2011 issue, was indeed impressive. But now, a team of researchers from the NSF Engineering Research Center for Extreme Ultraviolet Science and Technology (NSF EUV ERC) and Colorado State University (both in Fort Collins, CO), in collaboration with the University of California–Berkeley, and Oak Ridge National Laboratory (Oak Ridge, TN), have demonstrated a high-pulse-energy, 8.8 nm tabletop x-ray laser source that operates at a 1 Hz repetition rate.[1] Previous attempts to shorten the x-ray wavelength below 10.9 nm in plasma-based schemes typically limited the repetition rate to a few shots per hour.

Lower pump energy

Until recently, soft-x-ray lasers at wavelengths below 10 nm were created by pumping appropriate materials with tens

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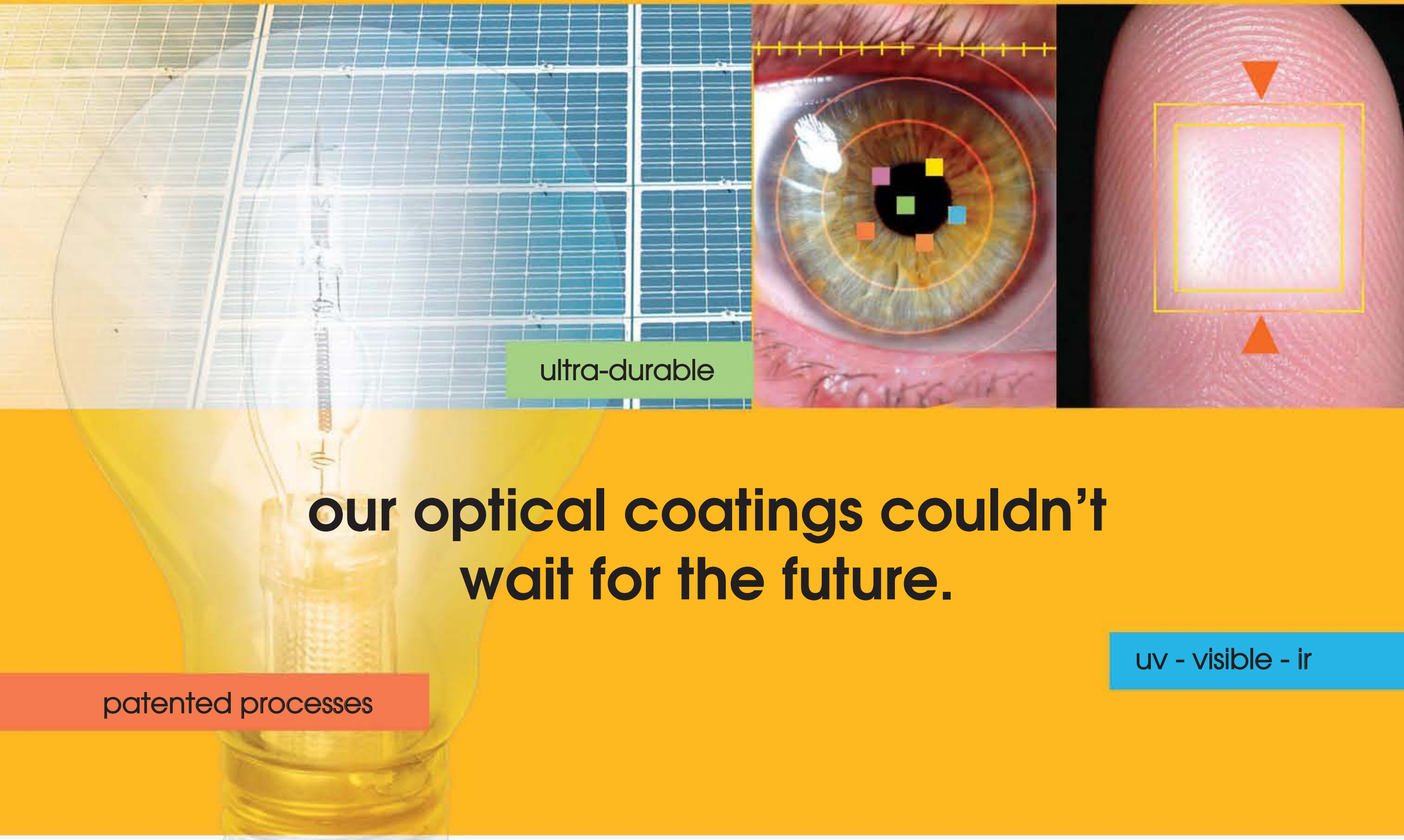

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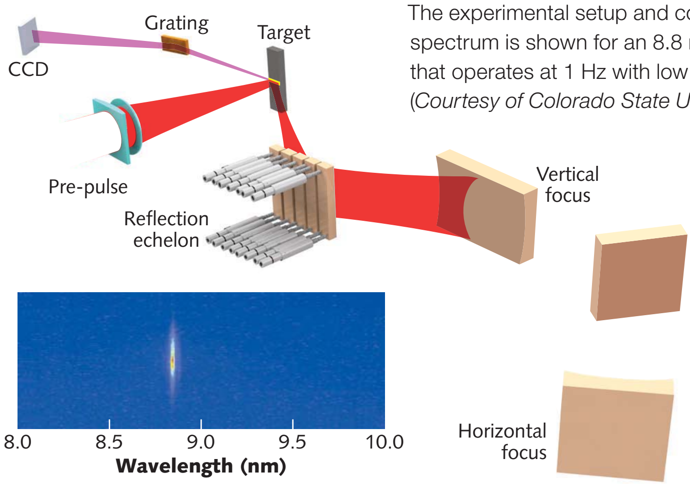
3300 Coffey Lane, Santa Rosa, CA 95403 Tel (707) 573-6700 / 866-433-7724 Fax (707) 573-6748 email: solutions@depsci.com of joules of energy. To achieve gain-saturated 8.8 nm lasing from a 1-to-2-mm-thick solid nickel-like lanthanum (La) target, the researchers pumped in only 7.5 J of optical energy.

The pump setup consists of two pulses from an 800 nm Ti:sapphire laser (see figure). The first normal-incidence prepulse has a 6×10^{12} W/cm^2 intensity with 210 ps full-width half-maximum (FWHM) duration and creates a 30 μm × 6.4 mm line focus via spherical and cylindrical lenses. This prepulse rapidly heats the plasma, resulting in a significant percentage of ions in the Ni-like state (La^{+29}). After the plasma expands, a second 4 J, 6×10^{14} W/cm^2 pulse with 3 ps FWHM duration is delivered at a grazing-incidence angle of 35°, heating the plasma to an electron temperature of approximately 850 eV and efficiently exciting ions to the laser's upper level. This angle of incidence, along with focusing elements to maintain a uniform 30 μm × 6.4 mm line focus, allows refraction to efficiently couple the pump-beam energy into the plasma and maximize x-ray emission.



The experimental setup and corresponding spectrum is shown for an 8.8 nm soft-x-ray laser that operates at 1 Hz with low pump energy. (*Courtesy of Colorado State University*)

To overcome the mismatch between the propagation velocities of the pump pulse and the amplified pulse, which normally limits the output, a five-mirror-segment reflection echelon was used to obtain quasi-traveling-wave excitation, significantly improving the laser output.

Measurements at the 1 Hz repetition rate were made by moving the La target at a rate of 200 μm/s to renew the surface after each laser shot. Operation of the soft-x-ray laser source at 8.85 nm reaches gain saturation with approximately 2.7 μJ of pulse energy, a gain coefficient of 33 cm^{-1}, and a gain-length product of 14.6.

Even shorter wavelengths

By reducing the duration of the main pump pulse to just 1.1 ps, the research team also demonstrated lasing at 7.36 nm in nickel-like samarium. As diode-pumped optical laser sources continue to improve, so too will sub-10-nm tabletop x-ray laser sources, which are instrumental in enabling such applications as sequential imaging of ultrafast nanoscale dynamic phenomena.

"These soft x-ray laser sources have the potential to enable tabletop-scale applications that require high pulse energy such as high-density plasma diagnostics or high average power such as nanoscale imaging and nanoscale dynamics studies," says David Alessi, a postdoctoral researcher at Lawrence Livermore National Laboratory (Livermore, CA), formerly in Jorge Rocca's group at the NSF EUV ERC. "The NSF EUV ERC will continue research and development of sub-10-nm soft x-ray lasers with the goals of improving their spatial and temporal characteristics and increasing their pulse energy." —*Gail Overton*

REFERENCE

1. D. Alessi et al., *Phys. Rev. X*, 1, 2, 021023 (Sept. 27, 2011).

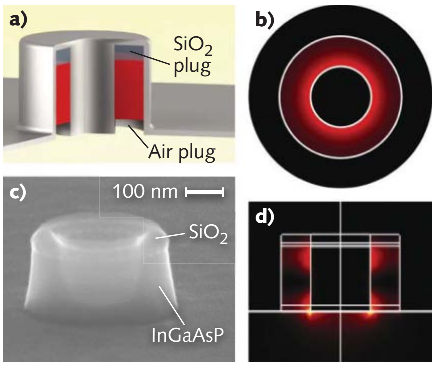
NANOPHOTONICS

Coaxial nanolasers have no threshold

Researchers have unveiled the smallest room-temperature CW lasers operating at telecommunications wavelengths ever produced—and they operate with practically no lasing threshold. The work has implications for on-chip optical communication and, if integrated into silicon-compatible platforms, for far-wider implementation in telecommunications.

Experts at the University of California–San Diego (UCSD) set out to get closer to the "ultimate nanolaser"—scalable, low-threshold, efficient, room-temperature, and of course nanometer-scale. They argue that the best examples of nanolasers so far fall down principally on the matter of threshold.[1]

"For subwavelength cavities, the metal loss dominates other sources of loss, such as scattering that is by itself higher in smaller lasers due to higher surface-to-volume ratios," says UCSD's Mercedeh Khajavikhan. "As a result, the pump power required to achieve lasing typically becomes prohibitively high. Because of the high metal loss, most previous nanolaser designs use metals merely to confine light in structures essentially similar to the conventional nonsubwavelength lasers, avoiding the concentration of fields near the metal. Our goal was to implement a structure that provides a scalable approach to laser miniaturization."



Diagrams reveal the construction (a) and mode structure (b and d) within the coaxial nanolasers; a scanning-electron micrograph shows the actual nanolaser (c). (*Courtesy of M. Khajavikhan*)

Khajavikhan explains that the UCSD group chose an approach different from any other demonstrated approaches for small lasers, using nanoscale coaxial-shaped cavities well known to electrical engineers and widely used as transmission lines in the microwave regime. What makes the coaxial cavities fit for the purpose is that such structures support a transverse electromagnetic mode no matter how small they get, which Khajavikhan says "makes them an ideal choice for deeply subwavelength lasers."

The team fabricated a number of the 100 and 175 nm laser cavities, each of which had a metallic rod at its center surrounded by rings of air, indium gallium arsenide phosphide, and silica, with the whole assembly then coated with a silver/aluminum alloy. The air and silica "plugs" serve to enforce world news

mode confinement. The lasers were then optically pumped using a commercial 1064 nm laser.

The nanoscale design achieves two things. The cavity quantum electrodynamic effects that come into play at those sizes coupled any spontaneous emission directly into the lasing mode. What's more, the transverse electromagnetic mode that defined the lasing was nearly 15 times smaller than the wavelength of the emitted light.

The output modes at 1260 nm and 1590 nm were imaged, showing their TEM character, and the devices were shown to couple as much as 99% of spontaneous emission into the lasing mode.

The team is well aware of the many implications of such threshold-free lasers—so work is already underway to implement electrical rather than optical pumping. "Realizing the revolutionary potential of these devices, our ambition goes beyond achieving electrical pumping," Khajavikhan says.

Applications that would follow include on-chip optical routing with significantly fewer limitations. "Because of their lack of threshold, these devices can be modulated rapidly, and thus can become a backbone for future telecommunication devices," notes Khajavikhan.

The team also envisions an array of phase-controlled nanolasers arranged to form a microlaser whose beam can be arbitrarily shaped, or putting the lasers to use in high-throughput sensing and spectroscopy systems. Shaya Fainman, senior author of the paper, says, "We feel this is just a beginning of a new family of light emitters with superior characteristics, and many advances in this new area are yet to come." —*Jason Palmer*

REFERENCE

1. M. Khajavikhan et al., *Nature* (2012); doi:10.1038/nature10840.

CORRECTION

The January 2012 World News story "DIAL in the Alps measures tropospheric water vapor," written by senior editor John Wallace, features updated and corrected data regarding the differential-absorption lidar (DIAL) system specifications and capabilities from InnoLas. Readers can visit the article page directly to view the updated version at http://bit.ly/ylnwnq.

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BusinessForum

Keep on growing

MILTON CHANG

This month's format is a little different than our typical Q&A session.

I was flattered when Conard Holton asked me to give the keynote at the Lasers & Photonics Marketplace Seminar at Photonics West. Given that the meeting was to be attended by 125 company executives, I picked business growth as a topic. I will summarize the first part of the speech here; you can view the entire video at www.laserfocusworld.com.

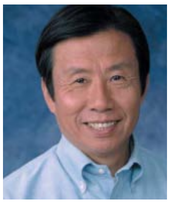
The first part of the talk centered on how a company could be managed for healthier growth, and the second part was on how we as a group can change the environment in which photonics companies operate. In my introduction, I noted the photonics industry lacks resources because most of the profits derived from photonics technology are made by companies that do not consider themselves as part of the photonics industry. Most of these companies contribute little to the betterment of our industry because we do not provide them with reasons to feel they have a vested interest.

I will cover the first part of the talk in this column and reserve the second part for the next issue. Since I have only a week or so between when this column is published and the next one is due, I urge you to write to me with your thoughts immediately so I can have the benefit of your wisdom. I first made the point that a company must grow, or it will wither over time. It would be deprived of resources to grow because investors would shun the company, and star performers would also leave to seek challenges and growth opportunities elsewhere and leave the company for people who "need a job."

Conceptually, the inability to grow is a self-fulfilling prophecy. I substantiated this claim by citing a recent *Wall Street Journal* story (Jan. 13, 2012) about Milliken & Co., a textile company in South Carolina that makes specialty fabrics such as for duct tape. The company was having its best economic performance ever because of its willingness to change. As most of us know, the textile industry has been on the decline for decades with competition coming from all parts of the world. The good news here is the photonics industry has abundantly more opportunity than the textile industry! I am not saying growth is easy, but for sure a company will stop growing if its leadership fails to seize growth opportunities. This usually occurs not because there is a lack of opportunity, but rather because everyone would stop trying, overwhelmed by reasoning out why the company cannot grow. Those who believe opportunities exist and look for them persistently may just find their next strategy.

In my book, *Toward Entrepreneurship,* I describe ways in which a company can streamline its operation and develop an organizational strategy to position itself for growth, and also how a company can systematically prospect for growth opportunities. In the speech I only covered the organizational aspect and referred the audience to get the rest from my book.

What has proven to work is to create a self-actualized organization based on Abraham Maslow's hierarchy of needs. The premise is that everyone wants to self-actualize, "be all that we can be" even though our capabilities, goals, and aspirations are all different. And if the interests of the company and the individual's need to self-actualize can be aligned, then everyone would feel they were working for themselves and naturally assume the responsibility to grow the business because it is in his or her best interest. Theoretically, then, all the company has to do is to hire capable people with good attitudes and provide them with the environment, resources, training, and guidance, and turn them loose for them to do their best. How can the company not succeed if everyone would—on their own—take on increasingly more responsibility to grow the business?...to be continued.



MILTON CHANG of Incubic Management was president of Newport and New Focus. He is currently director of Precision Photonics, mBio, and Aurrion; a trustee of Caltech; a member of the SEC Advisory Committee on Small and Emerging Companies; and serves on advisory boards and mentors entrepreneurs. Chang is a Fellow of IEEE, OSA, and LIA. Direct your business, management, and career questions to him at miltonchang@incubic.com, and check out his book *Toward Entrepreneurship* at www.miltonchang.com.

QI offers next-generation AFM imaging mode for nanometrology

HEIKO HASCHKE and **TORSTEN JÄHNKE**

A new atomic-force microscopy (AFM) quantitative imaging (QI) mode is not a product, but a new methodology that makes it easier to image difficult samples without the need for set-point or gain adjustment while scanning.

There are many challenges in applying atomic-force microscopy (AFM) to the high-resolution requirements of the modern user. No longer does the original AFM contact imaging mode developed 25 years ago provide the ability to produce images of samples in liquids without damaging the sample. While a variety of so-called noncontact methods have been introduced, they still cannot meet the requirements of researchers in the life sciences where samples are soft and delicate, requiring care in preparation and imaging in a quantitative manner. This user need has directed the developments of JPK Instruments and has led to a new quantitative imaging (QI) mode.

From the beginning of QI development, the design goals were clear: In order for life scientists more familiar with light microscopy operation to accept AFM and its new imaging modes, it was necessary to design a system with quick and intuitive processes that could be used in various environments such as air or liquid. The mode needed to handle "difficult" samples that are soft and/or sticky, perhaps loosely attached to the mounting substrate, or that have particularly sharp features/edges. This meant that the new nanometrology mode should provide extremely precise control of the force of the probe as it interacts with the sample at every imaging pixel.

New imaging modes must also provide quantitative data, and the QI mode offers mechanical, chemical, and electrical data. In addition, the quantitative provision of real-force curves while imaging delivers the maximum amount of data points. The area of cell adhesion, or the measurement of forces between a single molecule and another (or a surface), are rapidly growing application needs when using AFM in the life sciences.

Defining QI

The new QI, which is compatible with standard cantilevers, is a force-curve-based imaging mode where the user has full control over the tip-sample force at every pixel of the image, meaning there is no need for set-point or gain adjustment while scanning. Its tip movement algorithm—TipSaver—prevents lateral forces and controls vertical forces, making nondestructive measurements for cantilever tip and sample possible.

Coupled with ForceWatch technology, imaging problems with soft (hydrogels or biomolecules), sticky (polymers or bacteria), loosely attached samples (nanotubes or virus particles in fluid) or samples with steep edges (powders, MEMS structures) are removed. Essentially, ForceWatch uses a set of algorithms that closely monitor the

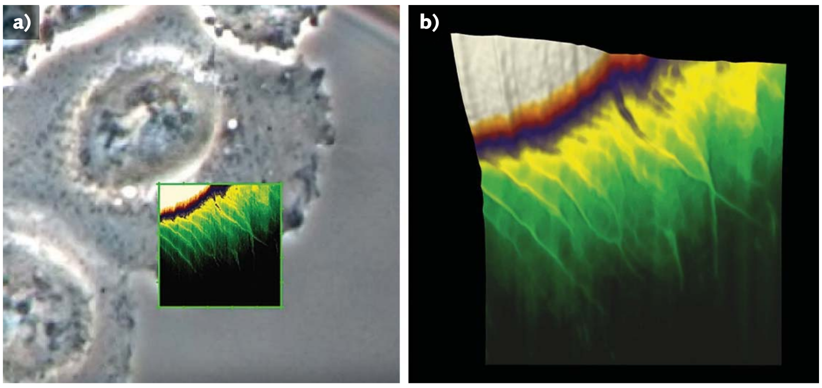


FIGURE 1. Living Chinese hamster ovary (CHO) cells are measured with a closed-loop quantitative imaging (QI) AFM scanning system in a Petri dish heater at 37°C in buffer solution. The optical phase contrast image is overlaid with the AFM height image (a), and a 3D topography image shows a scan with an area of 25 μm^2 (b). The *z*-range giving the height information is 3.6 μm.

feedback signal and make very rapid adjustments as signal changes are observed.

The QI mode is particularly useful in areas that demand both high resolution and force sensitivity such as in biology, and in polymer and surface science where samples have challenging physical parameters.

The only parameters that need to be set prior to imaging are the imaging force and the *z*-length for the acquired force curve per imaging pixel. Both parameters are intuitive and do not require detailed technical knowledge. In addition, both are measured precisely by ForceWatch and our capacitive sensor technology. Complex determination of driving frequencies and voltages with sweeps, amplitude setting, and phase corrections before imaging are obsolete.

There is no feedback loop in QI; therefore, no parameters will have to be set or optimized during imaging. Additional feedback loops such as phaselocked loop (PLL) or amplitude gain control (AGC) are unnecessary. This lack of feedback loops leads to absolutely independent imaging pixels, eliminating streaks caused by just one improper imaging point.

Piezo motion normal to the sample plane (*z*-axis) has been carefully optimized in QI in order to achieve comparable imaging speeds to all other AFM imaging modes. This optimization in the *z* direction was required to perform the force curves with reliable approach and retract rates essential for quantitative analysis, such as those required for indentation or adhesion applications.

Most important for the life sciences user, QI can be combined with all common optical imaging techniques such as high-numerical-aperture confocal laser scanning microscopy (CLSM) by using JPK's DirectOverlay approach that combines AFM and optical microscopy. It utilizes special optical calibration and import routines, and displays AFM simultaneously with optical microscopy information from the sample. Interesting locations on the sample can be identified with a wide variety of contrast methods, such as optical phase contrast, differential interference contrast (DIC), or variable relief contrast (VAREL).

In addition, the use of fluorescence techniques such as epi-fluorescence, confocal, or total internal reflection fluorescence (TIRF) microscopy provides insight into the behavior or location of particular molecules or species. Combining AFM imaging or force measurements with these optical methods on the same spot at the same time is not straightforward. The optical image acquisition is independent from the AFM image recording, meaning a tip-scanning AFM design is critical to this application and underscored through the optimal

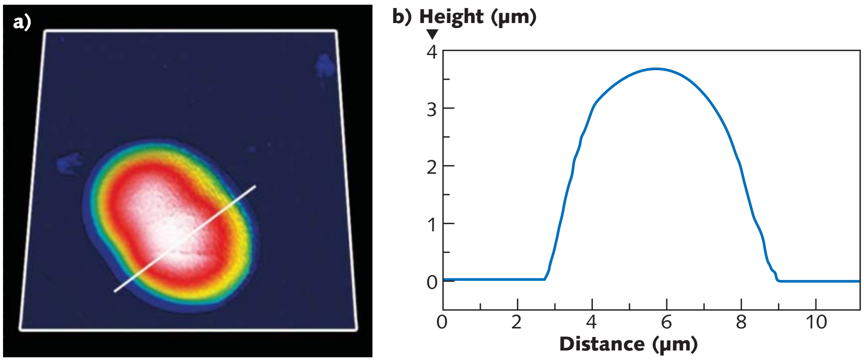


FIGURE 2. a) A 3D topography image of living cyanobacterium measured in buffer solution is shown with a linescan to measure the height of the bacterium indicated. The scan size is 10 µm^2 with a *z*-range of 4.8 µm, all in closed-loop. b) A cross-section of the bacterium is shown with a height of nearly 4 µm.

use of closed-loop imaging in the lateral direction (x, y) using capacitive sensors.

Quantifying difficult samples

During QI imaging there are no lateral forces applied to the sample, so imaging of loosely attached objects or even non-immobilized samples (often found in life science applications) is now possible. The force-based nature of QI allows imaging of taller objects with more sticky surfaces compared to conventional AFM imaging modes. Side-to-side rastering of a probe can sometimes damage or move the surface of such samples. This contrasts with a force-curve measurement that moves the probe up and down vertically, without dragging through the surface.

The QI multiscan feature allows unattended scanning of even centimeter-sized surface areas. This enables much larger areas to be scanned (hundreds of microns), improving the ability to locate, zoom in, and study specific "small" features on the nanometer scale since full data sets of force curves are stored for post-experiment processing by the user.

To give users a choice of capabilities, there is also a QI advanced software package that enables high-spatial-resolution quantitative measurement of nanoscale material properties such as stiffness, adhesion, dissipation, and more. It provides more data channels and features for data extraction and processing to analyze additional sample information. Depending on application, it is also possible to perform electrical conductivity or molecular recognition measurements from a single image.

FIGURE 3. A hexacontane sample is prepared and imaged on highly oriented pyrolytic graphite. The "green" image represents the height while the inlay is measuring the elasticity. The stripes are individual monomolecular layers of hexacontane and correspond to the length of the molecule (7.5 nm). The scan size is 5 μm^2 with the inlay being 300 × 300 nm. The z-height scale is 12 nm while the elasticity shows a range of 2.2 GPa.

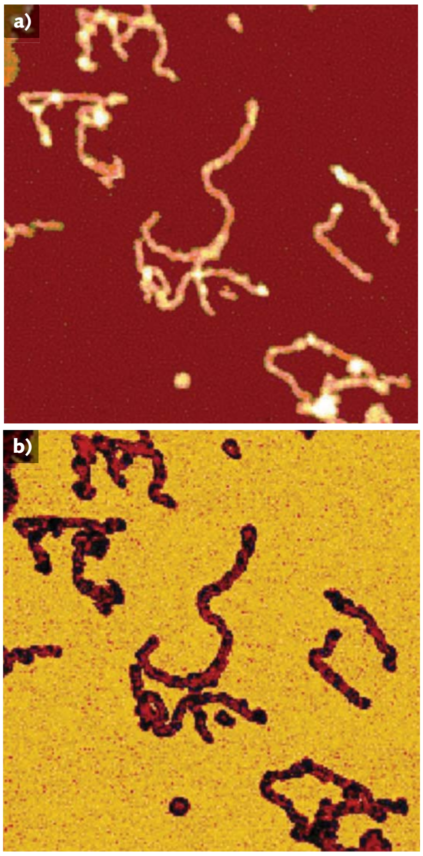


FIGURE 4. A topography image (a) and the elasticity information (b) are shown for a dendronized polymer after being absorbed onto freshly cleaved mica and measured under ambient conditions. The scan size was 500 × 500 nm with a z-range of 6 nm, while the elasticity range was 250 MPa. (*Sample courtesy of Prof A. Dieter Schlüter, ETH, Zurich, Switzerland*)

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Advanced controller systems now allow any signal measured in an experiment to be recorded and stored in parallel. Improvements in electronic components have enabled suppliers to offer a digital controller with extremely low noise levels; for example, JPK's Vortis SPM Control Station uses high-speed lock-in amplifier technology to provide precise amplitude and phase detection to enable sharper, more accurate, quantitative imaging.

And finally, all recorded data channels can be plotted as 3D images and—due to the force-spectroscopy nature of QI—as 3D images at different positions normal to the sample surface. For instance, a topography map of zero-interaction force can be plotted to yield more details on the unperturbed sample surface. For example, in JPK's data processing (DP) software, all data channels with full bandwidth at every imaging point are available for more flexibility. The DP software also offers several analysis algorithms for QI data, such as extracting adhesion values or providing Young's modulus information.

Applications

Using a JPK NanoWizard 3 AFM, living Chinese hamster ovary (CHO) cells in HEPES buffer (an organic chemical buffering agent) at zero imaging force were imaged for the first time (see Fig. 1). These images give new insights into the exact cell topography because the independence of every data point removes any scanning artifacts. This QI method was also used to image living and nonimmobilized cyanobacteria, which have also been acquired with zero imaging force in buffer solution (see Fig. 2). The absence of forces gives the precise topography without any image distortion.

Using the advanced version of QI mode, the elastic moduli as well as topographical information of $C_{60}H_{122}$ hexacontane molecules can be determined (see Fig. 3). During the adsorption process of hexacontane onto graphite, the individual molecules (approximately 7.5 nm long) align side by side to form long strips of molecules. Not only can these strips be

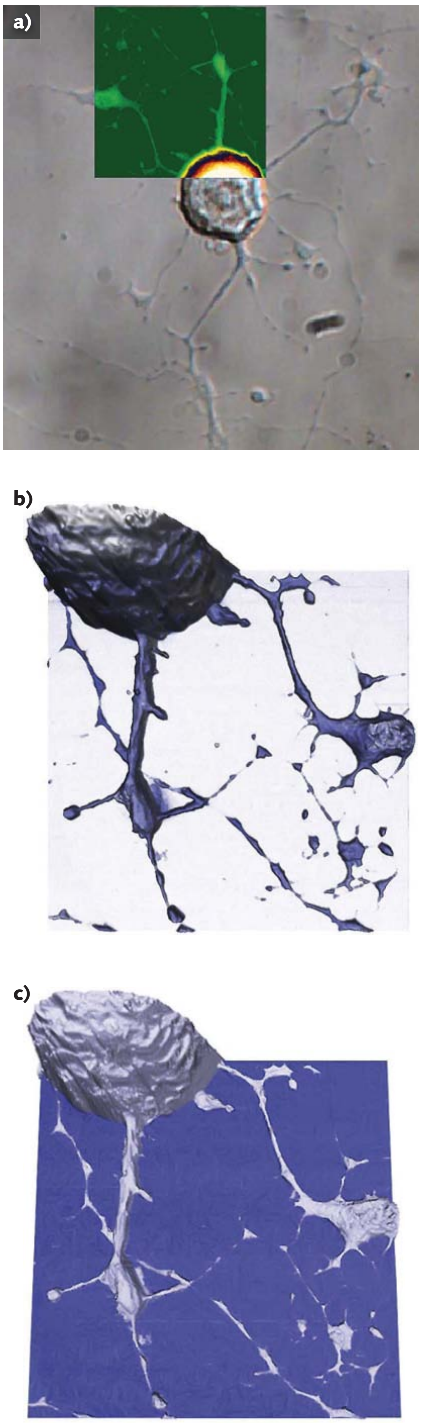

FIGURE 5. A living dorsal root ganglion is imaged in buffer, showing the differential interference contrast (DIC) view of the sample with the overlaid AFM height image (a). Also shown is the 3D topography image overlaid with adhesion data (b) and overlaid with the elasticity image (c). The scan size was 40 μm^2, with a *z*-range of 10 μm. The adhesion range is 600 pN, while the elasticity is 100 kPa imaged in closed-loop.

resolved, but also the difference of elastic moduli of 1.2 GPa between one single molecule and the end groups lining up with the end groups of the next row can be recorded.

In the study of single molecules, QI allows imaging of isolated individual molecules such as dendronized polymer chains—polymers with a polystyrene backbone and dendritic side chains. Overlapping of single molecules as well as twisting is clearly resolved in topography images (see Fig. 4).

An experiment with living dorsal root ganglion cells using QI in conjunction with DIC showed adhesion variations on an individual cell of several hundreds of piconewtons (see Fig. 5). This adhesion data is reliable due to the aforementioned optimized piezo motion normal to the cell surface, in this case ensuring a constant retract rate. Adhesion data can be plotted on top of a 3D topographical image with the DIC image in the background so that the scientist can conveniently and reliably correlate the adhesion data with topographical or optical contrasts.

Looking ahead, it is expected that QI will become a vital tool for the life-science microscopist in making rapid, quantitative, and accurate nanometrology measurements.

Heiko Haschke is head of applications and **Torsten Jähnke** is founder and chief technology officer of JPK Instruments AG, Bouchéstrasse 12, 12435 Berlin, Germany; e-mail: haschke@jpk.com; www.jpk.com.

Turbulent surveillance—or how to see a Kalashnikov from a safe distance

GLEB VDOVIN, MIKHAIL LOKTEV, and **OLEG SOLOVIEV**

No single technology solves the problem of imaging through turbulent atmosphere, but combining adaptive optics, real-time adaptation of system parameters, multiplexed imaging, and real-time processing provides an approach for improving results.

Long-range surveillance has numerous military, security, and navigation applications. One example from current news: It is critically important to distinguish a Kalashnikov assault rifle from a paddle in the hands of a suspected pirate, when the potential danger is still far away.

At first glance, the problem can be easily solved. Indeed, physics tells us that we should see a 1 mm mosquito at a 1 km distance with a 50 cm telescope. Although a bit bulky, such an optic is not rare even among amateur astronomers. However, a practical experiment would disappoint: The insect will remain invisible for any size of the instrument. Moreover, quite frequently, a much larger object—an apple, a firearm, or a human face—will remain unrecognizable at a long distance.

The resolution is limited by the air turbulence. According to the Kolmogorov turbulence model, solar radiation is absorbed over large areas, creating large-scale hot air movements. These movements scatter to some smaller-scale eddies and vortices, and the process scales down until the temperature differences are finally equalized in the so-called inner scale of turbulence.

The refraction in air depends on the temperature, so randomly changing distribution of the refraction index in the turbulence is optically seen as a blurry veil, preventing sharp imaging. Since most heat exchange happens near the ground, the strongest optical turbulence is observed in the boundary layer, just several meters over the ground, with even stronger turbulence over the areas that are subject to direct sunlight.

It is quite common to characterize imaging through turbulence with a single parameter, r_0. This parameter is defined by the largest aperture size that still provides near-diffraction limited imaging in the turbulent conditions. In astronomy, when observation is conducted through a relatively thin turbulent layer from the surface up through the atmosphere, the usual value of r_0 is in the range from 5 to 50 cm. However, horizontal imaging on a sunny day can easily result in r_0 of several millimeters, even for relatively short observation distances on the order of 1 km.

In a typical horizontal imaging scenario, both the optical aperture and the object size are usually much larger than the r_0 (see Fig. 1). The light bundles emitted by different object points go through different volumes of turbulence, resulting in statistically uncorrelated phase distortions for different object points, also called anisoplanatism.[1] The distortions are correlated within a small isoplanatic angle, that has the order of magnitude of r_0/L where L is the distance to the object, and the area of isoplanatic imaging, with the dimension of $\sim r_0$ called isoplanatic patch.

In the close vicinity to the aperture, all ray bundles pass through the

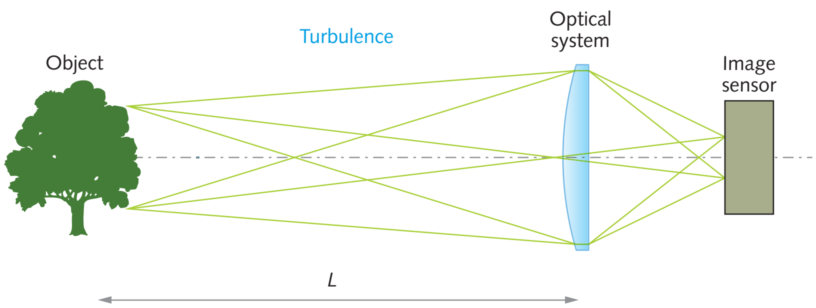

FIGURE 1. When imaging through horizontal turbulence, light bundles emitted by different object points go through different volumes of turbulence, resulting in statistically uncorrelated phase distortions for different object points.

same turbulence and the wavefront distortions introduced in this volume can be considered isoplanatic. To complicate the situation even further, not all wavefront distortions created by the turbulence reach the aperture. In the far field, the isoplanatic patch is not resolved by the optic, and the turbulence introduces geometric distortions and warps in the otherwise sharp image.

Correcting for aberrations

Adaptive optics (AO) is the first choice technology for correction of dynamic optical aberrations. It can be directly applied to the isoplanatic aberrations, introduced in the optical system itself, and in the close vicinity to the aperture, where the turbulence is still isoplanatic.

There are two ways to control the AO system: phase conjugation and optimization. Phase conjugation needs a bright point-like source for wavefront measurements. In astronomy this purpose is served by a natural or an artificial guidestar. Unfortunately, in horizontal imaging, there are very few scenarios when the object provides optical point-like reference to the observer. The problem of reference can be solved by correlation tracking of the chosen object feature; however, for correct sensing, the size of the feature should be smaller than the isoplanatic patch and the isoplanatic patch should be resolved by the optical system. This condition limits the number of usable scenarios.

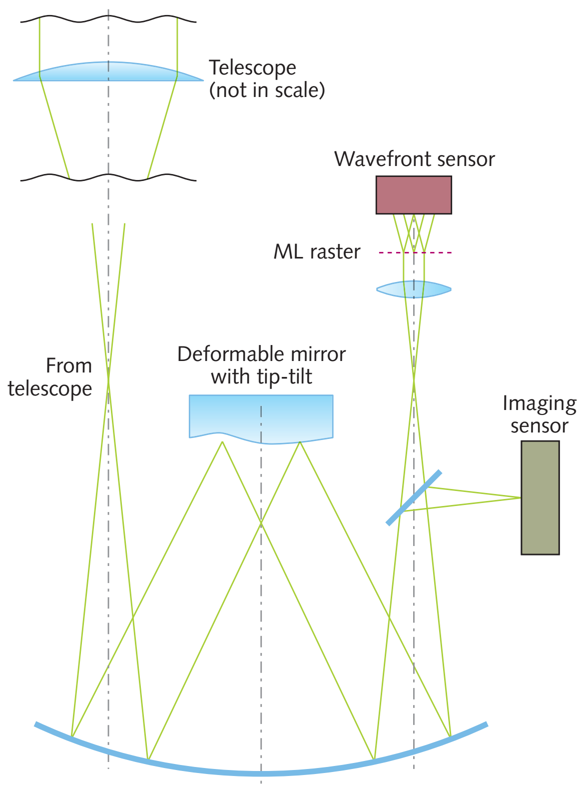

FIGURE 2. A portable AO system has been designed to correct the turbulence on a small telescope, usable for horizontal imaging.

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As an alternative, optimization relies on real-time trial and error search for the shape of the wavefront corrector that maximizes the quality metrics in the image; for example, the image sharpness. Although it does not need any specific reference, the real-time optimization requires a very fast wavefront control to be coupled to a very fast registration of the probe images—tens of thousands of frames per second is not the limit. Since the camera frame rate is limited by its sensitivity and the available light, the applicability of real-time optimization is mostly restricted to some special situations with very bright sources.

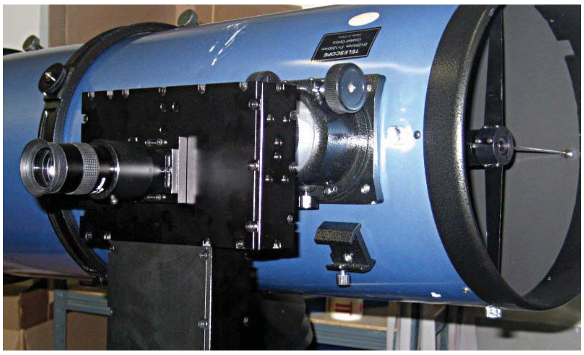

FIGURE 3. Portable OKO adaptive optics attachment for horizontal imaging has mounted on a 10 in. telescope.

If the object size is large and the turbulence is strong, the weight of the isoplanatic correctable component will be close to negligible, and the performance of AO can be found insufficient to justify its extra complexity. The AO performance can be improved by correcting only the wavefronts emitted by a single point of the object, realizing so-called "foveated" imaging (the fovea is the part of the retina that provides the sharpest image).

Generally speaking, foveated AO correction amplifies the aberration and fuzziness of the remaining image outside the isoplanatic patch. Furthermore, the size of the isoplanatic patch can be smaller than the resolution limit of the optical system, making the AO correction essentially useless.

In theory, the problem of a wide-field AO can be solved by a multiconjugate (volume) corrector with the refraction index volumetric distribution conjugated to that of the atmosphere. However, at the present time, the authors have no information about the existence of such a corrector. Even if it exists, control of volumetric phase represents an enormous technical problem.

System design

The optical scheme of a portable AO system that has been designed to correct the turbulence on a small telescope is shown in Fig. 2. An achromatic mirror system based on a modified Offner configuration re-images the telescope pupil to the OKO deformable mirror, specially designed to correct for atmospheric turbulence. The mirror combines the ability to correct all Zernike terms up to the third order, with an integrated tip-tilt stage to compensate for image shifts.

The complete unit, mounted on a 10 in. Newton, can be operated with an integrated Hartmann-Shack wavefront sensor controlled by the OKO FrontSurfer software either in the phase conjugation mode or in the optimization mode based on the real-time optimization of the image quality (see Fig. 3).

Since the applicability of AO for wide-field correction of atmospheric turbulence is limited—and in some cases impossible—other methods of enhanced atmospheric imaging are of a great interest. An alternative approach would be based on the computer processing of a number of images, obtained through uncorrelated turbulence realizations. The effect of turbulence can be mitigated by determining the difference between the unchanged object and changing turbulence.

To achieve uncorrelated input data, the observation should be done through different realizations of the turbulent atmosphere, by introducing delays between frames, or by splitting the pupil of the optical system to create multiple images through different turbulent paths.[2] Since a number of images are registered simultaneously, the system with multiplexed pupil allows for real-time imaging of moving objects, while the single-pupil time-multiplexed imaging introduces pipeline delay and cannot deal with moving objects. Figure 4 shows different implementations of the multiaperture system:

The direct solution (a) is represented by a number of identical optical systems.

A multiplexed pupil (b) features a microlens raster positioned in the pupil image for splitting the image field into a number of independent images obtained through different turbulent paths.

A plenoptic optical system (c) enables images through different turbulent paths to be obtained from the four-dimensional light field registered by the sensor.

In all cases, the size of the subaperture should be kept comparable to r_0 and follow the changing turbulence. This can be achieved by using zoom lenses in configurations a and c, and by changing the microlens arrays in the pupil plane for configuration b.

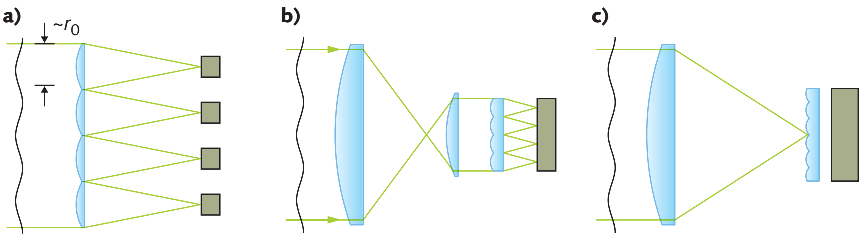

FIGURE 4. Three different configurations for multiaperture imaging are possible: a) a direct solution, represented by a number of identical optical systems; b) a multiplexed pupil, with a microlens raster positioned in the pupil image, for splitting the image field into a number of independent images obtained through different turbulent paths; and c) a plenoptic optical system in which images through different turbulent paths can be obtained from the 4D light field registered by the sensor.

ADAPTIVE OPTICS
continued

Multiframe processing methods are numerous and include variants of multiframe selective image fusion[3], applicable to the image distortions and warps in the far field, and deconvolution methods, applicable to the phase distortions. Deconvolution methods include blind deconvolution, deconvolution from the wavefront sensing, the Knox-Thompson method, bispectrum imaging, and variations of speckle imaging including methods based on projection on convex sets.[4] Regardless of the method, the optical system for multiframe processing should meet the following conditions:

The input pupil should be in the range of 1 . . . 5 r_0. This range provides relatively high probability of obtaining a lucky image[5], realizing optimal resolu-

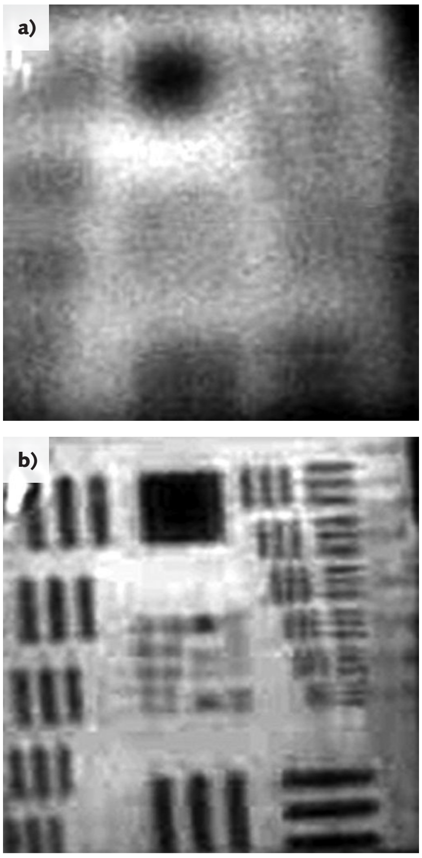

FIGURE 5. USAF resolution chart observed at a 2 km distance is used to illustrate the resolution gain obtained by combining adaptive optics and multiplexed imaging in an experiment through conditions of medium turbulence: Raw image (a) and image reconstructed using multiframe processing based on the projections on convex sets (b).

tion of the system including the aperture and the turbulence.

A number of uncorrelated images should be collected to mitigate the turbulence effects by multiframe processing. Either temporal or spatial multiplexing can be used to obtain these images.

In practice, with a small aperture the observable size of the isoplanatic patch can be much larger than predicted by the theory, because by limiting the aperture we also limit the maximum phase difference between any two aberrations produced by different object points.

If the sensor has a fixed pixel size, the system aperture and focal length should change adaptively in proportion with the turbulence scale r_0.

Synthetic approach

Although stronger turbulence would result in somewhat less detailed images, adaptation will keep the resolution of the system in the quasi-optimal range for the present conditions. Figure 5 illustrates the resolution gain obtained with the combination of adaptive optics and multiplexed imaging in an experiment through conditions of medium turbulence on a 2 km horizontal optical path.

We can conclude that no single technology solves the problem of horizontal imaging through atmospheric turbulence. A synthetic approach combining adaptive optics; real-time adaptation of the system parameters, such as the pupil size and the focal length; multiplexed imaging; and digital real-time processing solves the problem to some extent.

With this approach, significant improvements can be achieved in terms of a higher probability of obtaining a good image at a given moment of time, but no method can guarantee that a perfect image will be obtained at any time, especially when the turbulence is strong. There is considerable room for development and improvement in any of these directions. ◀

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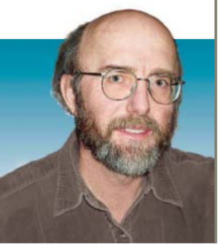

Ultrafast lasers make ultraprecise tools

JEFF HECHT contributing editor

By ablating small amounts of material at a time, picosecond and femtosecond lasers can cleanly machine brittle glasses and ceramics, as well as performing other delicate operations—including surgery—without damaging underlying material.

Improved technology has helped ultrafast lasers move beyond the laboratory into the worlds of industry and medicine, where they can perform precise and delicate operations. Their success comes from their ability to concentrate light energy into an interval of picoseconds to femtoseconds, and focus that light onto a small volume of space. That concentration provides the high intensity needed to ablate material from the surface quickly and cleanly, without damaging the underlying areas.

This combination of precision and delicacy is invaluable for applications such as machining brittle materials like glass or ceramics, or making clean holes in hard metals like turbine blades. It also has earned ultrafast lasers a niche in medicine, both for fabricating delicate biomedical devices, such as the stents used in coronary bypass surgery, and in performing sensitive medical procedures such as corneal surgery.

Laser-material interactions

Power intensity and pulse duration are key factors influencing how laser beams interact with materials. Over long time scales, a material absorbs a fraction of the light energy, converting it into heat, which can be conducted through the material. If the beam is powerful enough, it melts the material, and the molten material conducts heat to surrounding areas. Absorption, melting, and heat conduction dominate for time scales as short as nanoseconds.

Things change significantly when the pulse energy is delivered on time scales shorter than about 100 ps, with the transition depending on the material. As the peak power of the pulse rises, the peak intensity rises sharply. For example, microjoule pulses lasting 1 ps have a peak power of 1 MW and—when focused to a 5 μm spot, can produce peak intensities of about 4×10^{12} W/cm^2, enough to rip off the outer-shell electrons. The interactions are so fast that the ions are ablated from the surface before they can transfer energy to the underlying material. Energy transfer in this ablative mode depends less on material absorption than at lower intensities, but does vary among materials and with laser wavelength. For example, ultraviolet pulses cut transparent materials like glass better than near-infrared pulses, which glass transmits better.

The result is sometimes called "cold ablation." Although the surface briefly becomes very hot, the ions are ablated before they can heat or damage the underlying layers, as shown in Fig. 1. Thus picosecond or femtosecond pulses can remove very thin layers from delicate or fragile materials without damage. Polish researchers

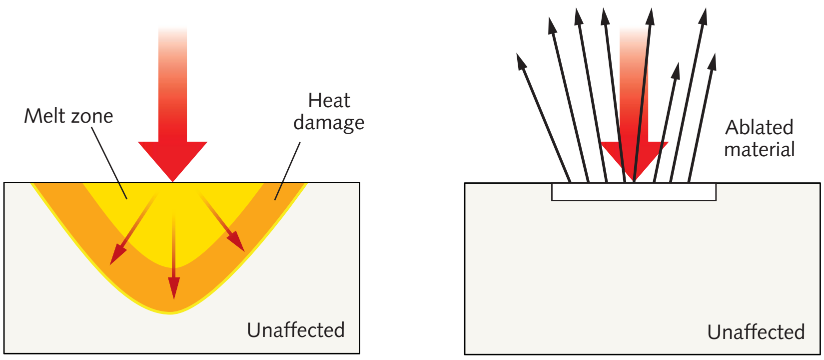

FIGURE 1. Effects of nanosecond pulses and femtosecond pulses are compared. The nanosecond pulse at left melts surface material before ablation, transferring heat to adjacent areas, which alters many materials. Femtosecond pulse at right ablates material by multiphoton ionization, with very little heat transfer to adjacent material.

have used 70 ps pulses with intensity just above the ablation threshold to remove transparent varnish from oil paintings, using optical coherence tomography to monitor removal.[1] Picosecond lasers can write patterns onto the head of a match without igniting it, says Joyce Kilmer of Photonics Industries (Bohemia, NY).

In general, picosecond ablation tends to be faster because the pulses usually carry more energy, but femtosecond ablation tends to produce smoother, more precise surfaces. The actual performance depends on pulse parameters, target material, and other considerations. Repetition rate is important because ablation blasts a plume of material into the path of the beam. Megahertz repetition rates may not leave enough time for the plume from one pulse to dissipate before the next one is fired. Kilohertz repetition rates allow time for that material to dissipate, so they may be more effective in removing material precisely.

Ablation thresholds in J/cm^2 for metals, semiconductors, and dielectrics*

Material	Fiber laser	Ti:sapphire
Copper	0.47	0.37
Aluminum	0.071	0.085
Titanium	0.12	0.1
Tin	0.058	0.057
Stainless steel	0.087	0.063
Indium phosphide	0.05	0.038
Gallium phosphide	0.053	0.04
Germanium	0.08	0.075
Silicon	0.12	0.1
Sapphire	1.9	1.9
Fused silica	2.9	3.6

*For 200 kHz, 350 fs pulses from a 1045 nm, Yb-fiber laser (middle column) and for 1 kHz, 150 fs pulses from a 780 nm Ti:sapphire laser (right column). (Data from Reference 5)

Materials working

The cold ablation process can be used for a wide range of materials, including metals, semiconductors, glasses, crystals, and ceramics. Typical thresholds for cold ablation range from 0.05 to 5 J/cm^2, as shown in the table for femtosecond pulses from ytterbium-fiber and Ti:sapphire lasers.[2]

Ultrashort pulses are particularly attractive for cutting or machining brittle materials, including glass, ceramics, silicon, and CIGS (copper-indium-gallium selenide, used in thin-film solar cells). The ablation process avoids cracks when drilling holes or cutting glass, producing sharp, clean edges and surfaces, as shown in Fig. 2. Thin glass plates used in liquid-crystal displays or on cell phones can be cut to shape by mechanically stressing them along a series of cold-ablation laser-drilled holes. Because ablation is a nonlinear process with a high threshold, pulses that are focused so laser power exceeds the ablation threshold only at the center of the focal spot can drill holes smaller than the diffraction limit.

Process dynamics can be complex for thin films, such as silica on silicon. Instead of ablating silica from the top down, picosecond pulses penetrate the transparent silica to melt the silicon, then evaporate enough of the melt to lift the thin film up from the substrate, reported Sonja Hermann of the Institute for Solar Energy Research Hameln (Emmerthal, Germany) and colleagues. Thus the threshold depends on the SiO_2 thickness.[3]

Picosecond pulses focused with high-numerical-aperture optics can etch features inside glass or other transparent materials without affecting the surface, because power density is much higher at the focus spot. For example, Benye Li of the Beijing Institute of Technology (Beijing, China) and colleagues wrote a long-period fiber Bragg grating across the core of a singlemode fiber with 35 fs pulses from a Ti:sapphire laser.[4] The grating produced 20 dB attenuation in the 1465–1575 nm band. By inducing birefringence in fused silica waveguides inside bulk glass, Luís Fernandes of the University of Toronto (Toronto, ON, Canada) and colleagues made 2-cm-long wavelength-selective directional couplers with extinction ratios to 24 dB. They wrote that the splitters "promise to open new directions for creating polarization-dependent devices in three dimensional optical circuits."[5]

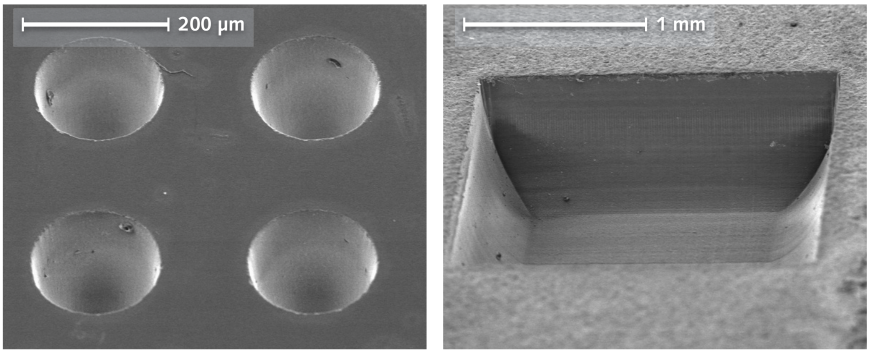

FIGURE 2. Ultrafast pulse micromachining of glass. a) 440 µm holes drilled in glass with 10 µJ pulses at 355 nm. b) 2 mm square area in Pyrex milled with 355 nm pulses. (*Courtesy of Coherent*)

Nanoparticles and nanofibers

Ultrafast lasers also offer a new twist to pulsed laser deposition. Nanosecond laser pulses have been standard for thin-film deposition, but they can splash 10 µm droplets onto the film. When Inam Mirza and James G. Lunney of Trinity College Dublin (Dublin, Ireland) examined the flux that nanosecond pulses produced from silver targets, they found that the ion flux exceeded the deposition rate, indicating some self-sputtering at the surface. However, they found the ion flux produced by femtosecond pulses was only 1% of the deposition rate, indicating that most of the ablated material formed nanoparticles.[6] Other studies show that size of the nanoparticles produced by femtosecond pulses depends on the laser flux, gas environment, and target materials.

Femtosecond pulses easily produce dense tangled masses of silica nanofibers, report Krishnan Venkatakrishnan and colleagues of Ryerson University (Toronto, ON, Canada). Focusing a 12.4 MHz train of 214 fs pulses from a Yb fiber to an intensity of 1.17 J/cm^2 on silicon produced four types of nanofilaments. The largest were hundreds of nanometers in diameter and as long as 10 mm. The finest fibers were tens of nanometers in diameter and stretched to hundreds of microns. However, the tangling makes study difficult.[7]

Medical applications

The ability of ultrafast pulses to cut cleanly without damaging surrounding areas or forming rough edges is vital both for processing medical implants and for delicate surgery.

Smooth surfaces are particularly important in stents, expandable tubes that are inserted into clogged arteries and opened to restore blood flow. The body sometimes reacts to the implant by coating the stent with scar tissue, which can re-clog the artery. Machining stents made of various materials with ultrafast lasers produces surfaces so smooth that they reduce the chance of scar tissue growth.

Femtosecond lasers also have become a standard tool for cutting flaps in the surface of the cornea to expose the interior for LASIK refractive surgery. A major attraction is its ability to cut the flaps more accurately than conventional surgery.

Now ophthalmologists are expanding femtosecond laser techniques to cataract surgery. One goal has been softening the hardened core of the lens that caused the cataract, so it can be removed easily. Another is performing the incisions needed to remove the lens and insert a replacement with minimal damage to other parts of the eye. Three companies are developing femtosecond laser systems for both processes.[8]

Results so far are encouraging. At the American Academy of Ophthalmology meeting in October, William Culbertson of the Bascom Palmer Eye Institute at the University of Miami School of Medicine (Miami, FL) reported that femtosecond laser treatment eased the surgical requirements and reduced ultrasound exposure during lens removal. At the same meeting, Mark Packer of the Oregon Health and Sciences University (Portland, Oregon) reported that the femtosecond laser surgery avoided the loss of critical corneal endothelial cells, which can be damaged in conventional cataract surgery.

Outlook

Ultrafast processing owes much to the industrialization of picosecond and femtosecond lasers so nonspecialists can use them in industrial and medical environments. So far it has been most successful in niche applications, and cost and the rate of material removal remain significant limitations. However, the performance advantages can be compelling for demanding applications, such as stents and delicate eye surgery.

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Lasers inject new life into projection displays

BARRY SILVERSTEIN and **ANDREW KURTZ**

A combination of 2D spatial light modulators and efficient solid-state lasers may enable the long-desired use of laser projection in cinemas.

Ever since lasers were invented more than 50 years ago, cinematography professionals have aspired to use laser light sources to project images. In the early 1960s, visible lasers were used along with galvanometer scanning mirrors for beam steering; this type of setup could project cartoonlike images on a screen with motion that was perceived as continuous due to the persistence of the human eye. These systems typically used gas lasers—often helium-neon, with a red output and less than a watt of optical power.

The situation improved during the 1970s via upgrades in laser powers to tens of watts and the availability of multiple wavelengths from bulky krypton and argon-ion lasers; these lasers required significant electrical power, high-volume water cooling, and substantial maintenance. Along with these new high-power lasers came new laser-safety issues, in which audiences (and, when used outdoors, vehicles such as airplanes) needed protection from the high-brightness beams.

Alternate scanning methods and laser technologies were developed and demonstrated, but the next major milestone was the development of the grating light valve (GLV) by David Bloom at Stanford University in the mid-1990s. The GLV (which was further developed at Silicon Light Machines) diffracts incident laser light on a pixel-by-pixel basis; the diffracted orders are then filtered to distinguish between on- and off-state light. When a linear GLV array is imaged onto a screen and scanned in one direction, a 2D image results.

In the early 2000s, Eastman Kodak developed an alternative device, the grating electromechanical system (GEMS), which advantageously shifts the diffracted orders out of the array direction of the device.[1] Using this device, a high-resolution, full-color imaging system including three linear pixelated modulators, an optical-parametric-oscillator (OPO) laser source, and a galvanometer scanner can project full 2D images (see Fig. 1). While this system provided compelling demonstrations, factors including the high cost of the lasers, the beam-quality requirements, laser speckle, and concern for laser-safety issues prevented commercial success.

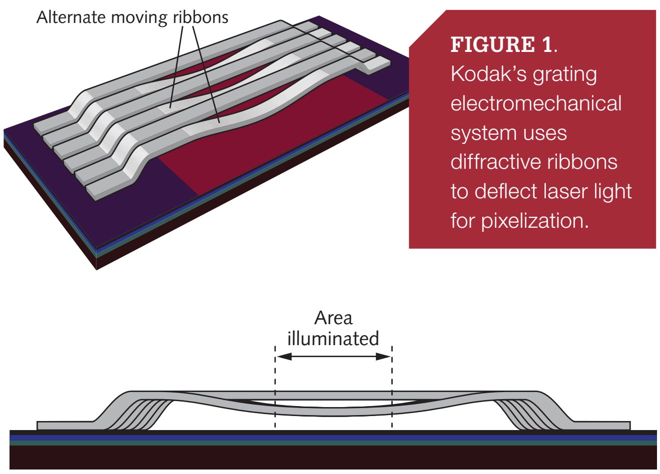

FIGURE 1. Kodak's grating electromechanical system uses diffractive ribbons to deflect laser light for pixelization.

In the meantime, the display industry continued innovating, developing HDTV-resolution flat-panel plasma and liquid-crystal displays (LCDs) to replace cathode-ray tubes (CRTs). Over time these technologies have matured, resulting in improved wall-plug efficiencies, high-brightness LED backlighting, and screen sizes reaching 100 in. diagonals.

In larger venues, film projection remains, but is gradually being replaced by digital projectors, using either liquid crystal on silicon (LCOS) or digital micromirror device (DMD) spatial light modulators (SLMs) having Digital Cinema Initiatives (DCI) studio specification "2K" (2048 × 1080 pixels) or "4K" (4096 × 2160 pixels) resolution. The modulators are illuminated by metal halide lamps or LEDs in lower-brightness noncinema applications and xenon lamps in large venues. These current displays are reliable and of high quality. So where do lasers fit?

Large image, small footprint

We believe that lasers will energize the large-projection-display field. While flat-panel displays meet most needs below sizes of 100 in., there are logistical and cost issues that gain relevance for display sizes larger than a 70 in. diagonal. Among these, the shipping, handling, and installation of such large pieces of glass present a difficult, costly, and labor-intensive operation. While contrast ratios, panel speeds, resolution, and even 3D capabilities have all improved substantially in flat-panel displays, ultimately the need to provide a large image with a smaller footprint presents opportunities.

This has been, for example, the driving force in the new picoprojector category: The ability to carry a 10–50 in. display in your pocket can be highly desirable. It can be expected that as projector size shrinks, energy efficiency (battery longevity) increases, and cost drops, picoprojectors will become more widely used. However, projectors relying on the current set of illumination sources have hit a design wall, which provides the juncture for a transition to lasers.

The most important limitation facing the projection industry is brightness. Displays are rarely too bright. In the cinema realm, where presentation quality is paramount, the environment is controlled; darkness accommodates the limitations of projection brightness as well as eliminates distractions for the viewers. Even in dark theaters, however, existing projectors tend to be too dim, according to many cinematographers and studio professionals. While conventional theaters typically show illumination levels between 11 and 14 foot lamberts (fL) in 2D presentations, many cinema experts would like to see screen-luminance levels exceed 100 fL.

In 3D presentation the situation is even worse, as many theaters struggle to hit 4 fL on their screens due to additional losses associated with 3D optics. This brightness level is a significant problem for the industry as viewers struggle to see details and fuse the two 3D images at these low levels.

The problem is that projectors with arc-lamp illumination are already fully optimized, with optics designed at the fastest speed possible to capture as much light and still deliver the required image resolution, contrast, and colors. At the same time, the arc lamps are built with a small arc gap to deliver a compromise between light output and a reasonable lifetime. In addition, the spatial light modulators are constrained to a small package and device size for reduced cost. Due to the resulting etendue and cost limitations, along with required quality parameters, optical-engine designers cannot provide more screen luminance without a source change.

This is true for high-end projectors like cinema projectors, where the optics are limited to f/2.4 optical systems, 6 kW arc lamps, and costly 1.4-in.-diagonal spatial light modulators. It is also true at the low end of the projection scale, where picoprojector size and low energy requirements dictate maximum efficiency at the smallest size. Therefore, modulators and optics need to shrink along with costs. The only way to do this is to capture more light and slow the system.

Lasers can do this. Lamps and LEDs emit in large angles (tens to hundreds

> The most important limitation facing the projection industry is brightness. Displays are rarely too bright. Even in dark theaters, existing projectors tend to be too dim.

of degrees) from relatively large areas (>1 mm), whereas solid-state lasers emit in small angles from small areas. As an example, 3 W green lasers from Necsel Intellectual Property (Sunnyvale, CA) have roughly 0.5° divergence angles and 0.1 mm emission diameters. This small source etendue allows optical designers to use the smallest SLMs and slow the optics for lower costs while providing optics that deliver higher contrast.

Furthermore, the narrow spectral bandwidths of lasers increase the projector color gamut, enabling an expanded color palette and better color reproduction. Most important, the projectors have a much higher optical efficiency and ability to deliver higher brightness at a lower energy usage (also lower heat generation). Another significant bonus of these lasers is their exceptionally long specified lifetimes—greater than 30,000 hours—which reduces operational costs for customers such as theaters and schools.

Lasers and 2D spatial light modulators

Rather than a modulated and scanned laser beam to provide images, the optimum system solution appears to be a combination of 2D SLMs as the imaging device and lasers as the illumination source.

While some companies, such as MicroVision (Redmond, WA), have created excellent picoprojectors using biaxial scanning galvanometers, the scanned laser sources have a very high brightness and short pulse time that creates an eye-damage risk for source fluxes above approximately 25 lumens. Using 2D SLMs with comparatively low-brightness laser light and long exposure times substantially decreases safety risks. Further, when properly combined with speckle-reduction techniques required to achieve quality images, the safety concern is reduced to something similar to that of conventional white-light projectors. This lower risk has allowed Kodak to receive a variance from the FDA to sell such laser projectors in cinema-type venues without individual site variances.[2] In the future, it is likely that laws will be changed to further simplify regulations, which will make commercialization much more practical and simple.

Fortunately, lasers have finally reached a starting cost of lower than about $50 per optical watt in volume, with a demonstrated reliability that can enable this market to move forward quickly. Numerous suppliers, including well-known laser companies

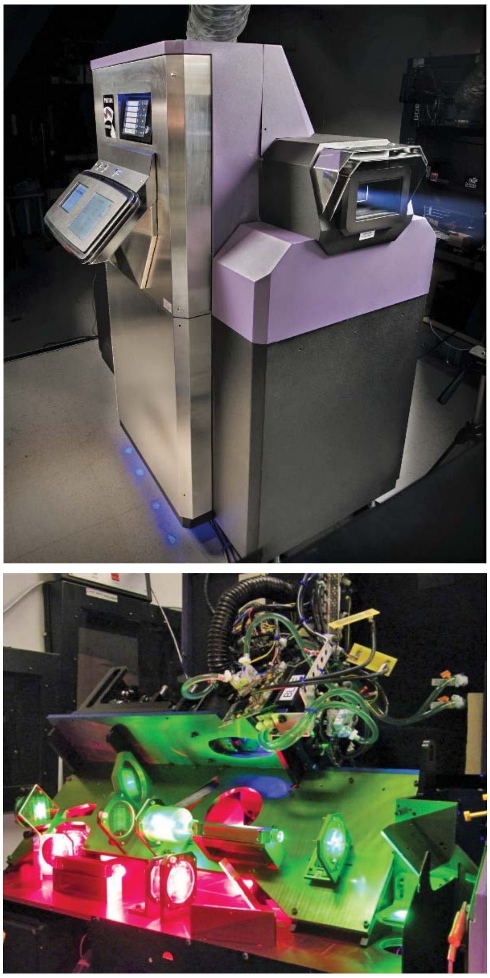

FIGURE 2. Kodak's laser projection technology prototype 3D cinema projector (top; inside view at bottom) demonstrates bright 3D, high contrast, and low operational costs to the cinema industry. (*Courtesy of Eastman Kodak*)

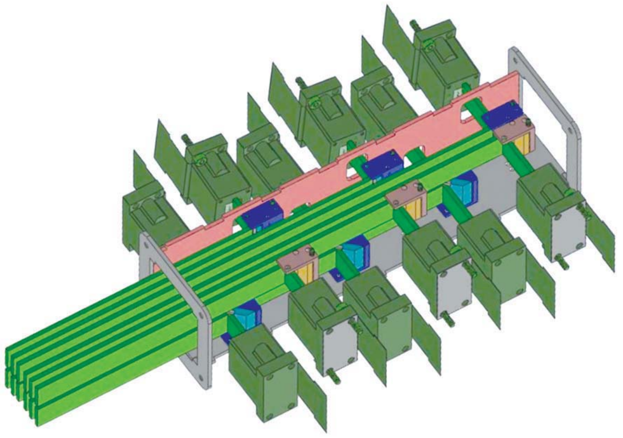

FIGURE 3. The outputs of twelve Necsel lasers are combined in free space to create a larger, single-color illumination path for a single-color channel.

such as Mitsubishi (Tokyo, Japan) and Nichia (Tokushima, Japan), combined with lamp suppliers that have moved into the laser technology space, such as Ushio (Tokyo, Japan) and Osram Opto Semiconductors (Regensburg, Germany), as well as many small startup companies such as EpiCrystals (Tampere, Finland) and CQ Laser Technologies (Nanjing, China), will offer a great selection of lasers in the near future. This competition will drive innovation, commercialization, higher electrical-to-optical efficiencies, and cost reduction to the benefit of projector manufacturers and consumers.

High-brightness demonstration

In early 2011, Kodak demonstrated an 11,000 lumen cinema-quality laser projector that provides exceptionally high-contrast 2D image quality, as well as designed-in bright 3D capability using passive glasses, which has kick-started this transition (see Fig. 2).[3] The projector uses twelve 3 W lasers in each of the red, green, and blue channels, whose light is then made uniform through individual integrating bars and directed to respective DLP devices (see Fig. 3). Each color channel has its own simple polarization switcher to provide alternating polarization states for the left and right viewing 3D mode. The optics were slowed from f/2.4 to f/6.0, while the conventional prism combiner was replaced with dichroic plates to improve contrast and further reduce costs. Speckle reduction was accomplished throughout the machine using multiple techniques strategically placed to keep the optical efficiency high while reducing optomechanical complexity.

Demonstration of this prototype projector showed that higher brightness, efficiency, contrast, and an equivalent cost structure can be achieved in comparison to conventional digital projectors, but with built-in passive 3D and substantially lower operational costs. In 2011, IMAX became the first company to exclusively license (in the "Digital Cinema" market) the technology for its highest-quality cinemas. Notably, this technology is extensible into the home theater, education, and business markets, where these same benefits can enhance projected-image quality and provide 3D while reducing cost through increased energy efficiency and longer light-source lifetimes.

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Small-pore microchannel plates forge ultrafast photomultipliers

JON HOWORTH, JAMES MILNES, and GARETH JONES

Thanks to military night vision advances, small-pore microchannel plates result in faster photomultipliers that compete directly with streak cameras in terms of dynamic range and time resolution in such applications as fusion diagnostics.

Microchannel plates enable very fast electron amplification and are used in premium quality photomultiplier tubes (PMTs) for applications such as fluorescence lifetime measurements, with single-photon counting jitter down to 30 ps. The analog pulsewidth depends upon the pore size of the microchannel plate, and military night vision has driven down the pore size in an effort to improve resolution. Using these small-pore plates has resulted in faster photomultipliers that compete directly with streak cameras in applications as demanding as fusion diagnostics. Similar tubes used in particle accelerators have achieved multiphoton jitter of less than 10 ps.

Over the past ten years Photek has undertaken extensive developments in our microchannel plate (MCP)-based PMTs to improve and define their speed, dynamic range, and gating ability, making these devices critical assets in some of the most prestigious research facilities in the world.

Speed

The "speed" of a PMT is essentially the spread in time of the PMT output from a very short optical input—a theoretical delta function that in reality only has to be shorter in time than the PMT response. Given that a PMT generates many electrons from very few (or even just one) from the photocathode, the spread is minimized by trying to make all of the electrons arrive at the anode at the same time.

The MCP structure provides an ideal gain medium for this multiplication process, consisting of a thin glass disk (typically 0.3–0.5 mm thick) full of millions of holes known as pores. Electrons are accelerated down these pores, usually 6 or 10 μm in diameter, and are amplified on each bounce. The small structure of the MCP pores means that the possible variation of path length for each electron is very small, so the arrival time is similar for all—hence a very fast response. Speed is further improved by making the pores smaller and therefore restricting the path length variation even more. Availability of MCPs with pore diameters of 3 μm has allowed Photek engineers to narrow the analog pulse shape of their fastest MCP-PMTs by as much as 25% (see Fig. 1).

Pore size defines the detector rise time or "leading edge," while the trailing edge and the overall analog pulse response time is dependent on the anode size and the quality of the match to the output transmission line. Anode size must be balanced between providing enough working area and avoiding excessive capacitance that will slow the trailing edge. The 50 Ω output transmission line has to be carefully tapered to avoid any sudden transitions that would produce ringing and reflections.

Mainly through an ongoing collaboration with the Atomic Weapons Establishment (AWE; Berkshire,

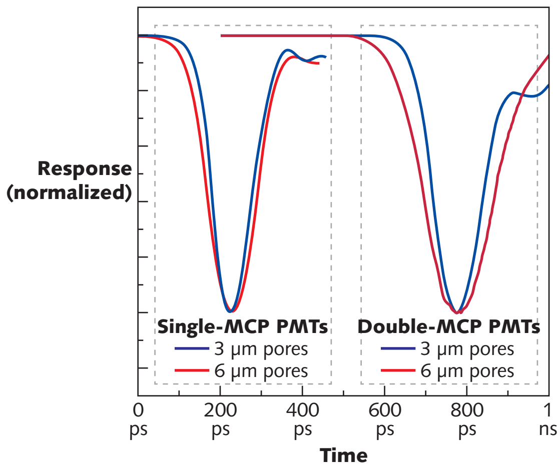

FIGURE 1. Speed of microchannel plate photomultiplier tubes (MCP-PMTs) improves when using smaller 3 μm pores instead of typical 6 μm pores.

England) over the last 10 years, these parameters have been optimized to produce single-MCP-PMTs with a pulse full-width half-maximum (FWHM) as low as 100 and 130 ps for a double-MCP-PMT, both with a 10-mm-diameter working area. The rise times can be as low as 60 and 75 ps, respectively. The collaboration is also producing a novel detector design that combines the speed of small-area MCP-PMTs with the light-capturing ability of the larger models with promising early results.

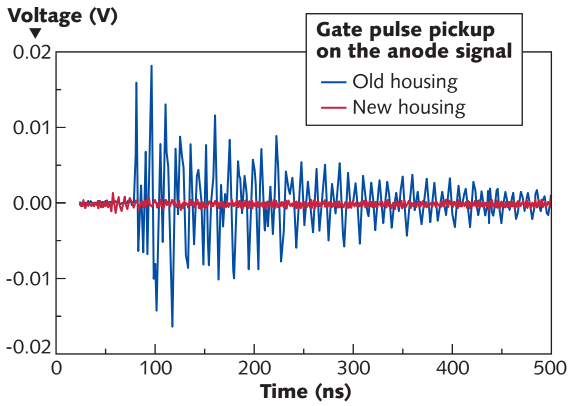

FIGURE 2. Gate pulse pickup in PMTs is improved by reducing the ground loop between gate input and signal output.

Dynamic range

The pulsed output of an MCP-PMT in analog mode is linear from a few microvolts to about 50 V into a 50 Ω load, so the lower end of the dynamic range is essentially limited by the noise floor of the measuring electronics—usually a high-bandwidth oscilloscope. The upper limit is due to space-charge effects between the MCP output and the anode.

Up until the recent developments of high-bandwidth, real-time oscilloscopes, there was difficulty in reading fast, single events. So traveling-wave oscilloscopes were developed by Tektronix and later by Greenfield that had good real-time bandwidth but also very high voltage input ranges.

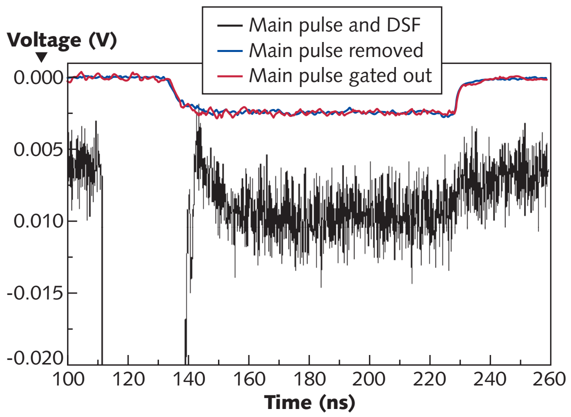

FIGURE 3. A simulation shows retrieval of the downscattered fraction (DSF) from the main pulse in neutron time-of-flight experiments by gating the MCP-PMT.

Gating ability

All MCP-PMTs can easily be activated or deactivated by applying a voltage pulse between photocathode and MCP. Commonly referred to as "gating," this is useful in removing unwanted dark counts (such as in time-resolved single-photon counting) or deactivating the PMT during a large, potentially damaging optical event when observing a much smaller event that occurs a short time before or after, such as in optical light detection and ranging (lidar) systems and in fusion diagnostics.

The proportion of the detector response from activated to deactivated is known as the "extinction ratio" and this has been measured at 10^8 for 300 nm, rising to 10^{13} at 600 nm in an MCP-PMT.[1] Using Photek gating electronics, we can achieve a transition from on to off (or vice versa) in just 3 ns on certain models with an accuracy of 50 ps.

However, some problems with gating an MCP-PMT include: 1) The photocathode is nominally at -5 KV, so the gate pulse must be AC-coupled; 2) the gate pulse itself is easily picked up by the anode; and 3) loss of stability of the PMT response after activation.

After extensive recent developments, we have reduced the gate pulse pickup to just a few millivolts, even on the fastest gating detectors, by carefully redesigning the housing to minimize ground loops between the signal and gate pulse connections (see Fig. 2). The stability of the PMT response after activation has also been significantly improved by providing a low inductance path for the gate pulse and stabilizing the power supplied to other components in the detector, insuring a clean delivery for the fast gate pulse to the photocathode with minimal ringing.

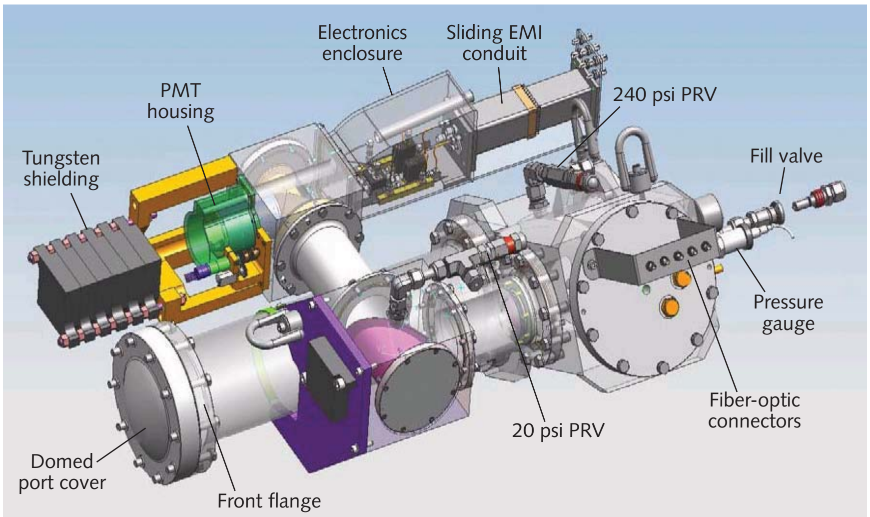

FIGURE 4. Small-pore MCP-PMTs are making their way into fusion energy studies. (*Courtesy of LLNL*)

Fusion diagnostics

Laser fusion experiments are underway at the Laboratory for Laser Energetics (LLE; Rochester, NY), Laser Mégajoule (near Bordeaux, France), and the National Ignition Facility (NIF). The radiation emitted from the tritium targets at these facilities spans about 19 orders of magnitude in around 2 ns, so the diagnostics present many challenges.

Vladimir Glebov at LLE was the first to use a Photek double-MCP-PMT (with a gain of 10^6) to cover the early stages of the experiment, together with a single-MCP-PMT (with a gain of 5×10^3) for the mid ranges and a photodiode with no gain at all to follow the final stages. NIF is currently using small, fast Photek PMTs with a 10-mm-diameter working area in the Gamma Reaction History (GRH) diagnostic, while the slower, larger 40-mm-diameter PMTs are being used in neutron time-of-flight (nTOF).

The application of PMT gating becomes particularly useful for nTOF diagnostics, where it is sometimes necessary to measure a small signal of "down-scattered" neutrons after a very large deuterium-tritium (DT) or hard x-ray signal, or to measure the neutron yield after a gamma flash in fast ignition experiments.[2] The ability to gate the PMT between these close-proximity events prevents detector saturation (see Fig. 3). Two driving pulses were injected into an LED to simulate the main pulse and the down-scattered fraction (DSF). The main pulse was then removed to show the DSF by itself, and then the

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main pulse was restored but effectively ignored by the detector by gating out that time period. This shows how gating provides the ability to pick out small signals very close to large events. The area ratio of the main pulse to the DSF was 1000:1.

Particle accelerator applications

Future particle physics experiments are likely to use MCP-PMTs to improve time and spatial resolution (see Fig. 4). It is unlikely that higher-energy colliders will be built in the foreseeable future, but improved detectors are planned. For example, at the KEK High Energy Accelerator Research Organization facility (Tsukuba, Japan), MCP photomultipliers have been chosen for the detector upgrade.

There are problems with the operational lifetime of MCPs, and Hamamatsu (Hamamatsu City, Japan) has improved life by inserting a very thin film approximately 8 nm thick between the photocathode and the MCP. In the US, the Large Area Picosecond Photo Detector (LAPPD) project aims to extend the operating life using completely new technology for the MCP. Instead of the traditional lead glass and hydrogen reduction, this project will use atomic-layer deposition to create the resistive and secondary electron-emitting layers.

High-energy particle accelerators often use Cherenkov radiation to detect the sub-atomic particles. The Cherenkov detectors generate extremely short light pulses containing many photons that effectively arrive at the PMT simultaneously. The presence of multiple photons in an event reduces the jitter of the time measurement even further. Experiments at Fermilab (Batavia, IL) have shown that the jitter of Photek MCP-PMTs can be as little as 7.7 ps for multiphoton events.

A key functionality required by particle accelerators is to have multiple parallel channels—often what is important is the detection of simultaneous multiphoton events at opposite sides of the collision point. Photek has collaborated with CERN (Geneva, Switzerland) and the University of Leicester (Leicester, England) to make multiple anode structures for MCP-PMTs to allow readout of simultaneous events and provide spatial information. This technology uses thin films printed onto a multilayer ceramic. An MCP-PMT with an 8 × 8 readout and an anode pitch of 1.6 mm (known as Hi-Content) has already been produced, and a 32 × 32 version with an anode pitch of 0.88 mm is about to be manufactured.

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Deep down and label-free: Bioimaging with photoacoustics

MIKE MAY

Laser-induced ultrasonic emission, converted to imagery, enables deep-tissue views of mechanisms in organs, cells, subcellular structures, and even biochemicals—without labels or dyes.

A nonionizing laser shoots through the skin into tissue and cells beneath the surface. The absorbed laser energy turns into heat, which sets off an ultrasonic emission that can be captured and converted into images. This technology, photoacoustic imaging, promises better views of mechanisms in organs, cells, subcellular structures, and even biochemicals. To make this technique widely available, though, researchers need commercial instruments, which are on the way.

To see life in its natural state, researchers want—as much as possible—imaging approaches that need no stains or labels. Photoacoustics provide this with "rich contrast," according to Lihong Wang, Gene K. Beare Distinguished Professor at Washington University in St. Louis, and inventor of three-dimensional photoacoustic microscopy (see http://bit.ly/h2EUI5).

The key is the wide range of biological materials that absorb the laser energy. "Almost anything absorbs it," he says. The list includes oxyhemoglobin, deoxyhemoglobin, melanin, lipids, DNA, RNA and more. So, as Wang says, "Photoacoustics can image cell nuclei in-vivo without staining."

The same cannot be said for other popular imaging techniques. For example, many molecules do not fluoresce, so they must be labeled to see them with fluorescent microscopy. "Then, we have to ask if the dye is safe *in vivo*," Wang points out. With photoacoustic

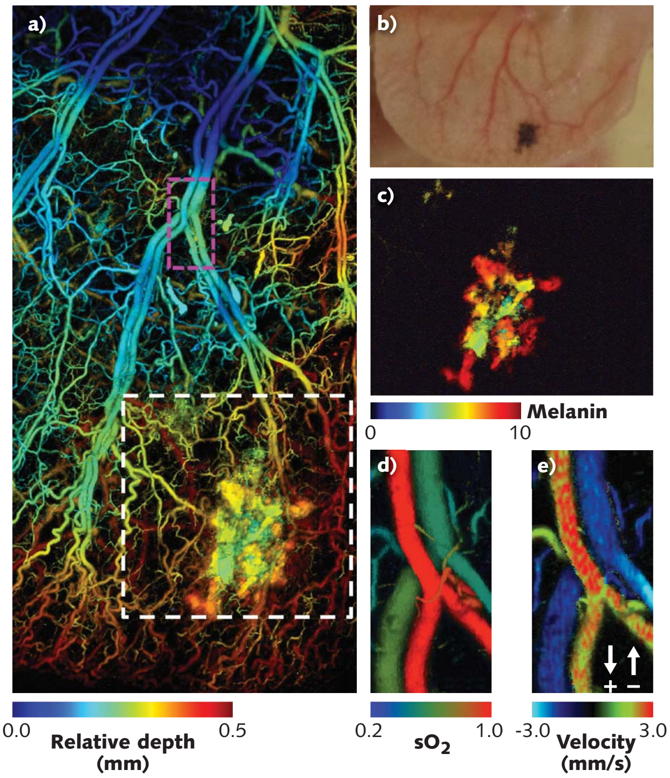

FIGURE 1. Photoacoustic microscopy provides anatomical, chemical, and dynamic imaging. Using 584 nm light to image a mouse ear bearing a xenotransplanted B16 melanoma tumor (white-dashed box in [a]), this image reveals a principal artery-vein pair (magenta-dashed box in [a]) that feeds and drains the tumor region. In this image, depth is color-coded: blue (superficial) to red (deep). For comparison to traditional microscopy, see the white-light photograph of the mouse ear (b), which is shown at lower resolution. Photoacoustic technology can also reveal melanin (c), and here the blood vessels are invisible due to the weak absorption of hemoglobin at the wavelength used. For examples of dynamic imaging, see the photoacoustic images of oxygen saturation in the principal arterial-vein pair revealed with dual-wavelengths excitation at 584 and 594 nm (d) and flow velocity imaging of the principal arterial-vein pair (e). The arrows show the directions of positive and negative flow, and pulsing is even visible. *(Courtesy of L. Wang)*

microscopy and no labels, researchers can view anatomical structure and function.

Moving into microscopy

Photoacoustic microscopy started as a two-dimensional approach used in industry. "People used it to image the surface of materials—nonbiological materials, like metals," says Wang. "We added time of arrival of the acoustic waves to get depth resolution. This turned 2D into 3D."

Now, Wang and his team push the third dimension of photoacoustic microscopy even deeper into tissue. To get more depth, though, spatial resolution decreases, and vice versa. "We've extended the imaging depth from 1 mm to 7 cm," he says. "So photoacoustic microscopy extends the depth of standard optical microscopy and has broken through what is called the optical diffusion limit for all existing optical microscopy technologies." So far, 220 nm is the highest resolution that Wang has reached with superficial optical-resolution photoacoustic microscopy.

To make this technology available to more researchers, Wang is working with Microphotoacoustics in New York, which has licensed his patents in hopes of making a commercial photoacoustic microscope. He also mentions working with Olympus on a multimodality microscope that would include photoacoustics along with confocal and two-photon microscopy.

As Wang says, "We provide a tool. We're willing to be the guys who serve the biomedical research and clinical communities."

Setting up a system

So far, researchers wanting to do biological research using photoacoustics have had to build their own systems. Increasingly, the pieces necessary for construction of such systems are becoming available for purchase. For example, GWU (Erftstadt, Germany) makes tunable light sources useful for photoacoustics. According to Günter Warmbier of GWU, the company's "most popular product is an OPO [optical parametric oscillator] pumped by a frequency-doubled Nd:YAG laser, which will be formally released soon." He adds, "We have several pre-production units in the field in customer labs."

A tunable laser lets users find the wavelength that works best for the material at hand. Different tissues and molecules absorb some laser energy better than others.

Nonetheless, getting a homemade photoacoustic system up and running takes some expertise. According to Roger J. Zemp, assistant professor of electrical and computer engineering at the University of Alberta and maker of his own systems, "It helps to have some experience in the field. It can be fairly tricky." The key issues revolve around setting up the parameters of the laser, focusing the light, receiving the acoustic signals and developing integrated scanning hardware and software.

For those with the expertise to make their own system, the price is dropping. Zemp mentions using a laser system in the past that cost $150,000, but says that a microchip laser can now be used for optical-resolution photoacoustic microscopy and purchased for less than $10,000. He adds, "A fiber laser can do a bit more, but it's slightly more expensive." Eventually, he expects to see a shoebox-size instrument.

Adding applications

VisualSonics (Toronto, ON, Canada) got into the high-frequency ultrasound market more than a decade ago. In recent years, this company wanted to expand the applications of its Vevo systems. "We want to provide applications that answer the biological questions that researchers deal with on a regular basis," says Catherine Theodoropoulos, director, product management at VisualSonics, "and we want to do that *in vivo* and in real time with extremely high resolution and sensitivity." Those desires focused VisualSonics on photoacoustics.

Early in 2011, VisualSonics introduced the Vevo LAZR photoacoustic imaging system, which is its Vevo 2100 system plus a tunable laser (670–980 nm), which adds the photoacoustic capability. Researchers who already own a

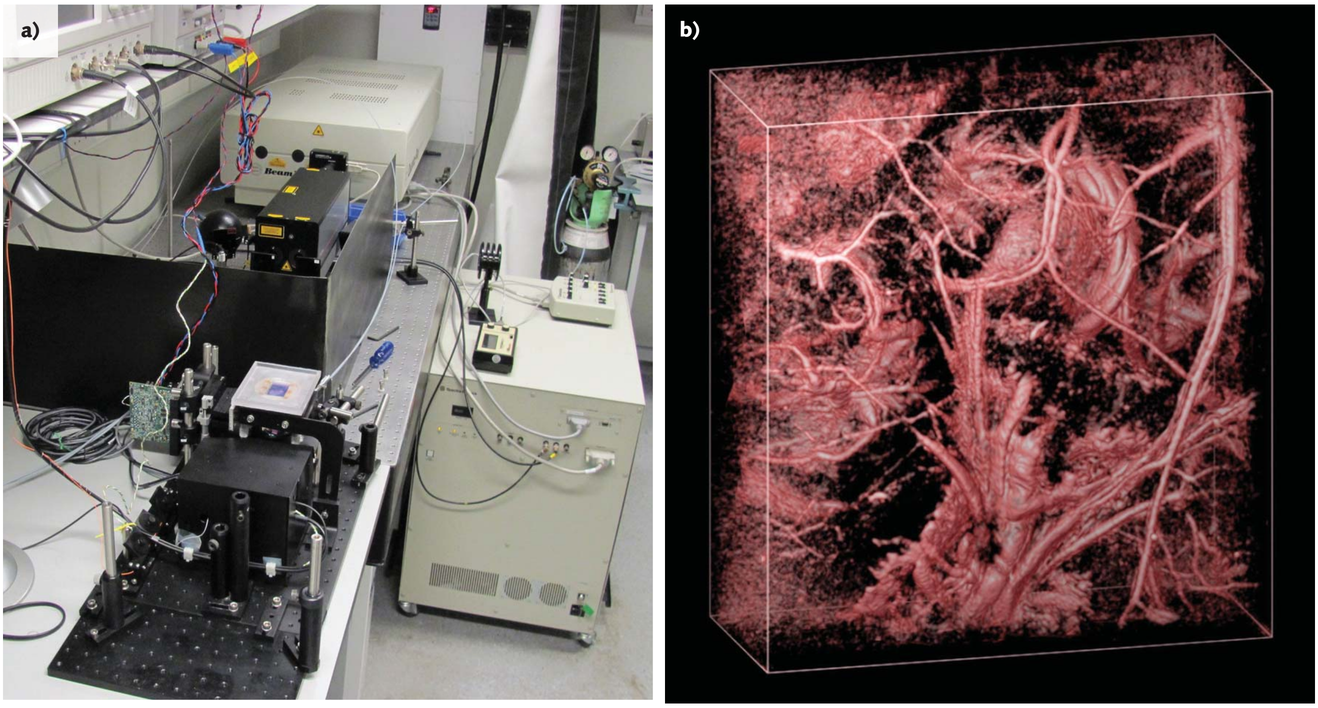

FIGURE 2. A photoacoustic imaging setup (a) that includes an Nd:YAG pump laser, plus an optical parametric oscillator (OPO) from GWU generated this view (b) of the abdominal blood vessels of a mouse. *(Courtesy of J. Laufer, University College London)*

Vevo 2100 system can upgrade to the photoacoustic version with the integration of the laser unit. "The photoacoustic side gives researchers a tool to look at nanoparticles and agents *in vivo* and real time, and understand what they are doing," Theodoropoulos says.

For now, VisualSonics aims the Vevo LAZR platform primarily at cancer biology. For one thing, this instrument can be used to study angiogenesis and blood flow related to tumors by quantifying oxygen saturation.

Like the Vevo 2100 system, the Vevo LAZR allows imaging of many organs, but with some constraints. With this photoacoustic system, researchers can image at high-resolution to about one centimeter. "We will improve on that," Theodoropoulos says.

Beyond cancer research, the Vevo LAZR technology could also be used in hemodynamics, or movement and functional status of the blood. Theodoropoulos adds that they "are getting preliminary data in brain, embryos and muscle."

Imaging dynamic processes

Since photoacoustic approaches can deliver 2D or even 3D images in real time, they might be applied to some of the deepest mysteries in biology. That's exactly the goal of Daniel Razansky, head of the Laboratory for Experimental Biological Imaging Systems and deputy director of the Institute for Biological and Medical Imaging at the Technical University of Munich and Helmholtz Center Munich in Germany. He is working on photoacoustic systems that will image dynamic processes, such as deep brain activity or real-time uptake of molecular agents.

He says, "My lab is designing and building this system all the way from instrument development, signal processing, and algorithmic research to validation in small animal studies and, potentially, clinical trials."

Razansky uses multispectral optoacoustic tomography (MSOT) to add molecular contrast materials—like dyes, proteins, and nanoparticles—in order to expand to even more molecular and functional imaging applications. "Maybe," he says, "we'll be able to image early molecular indications related to diseases, such as cancer, atherosclerosis, and Alzheimer's, or monitor efficacy of therapies and drugs in living tissues."

As Razansky's team expands its uses of photoacoustics, he also helps with the creation of commercial products. In 2010, one such product—the MSOT PCS-2 small animal scanner—was commercially launched by Munich-based iThera Medical.

As the basic research continues and more commercial products become available, we will be amazed by what we will soon see, thanks to laser-induced sound.

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All-fiber designs extend supercontinuum sources into the mid-IR region

MOHAMMED N. ISLAM

A supercontinuum laser based on an erbium/ytterbium power amplifier emits over approximately 0.8–4.2 μm, while a second version based on a thulium-doped power amplifier covers the 1.9–4.5 μm region, making these sources important for applications in defense, homeland security, and healthcare.

Supercontinuum lasers combine the broadband attributes of lamps with the spatial coherence and high brightness of lasers. By exploiting a modulational instability initiated supercontinuum (SC) mechanism, an all-fiber-integrated SC laser with no moving parts can be built using commercial-off-the-shelf components.

Our team at the University of Michigan has developed and commercialized through Omni Sciences (both in Ann Arbor, MI) a mid-infrared SC laser (MISCL) that spans the 0.8–4.5 μm wavelength range. One version of this MISCL is based on an erbium/ytterbium power amplifier, while a second version is based on a thulium-doped power amplifier. The fiber laser architecture is a platform where SC in the visible, near-infrared (near-IR), or mid-IR can be generated by appropriate selection of the amplifier technology and the SC generation fiber.

The bandwidth of the SC laser is broad like a lamp, while the spatial coherence and high intensity or brightness of the output is like a laser, leading some to call the SC laser "the ultimate white light."[1] But until now, SC lasers were used primarily in laboratory settings since typically large, tabletop, modelocked lasers were used to pump nonlinear media such as optical fibers to generate SC light. But now, those large pump lasers are being replaced with diode lasers and fiber amplifiers that gained maturity in the telecommunications industry.

By exploiting the natural physics of optical fiber, our group has made three major breakthroughs in SC lasers. First, we have extended the wavelength into the mid-IR region, ranging from approximately 0.8 μm near the edge of the visible spectrum, through the near-IR region from roughly 1–2 μm, and reaching most of the mid-IR region from approximately 2–4.5 μm. Second, we have eliminated the need for a bulky modelocked laser using telecommunications components. And finally, we can scale the power to 10 W or higher simply by increasing the repetition rate and using a high-power fiber amplifier, enabling practical commercial applications in defense, homeland security, metrology, and healthcare.

Modulational instability-initiated SC generation

Our all-fiber-integrated, high-powered MISCL light source is elegant for its simplicity (see Fig. 1). We start with a distributed feedback (DFB) laser diode with a wavelength near 1550 nm whose approximately 0.5–2.0 ns pulsed output is amplified in a multiple-stage fiber amplifier. The first stage pre-amplifier is a standard erbium-doped fiber amplifier (EDFA) designed for optimal noise performance. Between amplifier stages, bandpass filters block amplified spontaneous emission and isolators prevent spurious reflections. The power amplifier stage uses a

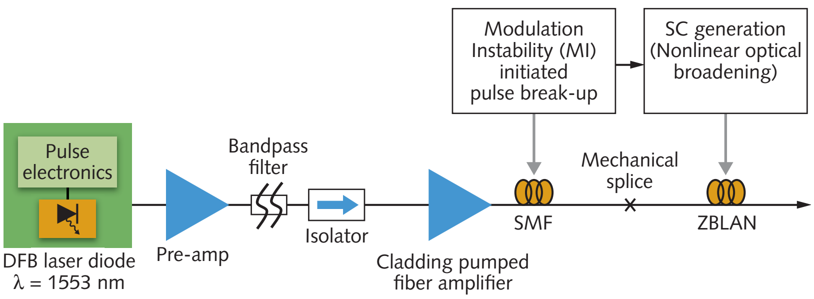


FIGURE 1. The simple architecture is shown for a mid-infrared supercontinuum laser (MISCL) using modulational instability initiated SC generation.

cladding-pumped fiber amplifier that is optimized to minimize nonlinear distortion. This pump-laser configuration is a common and standard telecom design.

The SC generation occurs in the relatively short lengths of fiber that follow the pump laser. One or two meters of standard singlemode fiber (SMF) after the power amplifier stage are followed by several meters of SC generation fiber. In the SMF, the peak power may be several kilowatts and the pump light falls in the anomalous group-velocity dispersion regime—often called the soliton regime. For high peak powers in the dispersion regime, the nanosecond pulses are unstable due to a phenomenon known as modulational instability, which is basically parametric amplification in which the fiber nonlinearity helps to phase match the pulses.[2] As a consequence, the nanosecond pump pulses are broken into many shorter pulses as the modulational instability tries to form

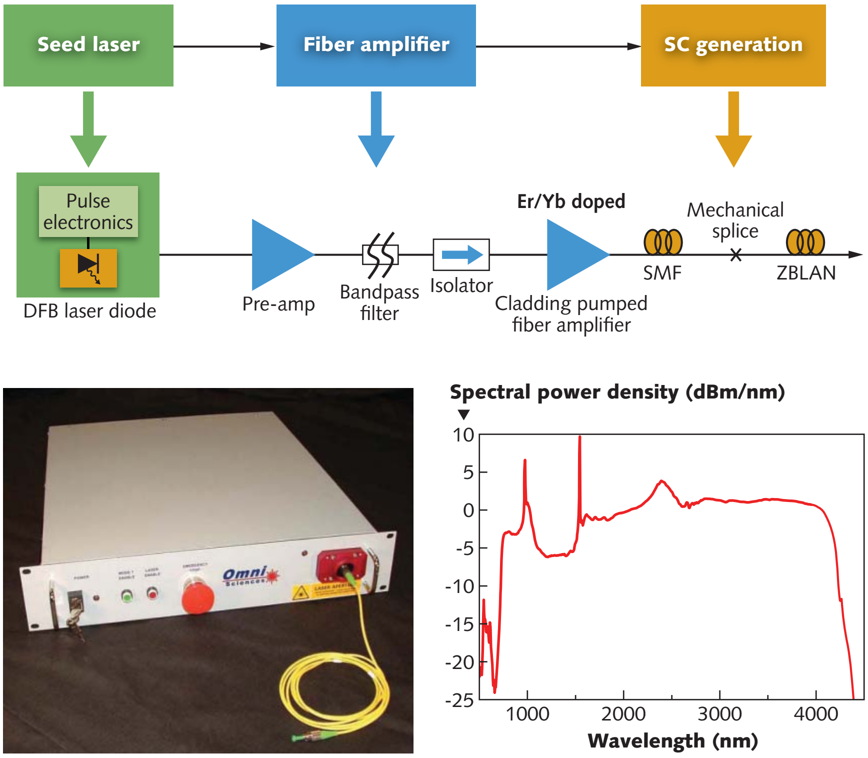


FIGURE 2. The spectral output is shown for a Gen I MISCL with erbium/ytterbium power amplifier.

soliton pulses from the quasi-continuous-wave background.

Although the DFB laser diode and amplification process starts with nanosecond-long pulses, modulational instability in the short length of SMF fiber forms approximately 0.5 ps to several-picosecond-long pulses with high intensity. Thus, the few meters of SMF fiber results in an output similar to that produced by mode-locked lasers, except in a much simpler and cost-effective manner.

The short pulses created through modulational instability are then coupled into a nonlinear fiber for SC generation. The nonlinear mechanisms leading to broadband SC include four-wave mixing or self-phase modulation along with the optical Raman effect.[3] Since the Raman effect is self-phase-matched and shifts light to longer wavelengths by emission of optical phonons, the SC spreads to longer wavelengths very efficiently. The short-wavelength edge arises from four-wave mixing, and often the short wavelength edge is limited by increasing group-velocity dispersion in the fiber. In our experience, of the particular fiber used for sufficient peak power and SC fiber length, the SC generation process will fill the long-wavelength edge up to the transmission window.

Mature fiber amplifiers for the power amplifier stage include Yb-doped fibers (1060 nm), Er/Yb-doped fibers (1550 nm), or Th-doped fibers (2000 nm). Other candidates for SC fiber include fused silica fibers (for generating SC between 0.8 and 2.7 μm), mid-IR fibers such as fluorides, chalcogenides, or tellurites (for generating SC out to 4.5 μm or longer), photonic crystal fibers (for generating SC between 0.4 and 1.7 μm), or combinations of these fibers. By selecting the appropriate fiber-amplifier doping and nonlinear fiber, SC can be generated in the visible, near-IR, or mid-IR wavelength region.

MISCL performance

Our Gen I MISCL uses an Er/Yb-doped fiber amplifier for the power amplifier and a ZBLAN fluoride fiber for 3.9 W average-output-power SC generation (with a 50% duty cycle modulation) from approximately 0.8–4.3 μm (see Fig. 2). Because the broadband spectrum emerges at the output of a singlemode fiber, the entire spectrum emerges in a spatially coherent, nearly transform-limited beam that can propagate for long distances. For example, beam propagation for a Gen I MISCL over the wavelength range from 2.5–3.5 μm is within 20% of a transform-limited Gaussian beam (M^2 <1.2).

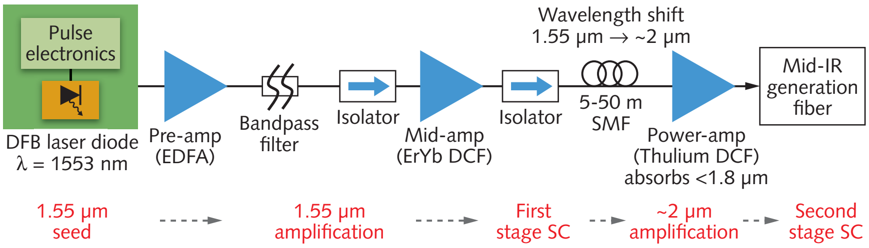
In a second-generation MISCL (Gen II), the power amplifier is a Th-doped fiber amplifier and the SC generation fiber is again a ZBLAN fluoride type. The Gen II MISCL operates continuously from about 1.9–4.5 μm at a total average power of 2.6 W, with an approximate 0.7 W time-averaged power in wavelengths beyond 3.8 μm—again with a 50% duty cycle modulation (see Fig. 3).[4] The Th amplifier spectral range begins closer to 1.9 μm, but the long-wavelength edge extends about 270 nm beyond the Gen I system.

The MISCL output power can be varied by changing the system repetition rate. In the Gen II MISCL we varied the system repetition rate between 125 and 500 kHz and were able to change the mid-IR output power between 0.4 and 1.6 W, respectively, with a very similar output spectrum.

MISCL applications

In defense and homeland security applications, the MISCL spectrum emulates the blackbody radiation of hot objects and overlaps with the vibrational and rotational resonances in many solids. For example, most heat-seeking missiles target the heat of the engine, which has a spectrum from roughly 1.5–5 μm, allowing the MISCL to be used as a light source in directed IR countermeasure (IRCM) systems that, unlike most other lasers, cannot be defeated by using filters.[5]

Many solids, including explosives and firearms, have distinct spectra over the near- and mid-IR wavelength ranges, allowing the MISCL to be used in spectral fingerprinting to examine the pattern of spectral lines—rather than only one or



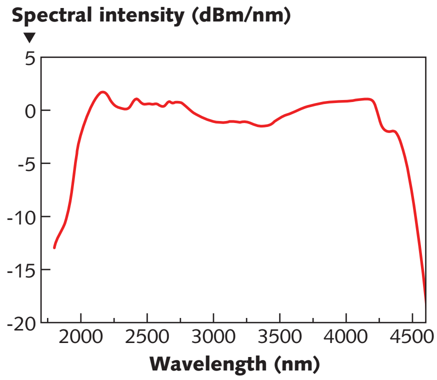


FIGURE 3. Spectral output shifts to longer wavelengths for a Gen II MISCL with a thulium-doped power amplifier.

two lines—for standoff detection of solid targets with diffuse reflection spectroscopy.[6]

The MISCL's broadband spectrum is also advantageous in metrology applications. Broad spectral width permits precise depth spatial resolution, and the spectral dependence of reflected light can be used for measuring properties of a surface such as surface roughness. We have used a visible SC laser to obtain 3D images of solder balls on a semiconductor die with 125 nm axial and 15 μm lateral resolution.[7] For a different application, a near-IR MISCL performed high-accuracy, noncontact roughness measurements of flat and curved machined parts in automotive powertrain systems over the industrially relevant range of 0.05–0.35 μm.[8]

For medical diagnostics and therapeutics in healthcare applications, the carbon-hydrogen bonds that are the main building blocks of lipids (fat, cholesterol, fatty acids) have their fundamental vibrational and rotational bonds between 3.3 and 3.6 μm, which fall nicely within the MISCL wavelength range, allowing it to be used as a source for absorption spectroscopy of the constituents of normal artery and atherosclerotic plaque, including adipose tissue, macrophages, and foam cells.[9] By using a MISCL in the carbon-hydrogen fatty acid and cholesterol esters absorption wavelength, we can demonstrate differential damage of lipid-rich adipose tissue without damaging the protein-rich blood vessel wall. Given the widespread healthcare problems with obesity and cardiovascular disease, there are bound to be many further healthcare applications arising in the future.

The simple MISCL design produces broadband output in a nearly transform-limited, spatially coherent output beam that lends itself to novel applications now and in the future. As telecom components and pump laser diodes scale up in power, so too will the output from SC lasers—scaling up to 10 W and more. ◀

ACKNOWLEDGMENT

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Air-core microstructured fibers provide low-loss, broadband terahertz guidance

JESSIENTA ANTHONY, RAINER LEONHARDT, SERGIO LEON-SAVAL, and ALEXANDER ARGYROS

Kagome air-core microstructured polymer fibers are a new class of broadband terahertz waveguides with low loss and low dispersion characteristics.

Guiding terahertz radiation in waveguides continues to be one of the most engaging research areas in terahertz science. The lack of highly transparent materials in the terahertz band motivates the search for desirable waveguides that not only offer lossless terahertz propagation, but also low dispersion and highly flexible terahertz waveguiding. Conventional waveguides such as terahertz fibers made of sapphire and polymer tubes, as well as metallic-based wires and plates, have been intensely investigated over the years.[1]

In contrast, a new class of terahertz waveguides draws on the knowledge and the technology of photonic-crystal fibers (PCFs) developed for the visible to mid-IR spectral regions for use in the terahertz frequency range.[2] Of particular interest are hollow-core PCFs that allow light guidance in the air core, providing a promising platform for lossless transmission with very low dispersion. We recently demonstrated terahertz guidance in air-core "kagome" polymethylmethacrylate (PMMA) PCFs with measured propagation losses reduced by 20 times compared to the material losses, and also achieved low dispersion over a broad transmission region.[3] ("Kagome" refers to the pattern used in the PCF, which looks similar to a trihexagonal tiling.)

The kagome fiber that we investigated is drawn from a preform that is made by stacking PMMA tubes in a triangular lattice with the core formed by removing seven tubes from the stack (see Fig. 1). The drawn fibers have core diameters of 1.6 mm (Kagome-1) and 2.2 mm (Kagome-2), with outer diameters of 5 mm and 6.8 mm, respectively.

Standard measurement techniques employing a terahertz time-domain spectroscopy setup are used to evaluate these fiber samples. In this setup, light pulses with an 800 nm wavelength and a pulse duration of 80 fs from a Ti:sapphire laser are split into two arms: a pump beam that impinges on a surface emitter and generates terahertz pulses via optical rectification, and a probe beam that optically gates a photoconductive antenna detector. This detector directly maps the terahertz electric field that arrives at the antenna as a function of the delay time between the pump and the probe beams. For good mode matching and thus high coupling efficiencies, we incorporated specially designed symmetric-pass terahertz lenses with a focal length of 75 mm and a numerical aperture of 0.33.[4]

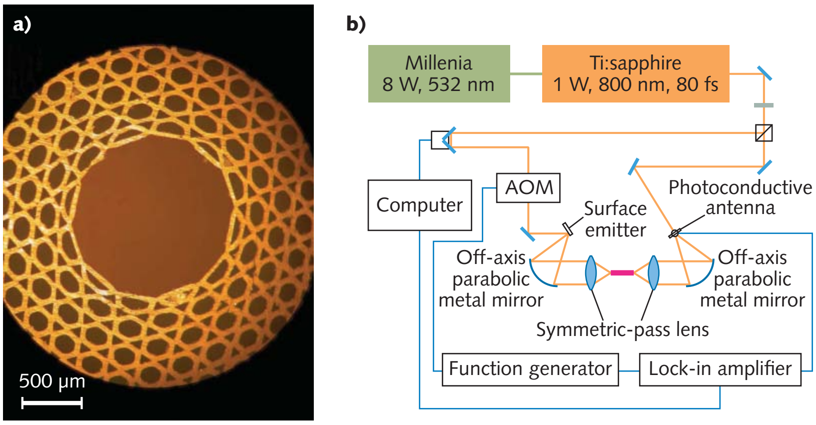

FIGURE 1. A micrograph of a Kagome PMMA fiber shows its lattice structure and hollow core (a). The terahertz-TDS setup (b) used to characterize the fiber section (magenta color) includes an acousto-optic modulator (AOM), two off-axis parabolic metal mirrors (OAPMs), a photoconductive antenna (PCA), and a symmetric-pass (S-P) lens. *(Courtesy of J. Anthony)*

Performance of terahertz kagome fibers

The underlying guiding mechanism of the kagome fibers does not rely on a photonic bandgap (an absence of photonic states in the cladding structure) to confine light in the core, but relies on an inhibited coupling mechanism instead, in which there is a reduced interaction between the core-guided modes and the cladding modes.[5, 6] The latter modes originate from the modes that are supported by the dielectric struts in the cladding. Strong power coupling between the modes occurs when they are at resonance. At nonresonant frequencies, however, the minimized physical overlap between the core and the cladding modes allow the core mode to remain propagating with low leakage (low loss).

By computing and comparing the Fourier transforms of the temporal signals with and without the fibers, we can extract the attenuation coefficient and the phase index of the guided mode in the fibers. Power-attenuation coefficients for the fibers, averaged over several lengths, can be seen in Fig. 2. The spectra show distinct loss peaks at certain frequencies, which we have identified as the resonant frequency (highlighted as a gray area in the figures) of the cladding mode.

Experimentally, at the resonant frequency we observed that the fundamental mode leaks into the cladding regions without vanishing. In the transmission windows, we found loss coefficients of about 1 cm^{-1} (4.3 dB cm^{-1}) between 0.75 and 1.1 THz for Kagome-1 and less than 0.6 cm^{-1} (2.6 dB cm^{-1}) in the 0.65–1.0 THz range for Kagome-2. The agreement with simulation results calculated using a finite-difference frequency-domain method is exceptional for Kagome-1 and still quite good for the Kagome-2 data. From these measurements, we estimate coupling efficiencies as high as 60% can be achieved with our lenses.

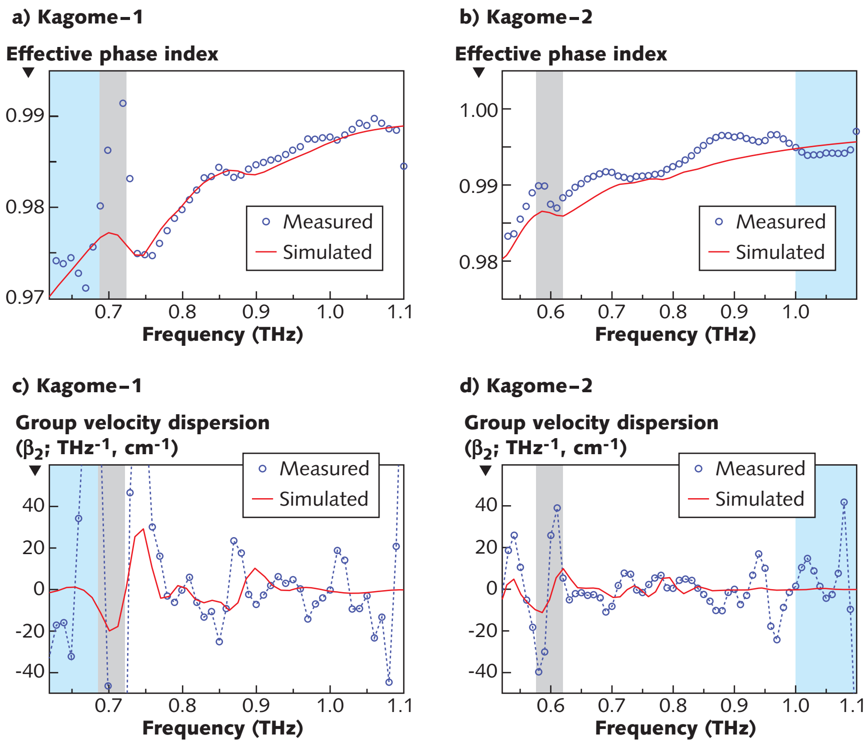

FIGURE 3. Mode-phase refractive indices (a, b) and group-velocity dispersion parameters (c, d) of the kagome fibers. Highlighted gray areas are regions where high losses occur at resonance, expected from the simulations. Light-cyan regions correspond to low signal-to-noise ratio in the experiments.

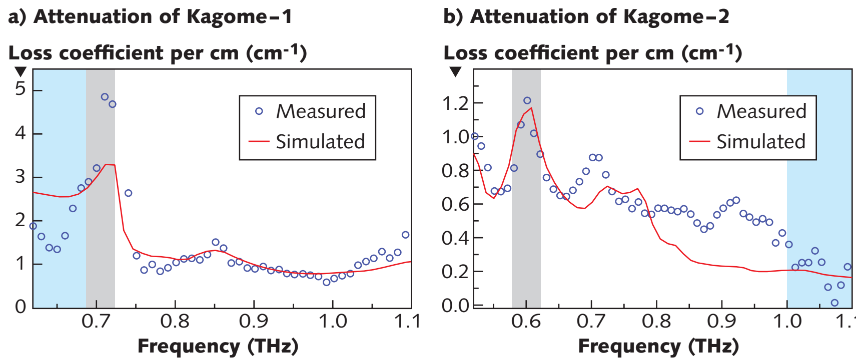

FIGURE 2. Kagome-1 and Kagome-2 loss spectra, respectively, are depicted (a, b). The highlighted gray areas are the regions where high losses occur at resonance, expected from the simulations. The light-cyan regions correspond to low signal-to-noise ratio in the experiments. The discrepancies shown between the experimental data and the simulation results are the consequences of surface roughness, as well as small imperfections of the fiber cross-section along the lengths of the fiber (variations in strut thickness affect the position of the loss peaks).

Lower losses in larger fiber

Comparing the data of the two fibers, the 38% lower losses achieved by the Kagome-2 are due to the larger core size of the fiber. The extent of the spatial overlap of the modes in the larger-core fiber is diminished due to the greater distance of the cladding walls from the center of the mode in the core. The core is sufficiently large to make the material absorption negligible, which also eliminates the need for using lower-loss materials. This is supported by simulations of an identical structure to Kagome-2, where we reduced the fiber material losses by 60 times in comparison to that of the PMMA, yet the loss figure obtained from this simulation was approximately the same as for the PMMA fiber.

Figure 3 shows the phase index of the fiber modes calculated from the extracted phase details and adjusted for the 2π phase ambiguity. In the resonance regimes (highlighted gray areas) we see that the rapid changes in the phase index of the modes do not originate from the noise of the data, but are the signatures of the limit of the phase mismatch or the avoided crossing between the core and the cladding modes. Outside the high-loss regions, the core mode propagates with an effective phase index close to that of air, showing good agreement with the simulation results.

For broadband pulse systems, it is important to evaluate the group-velocity dispersion (GVD) of the pulses propagating through the kagome fibers. The GVD parameter is the measure of the pulse spreading over the distance traveled and is analytically expressed as $\partial^2\beta/\partial\omega^2$, where β is the propagation constant related to $n\omega/c$ (n is the effective mode phase refractive index; ω is the angular frequency; and c is the speed of light).

As shown in Fig. 3, the GVD parameter evaluated from the experiments conforms to the pattern exhibited by the GVD values obtained from simulations in the range where the signal-to-noise ratio is large. The larger fluctuations in the data points, especially at higher frequencies, are caused by the amplification of the noise as a result of differentiating the function of the phase index twice. Overall, both of the kagome fiber GVD simulation results show they can achieve very low dispersion over a wide spectral band, comparable to what can be achieved, for instance, in a solid-core PCF.[7]

These low-loss, low-dispersion kagome terahertz fibers may find niches not only in broadband terahertz guidance, but also in terahertz-sensitive sensing of thin films deposited in the fiber structure and studies of terahertz light-matter interaction with gases and plasmas inside the fiber core. ◄

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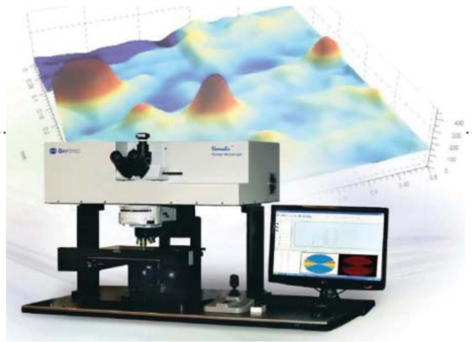

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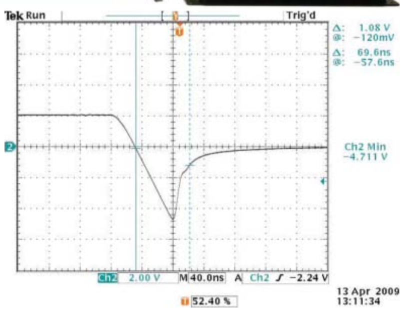

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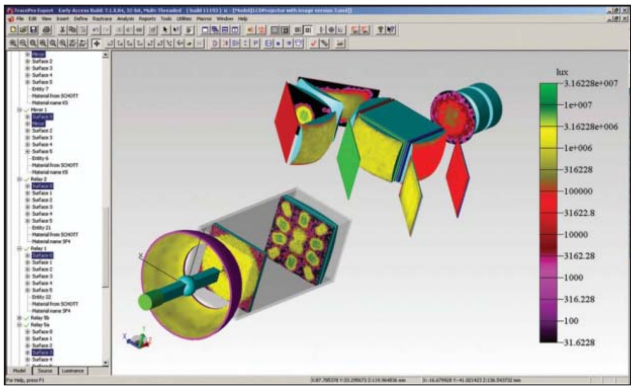

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IN MY VIEW

BY JEFFREY BAIRSTOW

The coming switch to LED lamps

In the fast-moving semiconductor world, it's kind of peculiar how the same players develop similar products but they rarely manage to make the one truly great hit. Ignore the software developers who are off on cloud nine with their abominable "social networking" software packages. I'm talking about hard-core products and associated programs that real engineers put together.

Having said that, does the name "Nakamura" mean anything to you? Probably not, unless you are a Japanese semiconductor designer. In Japan the name is especially well known in the rapidly expanding world of electric lamps that are not incandescent. LEDs and LCDs are prime examples of this new breed of industrial and domestic lamps. Professor Shuji Nakamura has had a hand in the development of all these non-incandescent lamps.

Nakamura's latest and brightest is an LED based on gallium nitride (GaN). The problem is that GaN chips are difficult to manufacture in large quantities. This is where Professor Nakamura steps in. In a prior incarnation, Nakamura successfully developed the blue semiconductor LED, a notoriously difficult thing to do at the time. Just to make life even more difficult for him, Nakamura's then employer, Nichia, threw the Japanese legal code at Nakamura, who in a Dickensian battle won his case but who also lost his prime research position at Nichia.

Fortunately, Nakamura found a home in the well known Materials Department at UCSB (University of California–Santa Barbara). He also joined a team of developers of GaN devices under the wing of Eric Kim, a former Intel executive. Kim's company, Soraa Inc. (Fremont, CA), recently obtained more than \$100 million of venture financing with the help of legendary Silicon Valley venture capitalist Vinod Khosla.

Nakamura also won the Finnish 2006 Millennium Technology Prize, worth about \$1.5 million, for his work on blue and white LEDs. This is the technology used today in the high-performance Blu-ray disc players.

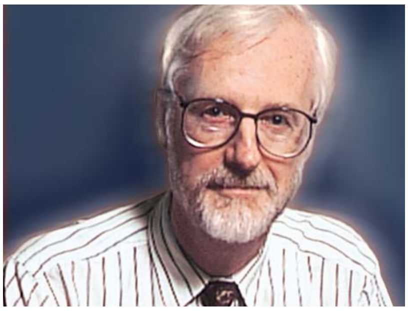
Soraa is facing several major international makers of incandescent lamps, many of which are also researching LED lamps. The makers are working hard to get the manufacturing costs down for the market-leading 60-W-equivalent lamps. The Lumileds division of European giant Philips NV expects to have a single-chip lamp comparable to the conventional 50 W bulb for a retail price of \$50 by year's end.

Soraa is expected to have a comparable product available using a technology called GaN on GaN. This product can be made on a conventional silicon wafer line, thus bringing down manufacturing costs. However, the yield of a GaN wafer is much lower than a conventional silicon wafer line. Nonetheless, Nakamura is confident that Soraa will have a competitive product by year-end.

Soraa may be in the right place at the right time with this new product. According to Ryan Sanderson of IMS Research, "Demand for LED lighting solutions is increasing rapidly for all applications from low-power residential retrofit LED lamps to high-power commercial and industrial LED luminaires for applications such as street lighting."

Although Soraa appears to have the pole position with GaN on GaN technology, several Taiwanese semiconductor makers are reporting significant success with alternative technologies, such as GaN on silicon. In my view, the companies with the deepest pockets for refining their manufacturing processes will win the initial battles, but in the long run, single-chip lamps appear to be poised to win overall.

Once more, Shuji Nakamura seems to be leading the pack in research, but Soraa may not have the long-term funding of a Phillips or a GE to become a leader in the mass-market production of LED lamps.



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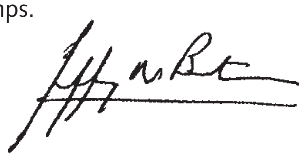

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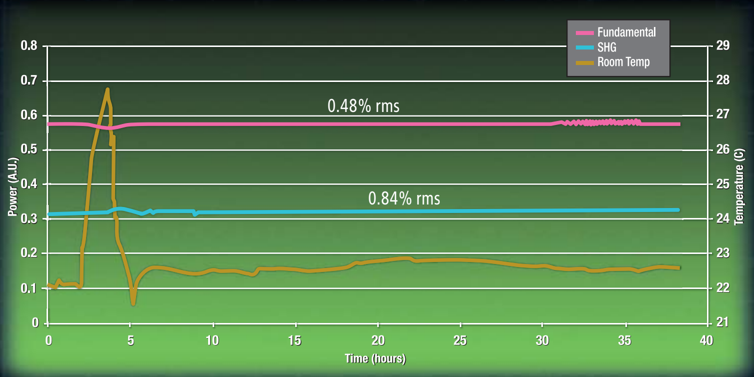

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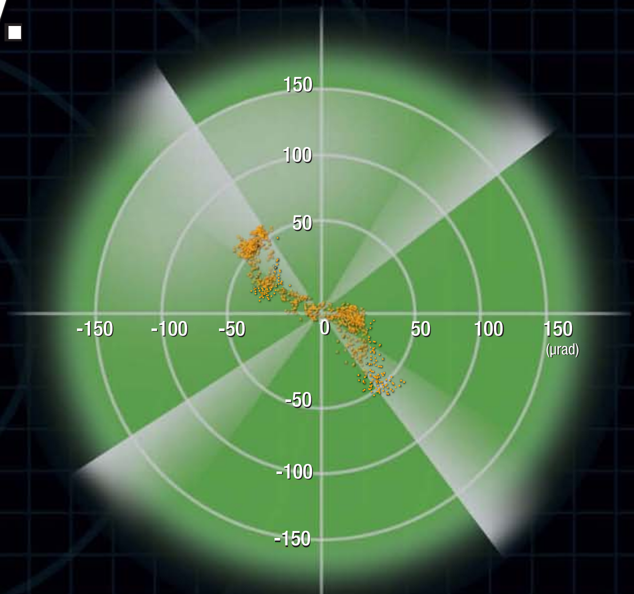

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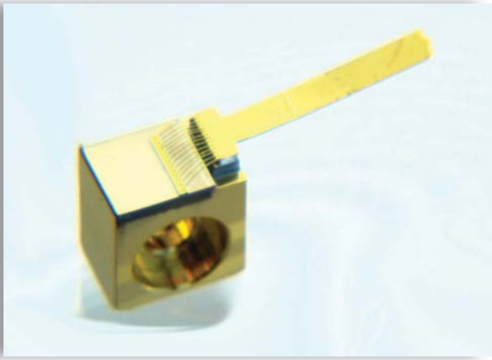

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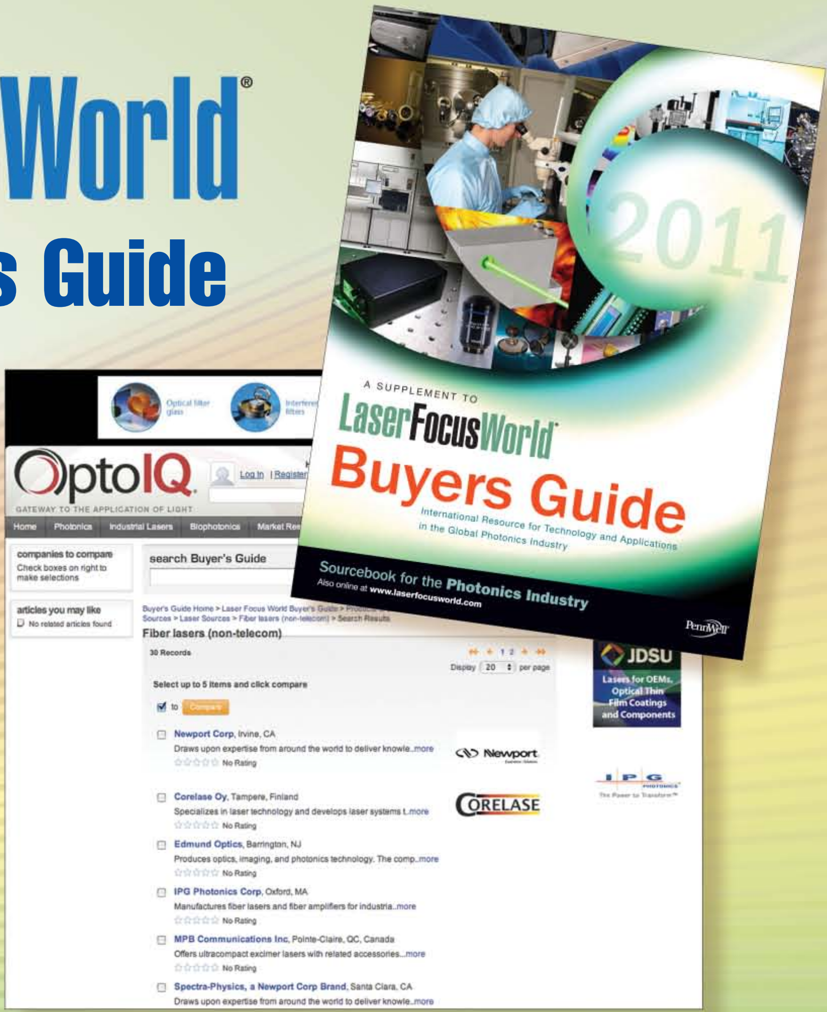

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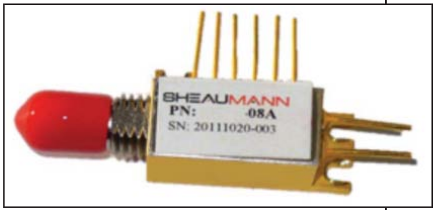

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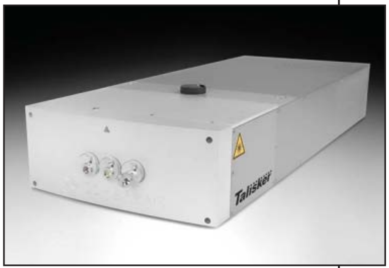

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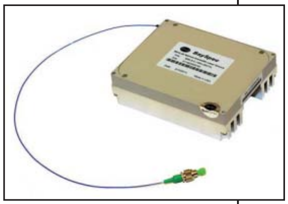

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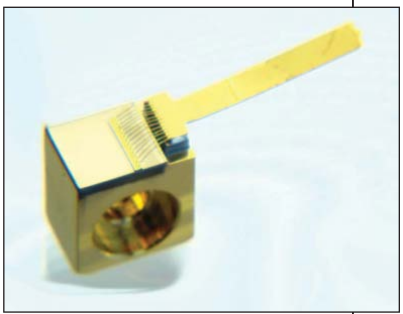

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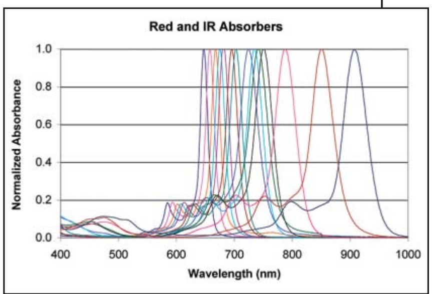

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APRIL 2012

April 9–13 **Materials Research Society Spring Meeting 2012** *MRS* San Francisco, CA, USA www.mrs.org

April 11–13 **Photonix Expo & Conference 2012** *Reed Exhibitions Japan* Tokyo, Japan www.photonix-expo.jp/en/

April 16–20 **SPIE Photonics Europe 2012** *SPIE* Brussels, Belgium http://spie.org/photonics-europe.xml

April 17–19 **Smart Fabrics 2012** *IntertechPira* Miami, FL, USA www.smartfabricsconference.com

April 18–30 **ECIO 2012 – 16th European Conference on Integrated Optics** *ICFO* Barcelona, Spain www.ecio2012.com

April 23–27 **SPIE Defense, Security + Sensing** *SPIE* Baltimore, MD, USA http://spie.org/defense-security-sensing.xml

April 28–May 3 **SVC TechCon 2012 – Society of Vacuum Coaters 55th Annual Technical Conference** *SVC* Santa Clara, CA, USA www.svc.org

MAY 2012

May 6–11 **CLEO 2012 – Conference on Lasers and Electro-Optics** *OSA* San Jose, CA, USA www.cleoconference.org

May 9–11 **AKL – International Laser Technology Congress** *Fraunhofer ILT* Aachen, Germany www.lasercongress.org

May 20–23 **Optical Interconnects Conference** *IEEE Photonics Society* Santa Fe, NM, USA www.photonicsconferences.org

May 22–25 **Optatec 2012** *P.E. Schall GmbH & Co.* Frankfurt, Germany www.optatec-messe.com/en/optatec

JUNE 2012

June 1–2 **2012 International Conference on Solid State and Materials** *ICSSM* Los Angeles, CA, USA www.hkedu.biz/icssm2012/index.htm

June 3–8 **Display Week 2012** *SID* Boston, MA, USA www.sid.org

June 4–8 **2012 International Workshop on EUV Lithography** *EUV Litho Inc.* Maui, HI, USA www.euvlitho.com

June 6–8 **Photonics North 2012** *SPIE/ICIP* Montreal, QC, Canada www.photonicsnorth.com

June 11–14 **QIRT 2012 – Quantitative Infrared Thermography Conference** *University of Naples Federico II* Naples, Italy www.qirt2012.unina.it

June 19–21 **AATExpo 2012 – Assembly & Automation Technology Expo** *UBM Canon* Chicago, IL, USA www.canontradeshows.com/expo/aatexpo11/

JULY 2012

July 1–6 **SPIE Astronomical Telescopes and Instrumentation 2012** *SPIE* Amsterdam, the Netherlands http://spie.org/astronomical-instrumentation.xml

July 9–11 **Summer Topicals 2012** *IEEE* Seattle, WA, USA www.sum-ieee.org

July 10–12 **Semicon West 2012** *SEMI* San Francisco, CA, USA www.semiconwest.org

July 10–12 **Intersolar North America 2012** *Solar Promotion International GmbH* San Francisco, CA, USA www.intersolar.us

July 25–27 **MATADOR Conference** *University of Manchester* Manchester, England https://www.meeting.co.uk/confercare/matador2012/

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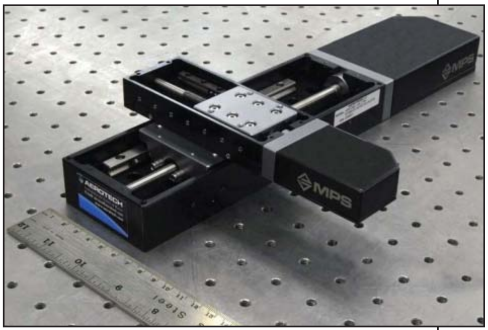

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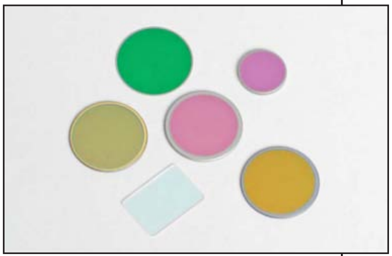

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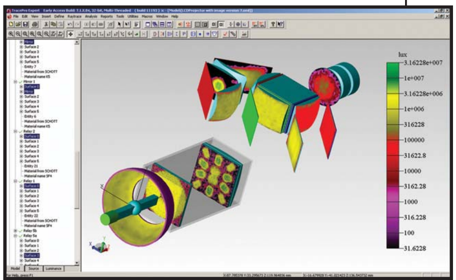

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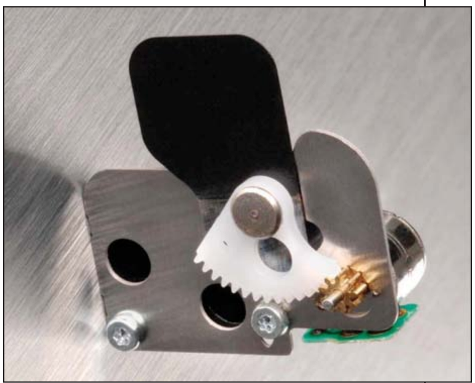

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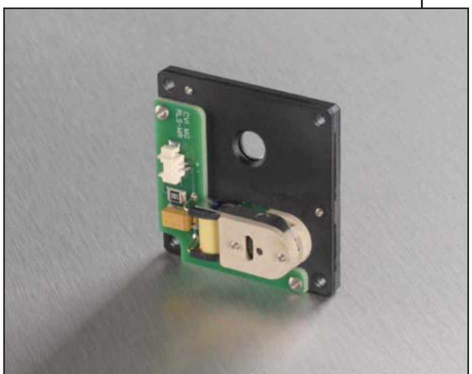
Heavy Duty Laser Shutter

- Multimillion cycle life
- Fail-safe magnetic return
- No separate controller required
- High LDT blade coating



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