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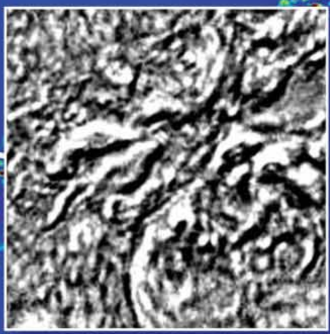

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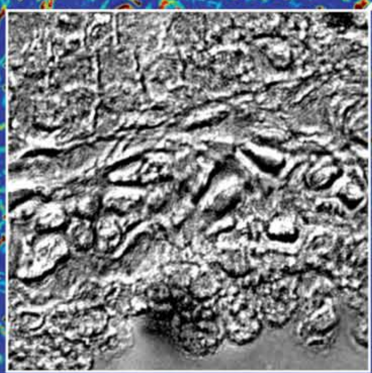

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AUGUST 2012 ▪ VOL. 48, NO. 8

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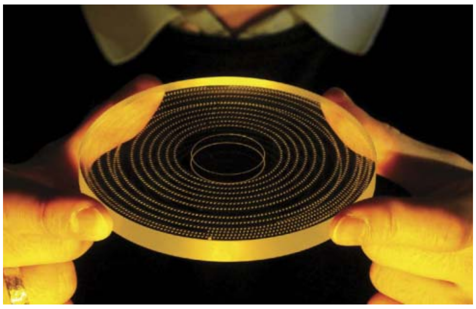

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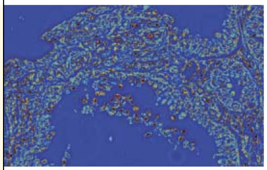

41 COVER STORY
Noninvasive contrast-generating microscopy methods are moving clinical pathology toward real-time disease diagnosis. A quantitative phase image of a prostate biopsy is stitched together from many smaller field-of-view images. Gradient-field microscopy (GFM) images zoomed in black-and-white show the same biopsy tissue. (*Courtesy of University of Illinois at Urbana-Champaign*)

Coming in September

Celebrating 50 years of laser diodes: Direct diode pumping of Ti:sapphire lasers

Christopher Wood of KMLabs details a new approach to pumping modelocked Ti:sapphire ultrafast lasers: using blue laser diodes for direct pumping. Replacing yttrium vanadate ($Nd:YVO_4$) pump lasers with blue diodes greatly reduces the overall ultrafast-laser size and makes it more reliable, more rugged, and less expensive—and is a symbol of how far laser diodes have come in their 50 years of development.

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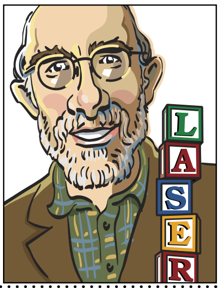
More Features, News & Products

cool content

Blog: Spectral Bytes – NEW!

Chew on this

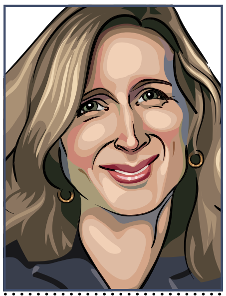
Laser Focus World contributing editor and industry expert Jeff Hecht serves up his thoughts on everything in the spectrum of photonics and optoelectronics, starting with an interest in optics that stems from an early fascination with astronomy. Snack on Spectral Bytes during your next break!
http://bit.ly/R3G7oV



Blog: Photonics Education Corner

Filling Your Workforce Pipeline—Part 2 —Actions You Can Take

One of the commenters on part 1 of this post suggests that the shortage isn't in technicians, it's in higher-level engineers. He points out that engineering is competing (and losing out) against medicine and law. True, and whether it's technicians, engineers, or both in your city, we need to keep more kids interested in STEM (science, technology, engineering and math).
http://bit.ly/Oxw4UI



Video: Weekly Newscast

Fix your focus on our 'fast five'

Our photonics correspondent Lee Mather brings you the quick takes on top stories from Laser Focus World, BioOptics World, and Industrial Laser Solutions for express delivery every week. From leading-edge research and commercial developments to late-breaking company news and market reports, you'll find all the news you need in five minutes or less.
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trending now

'Digest' optical principles of microscopy
Our technical digest "Medical Imaging: Innovations in Microscopy" highlights both enhancements and a redesign approach to the optical microscope.
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See the latest Video Interview
Chief editor Conard Holton talks optics shop with ASE Optics' Chris Cotton, who notes areas of growth for optics, such as biomedical and industrial imaging.
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Panoramic Optics

Two freeform reflectors control ray bundles exactly
The use of two reflectors in freeform optics results in exact solutions for manipulating rays to form panoramic and other types of images.
Christopher Croke and R. Andrew Hicks
http://bit.ly/SXIjfT

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editor's desk

Antidote to short-term thinking

Uncertainty and turmoil in global markets is raising economic concerns, but for investors in and members of the photonics community the long-term value of photonics remains clear. The forthcoming "Harnessing Light" report, to be introduced at the SPIE Optics+Photonics Conference in San Diego (August 12–16), will be an opportunity to describe to the public and policy makers the critical roles that we know optics and photonics play in our economy, security, and personal lives.

The report is published by the US-based National Academies and written by photonics researchers and business leaders. If the companies, research groups, and professional societies in the photonics community work to advance its findings, then real progress could be made in priorities such as ensuring competitive strength, meeting workforce needs, and continuing to build a sound research and manufacturing infrastructure.

For our part, the staff of *Laser Focus World* will continue to bring our worldwide audience articles on the most recent technology developments, market trends, and products. Our cover article reports on work by researchers at the University of Illinois at Urbana-Champaign that uses gradient field microscopy to help change clinical pathology (page 41). Other reports show advances in green laser diodes for highly efficient displays (page 20) and the growing use of optical fibers for sensing in harsh environments, such as oil and gas wells (page 27). And contributing editor Jeff Hecht summarizes many of the recent developments in quantum-cascade lasers, which are enabling exciting applications that range from sensitive measurement devices to military countermeasures (page 53).

As photonics entrepreneur and investor Jan Melles writes in this issue's Market Insights column (page 37), the investment of sufficient funds for R&D is critical to ensuring the success of individual companies. We urge a similar way of thinking when it comes to photonics and the future.

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

LaserFocusWorld

Christine A. Shaw Senior Vice President & Group Publisher, (603) 891-9178; christines@pennwell.com
W. Conrad Holton Editor in Chief, (603) 891-9161; cholton@pennwell.com
Gail Overton Senior Editor, (603) 305-4756; gailo@pennwell.com
John Wallace Senior Editor, (603) 891-9228; johnw@pennwell.com
Carrie Meadows Managing Editor, (603) 891-9382; carriem@pennwell.com
Lee Mather Associate Editor, (603) 891-9116; leem@pennwell.com

CONTRIBUTING EDITORS
Jeffrey Bairstow In My View, inmyview@yahoo.com
David A. Belforte Industrial Lasers, (508) 347-9324; belforte@pennwell.com
Jeff Hecht Photonic Frontiers, (617) 965-3834; jeff@jeffhecht.com
D. Jason Palmer Europe, 44 (0)7960 363 308; djasonpalmer@gmail.com

Adrienne Adler Marketing Manager
Suzanne Heiser Art Director
Sheila Ward Production Manager
Chris Hipp Senior Illustrator
Debbie Bouley Audience Development Manager
Alison Boyer Ad Services Manager

PennWell

EDITORIAL OFFICES
Laser Focus World
PennWell Corporation
98 Spit Brook Road, LL-1, Nashua, NH 03062-5737
(603) 891-0123; fax (603) 891-0574
www.laserfocusworld.com

CORPORATE OFFICERS
Frank T. Lauinger Chairman
Robert F. Biolchini President and CEO
Mark Wilmoth Chief Financial Officer

TECHNOLOGY GROUP
Christine A. Shaw Senior Vice President/ Group Publishing Director

Subscription inquiries
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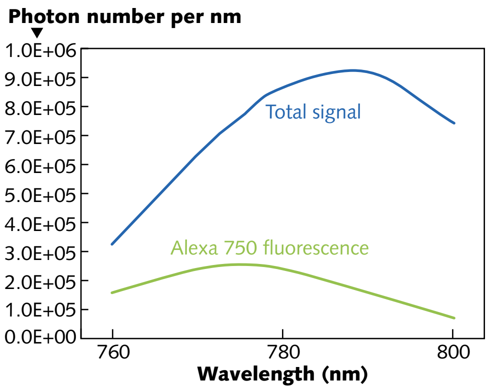
newsbreaks

Software simulates laser-based measurements for flow cytometry

Researchers at Simphotek Inc. (Newark, NJ) have developed a simulation tool that uncovers hidden mechanisms of potential false readings in flow cytometry. Flow cytometry is used extensively in biology and medicine, where a group of cells labeled with a fluorescent probe molecule or dye is focused into a single cell stream passing through a laser light source. The fluorescent light is filtered and sampled by an array of detectors. Traditionally, one light source and one type of probe molecule/dye have been used, but additional information can be obtained if multiple lasers and multiple probes fluorescing at different wavelengths are used. By using its SimphoSOFT software, Simphotek's R&D team recently discovered that significant false signals may occur in multiwavelength and multiprobe experiments not only due to fluorescence overlap, but also the often unanticipated phosphorescence overlap.

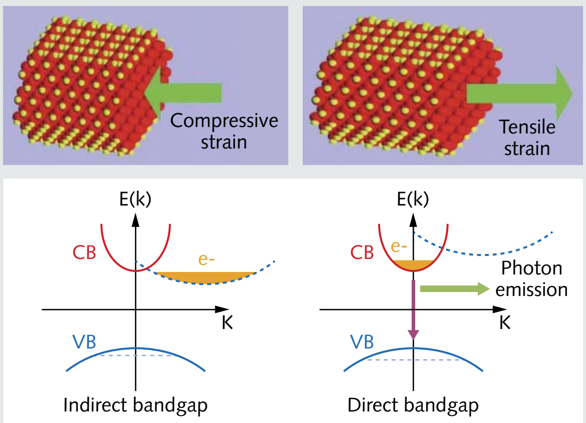
Phosphorescence emission generally has not been considered problematic in flow cytometry. However, numerical simulations performed by the group show that problematic or false signals from phosphorescence can range from 40% to greater than 500% of the correct (fluorescence) signal, leading to possible misinterpretations of biological results—for example, cancer cells not present when, in fact, many are. In some cases, measuring the signals in wavelength or detector channels before and after each probe is used may mitigate or reduce spectral overlap; however, false results may be unaccounted for due to limited detector sensitivity. SimphoSOFT can select a particular combination of probe molecules ahead of measurements by determining if the probe molecules may be problematic, and can correct and/or check post-experiment measurements by calculating and removing any undetected false signals.



In addition to emission intensity, the group's software also calculates photobleaching, singlet oxygen formation, energy transfer, and upconversion in multiple fluorescent probes used in biology and medicine. *Contact Mary Potasek at* mpotasek@simphotek.com.

Strain controls spontaneous emission in silicon nanowires

The direct bandgap due to quantum confinement, adjustable bandgap, sensitivity to surface ligands and mechanical excitation, and compatibility with mainstream silicon technology of silicon nanowires makes them excellent candidates for optoelectronic devices. Now, researchers at the University of Waterloo (Waterloo, ON, Canada), in collaboration with Texas A&M University–Kingsville and University of Washington–Seattle, have discovered that uniaxial strain can modulate the spontaneous emission of photons in silicon nanowires—a finding that improves the potential for these devices to function efficiently in a variety of optoelectronic applications, including a mechanism for lasing.

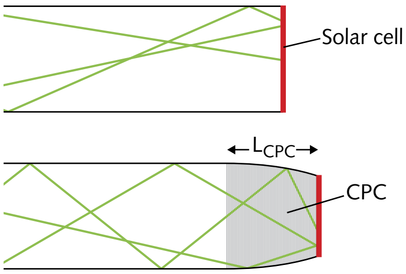


Using silicon nanowires ranging in diameter from 1.7 to 3.1 nm that have a direct bandgap at 0% strain, the researchers showed that compressive strain increased spontaneous emission time by one to two orders of magnitude. This occurs due to either the change of wave-function symmetry or direct-to-indirect bandgap conversion. To create a population inversion in silicon nanowires, current can be injected in a compressively strained nanowire with an indirect bandgap in which the light emission is a slow second-order process (mediated by phonons). During strain release or by applying tensile strain, the initial population can scatter into the direct sub-band via fast electron-phonon scattering processes. This initiates lasing if the nanowire is embedded in a suitable mode-enhancing cavity. *Contact Daryoush Shiri at* dshiri@uwaterloo.ca.

newsbreaks

Luminescent solar concentrator gets more efficient with addition of CPC

Luminescent solar concentrators (LSCs) are slabs of transparent material containing a dye or other material that absorbs light at one wavelength and emits at another; the light collects via total internal reflection at the edges and is concentrated. Compound parabolic concentrators (CPCs) are nonimaging optics that maximally concentrate angularly spread incoming light. These two devices have been independently used to concentrate solar radiation; now, researchers at Pennsylvania State University (University Park, PA) are combining the two to boost the concentration ratio of LSCs.

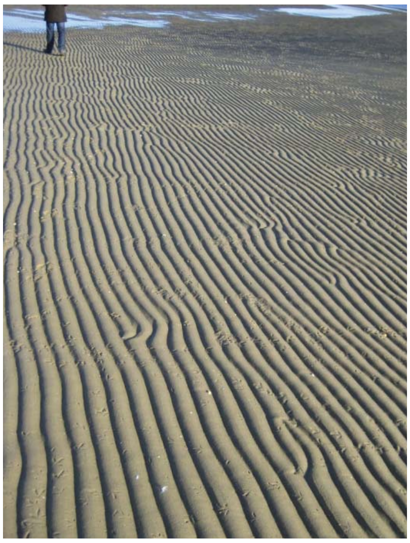


At the moment existing only as a simulation, the design modeled by the researchers boosts the concentration ratio of the combined device (see figure, bottom) by 23% over that for the LSC alone (see figure, top), while maintaining greater than 90% of the original LSC's optical efficiency. This is when applied to only a single edge of the LSC. If applied to all four edges of the LSC, the intensity is boosted by 35%, still maintaining greater than 90% of the original optical efficiency. The addition of the CPCs would allow smaller photovoltaic cells (the most expensive component of a luminescent solar concentrating system) to be used, while contributing only a small amount to manufacturing costs.

The researchers say that LSCs with highly directional luminescence in particular will benefit highly from the addition of CPCs. *Contact Noel Chris Giebink at* ncg2@psu.edu.

newsbreaks

Ultrashort laser pulses mimic natural wave patterns



Researchers at the University of California–Los Angeles (UCLA) and the University of Göttingen (Göttingen, Germany) have used a unique high-speed measurement technique to demonstrate that patterns that develop in ultrafast laser pulses mimic wave patterns found in nature. Not otherwise discernible with conventional ensemble measurement methods, the patterns were seen by analyzing single-shot spectra of "modulation instability"—a nonlinear interaction that leads to pattern formations in nature such as sand ripples, water waves, and heart rhythms—produced by ultrashort laser pulses in optical fibers.

In the experiment, 1550 nm, 25 MHz repetition-rate, 3 ps pulse-duration laser pulses are injected into a nonlinear optical fiber to create spontaneously growing oscillations (frequency modes) that are then captured by stretching the output in a spool of dispersive fiber to record the subnanometer optical spectrum of each pulse. Statistical analysis of the thousands of individual pulses allows the researchers to identify an interactive effect between the frequency modes: within a pulse, overlapping modes at similar frequencies either unite or suppress each other, leaving only one to dominate in the end. Conventional time-averaged measurement records spectrally broad modulation-instability sidebands (well-known in nonlinear optics), hiding the interactive effect between the underlying discrete modes. Their observations suggest that similar interactions may be at work in other physical contexts (for example, sand undulations) in which single temporal or spatial patterns become dominant. *Contact Daniel Solli at* solli@ucla.edu.

1D beam steerer operates at MHz speeds, will go much higher

A high-speed laser-beam steering technique developed at Lincoln Laboratory (Lexington, MA) currently can steer at a 40 MHz speed and has the potential to reach gigahertz steering speeds. The one-dimensional steerer is based on a six-element optical phased array and subsequent coherent beam combining. The total optical output power of the device is now 396 mW and can be scaled to multiwatt output. A stochastic-parallel-gradient-descent (SPGD) algorithm is used to maintain the phaselocking, keeping the on-axis intensity high.

The output from a narrow-linewidth Nd:YAG laser is split and sent to six commercial lithium niobate phase modulators (with phase adjusted by varying the current) and then amplified by an array of diffraction-limited slab-coupled-waveguide semiconductor amplifiers. The SPGD algorithm, which is controlled by real-time Linux software, dithers the phase of the modulators at 1 kHz to obtain the phase corrections needed to maximize the on-axis intensity. A movable fiber-coupled (6.25-μm-diameter fiber tip) high-speed indium gallium arsenide detector is used to sample and measure the beam-steering performance at high speeds. The experimental full-width at half-maximum (FWHM) central lobe width was measured to be 565 μrad (only 5% above the ideal); the steering range was 0.24°, limited by the array diffraction-lobe spacing. *Contact W. Ronny Huang at* we1748@mit.edu.

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Superior Reliability & Performance

world news

sapphire fibers improved
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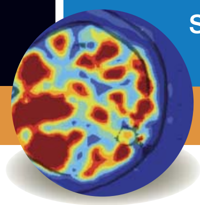

Technical advances from around the globe

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ULTRAFAST LASERS

Few-cycle pulses create intense attosecond bursts

A pan-European team of researchers has succeeded in creating isolated attosecond pulses with unprecedented intensity. The technique opens the way for material-physics investigations using both attosecond-scale pump beams and probe beams. The approach behind the advance makes use of few-cycle, femtosecond-scale pulses to ablate the surface of a mirror, creating a plasma. Two separate but related conversion processes then come into play, with their relative contributions dependent on the input intensity.

One of them, coherent wake emission (CWE), is a recently discovered effect, first put forth by Fabien Quéré of the Department of Research in Condensed Matter, Atoms, and Molecules at CEN Saclay (Gif-sur-Yvette, France) in 2007.[1] Coherent wake emission is a kind of "push-pull" effect on the plasma electrons: As the plasma oscillations flow into and out of phase with the input laser's electric field, they are periodically excited by attosecond electron bunches, resulting in the emission of sub-femtosecond harmonics up to the plasma frequency.

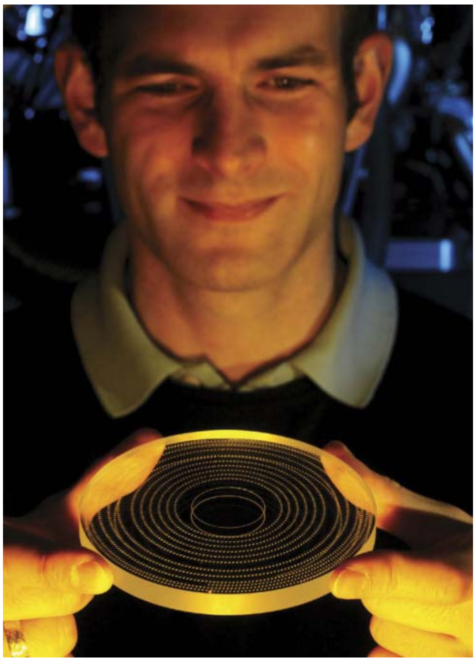
Since that time, such short pulses have been created by exploiting CWE, notably by a collaboration led by researchers at the Max Planck Institute for Quantum Optics (MPQ; Garching, Germany), who recently used extreme-UV (XUV) autocorrelation to get a full temporal characterization of their sub-femtosecond pulses.[2]

Relativistic oscillating mirror

However, at a threshold intensity, another effect becomes dominant: The relativistic oscillating mirror, or ROM. The ROM effect occurs when the intense input field drives the surface of the plasma, causing electrons to oscillate at relativistic speeds. The periodic phase modulation in the reflected beam gives rise to harmonics of the laser frequency, and the conversion process can lead to higher output photon energies than CWE.

Now the MPQ researchers, in collaboration with researchers at the Foundation for Research and Technology Hellas (Crete, Greece) and Queens University Belfast (Belfast, Ireland) are pushing ROM to its limit, demonstrating the first relativistic harmonic generation triggered by few-cycle pulses. The team used a laser source based on noncollinear optical parametric chirped-pulse amplification to create input pulses of 8 fs duration—just three cycles of the field—and 16 TW of peak power, incident on a fused-silica blank as the solid-target source of the plasma.

The researchers found that the output neatly matched their particle-in-cell simulations of the ROM process: For 17% of the input pulses, a single XUV attosecond-scale pulse was created, with a wavelength as small as 17 nm. About a third of the time, a pair of pulses was produced, and half the time, a triplet.[3] The team estimates that future improvements to their laser, bringing it down to a 5 fs pulsewidth, will result in a greater than 50% chance of single pulses.



Patrick Heissler, lead author of the study, holds a silica blank; plasma formation destroys small regions on the rotating blank. (*Courtesy of T. Naeser*)

Moving target

Patrick Heissler, lead author of the study, believes the method holds more promise for future attosecond pulse sources than more established methods. "The approach to isolated attosecond pulse production we demonstrate promises unprecedented attosecond pulse intensities," he says. "Compared to state-of-the-art attosecond pulse sources based on gas harmonics, higher conversion efficiencies into the XUV are predicted. Due to the direct use of the plasma medium, no limitations on the laser pulse intensities are implied and hence a high-intensity driving laser can be efficiently exploited."

However, the creation of the plasma that drives the whole technique is

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inherently a destructive process (see figure). "A very clean interaction surface is necessary but the target surface is destroyed with every laser shot. Hence, a fresh piece of target needs to be provided for every new laser pulse," says Heissler. "In current systems, the used glass target is rotated and/or shifted to provide a clean surface, allowing repetition rates on the order of kilohertz. For future experiments, new target systems like tape drives or liquid jets need to be developed."

Once target issues are addressed, though, the only limiting factor in the XUV photon energy and attosecond pulsewidth at the output is the intensity and pulsewidth of the input laser.

—Jason Palmer

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2. R Hörlein et al., *New J. Phys.*, 12, 043020 (2010).
3. P. Heissler et al., *Phys. Rev. Lett.*, 108, 235003 (2012).

MICRO-OPTICS

Stack-and-draw produces nanostructured lenses

A stack-and-draw process for fabricating nanostructured micro-optics developed by engineers at Heriot-Watt University (Edinburgh, Scotland) and the Institute of Electronic Materials Technology (Warsaw, Poland) is pointing the way to low-cost manufacture of microlenses and other small optical elements.[1] In addition, it allows the making of novel broadband birefringent micro-optics.

In the process, many glass rods of a certain diameter between 0.25 and 1 mm are assembled by hand into a fiber preform that may contain between 2000 and 10,000 individual rods (see figure). The preform, on the order of 50 mm in diameter, contains rods of one type of glass in a matrix of a second type of glass. The preform is then drawn down to a 1 mm diameter; these intermediate preforms are then arrayed together to an approximately 50 mm diameter and drawn down again to a 1 mm final diameter or smaller.

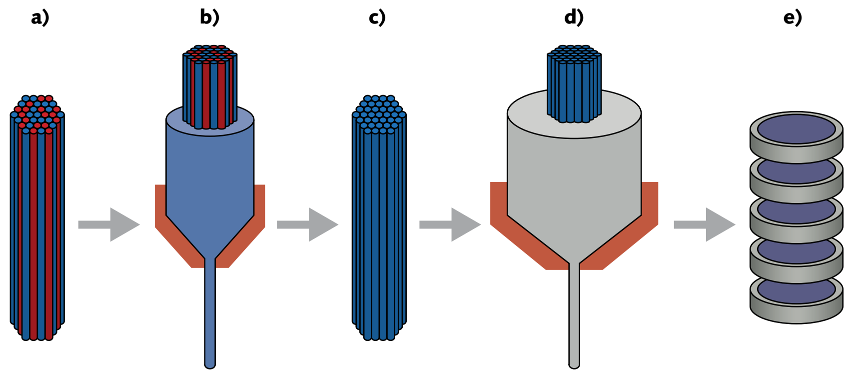
The result is a nanostructured glass with a refractive index intermediate between the two starting glasses. By varying the ratio of the rods in the preform, the index can be custom-tailored. And, by assembling intermediate preforms together that have different refractive indices, the result is a microlens with areas of differing index—for example, a Fresnel-type microlens with rings that each have their own distinct indices.

The two glasses must have matching mechanical and thermal properties so that there are not discontinuities when the preforms are drawn. The

experimenters used F2, an off-the-shelf glass by Schott (Mainz, Germany), and a custom glass termed NC21A developed at the Institute of Electronic Materials.

The final nanostructure is far enough below a wavelength in period that no diffraction occurs in the rod lattice; instead, an effective refractive index is the result, with the index being a spatial average of the refractive indices of the component nanorods. To confirm this theoretically, the researchers compared their effective-refractive-index calculations with a fully vectorial solution to Maxwell's curl equations and found the difference was small.

An example fabricated microlens contains seven different kinds of "metarod" (the structures corresponding to the intermediate preforms); each metarod is 1.2 μm in diameter and contains 2500 rods within it of 20 nm diameter. About 10,000 of these metarods are hexagonally packed in a Fresnel-zone pattern to form the lens. Fabricating the lenses is easy: Just take a lateral slice from the final drawn fiber and polish the faces flat. Diffraction-limited performance was achieved at 633 nm (0.6 μm spot size) and 850 nm (0.9 μm spot size).



In the stack-and-draw process, an array of glass rods with differing indices (a) is placed in a glass cladding (b) and drawn down to produce a metarod (c). Many metarods (d) are then placed together and drawn down again to provide the final structure, which can be sliced up into microlenses (e).

Form birefringence

A different type of nanostructure can be created that has form birefringence—which could be taken advantage of in some situations. If the initial structure to be drawn down consists of glass slabs with alternating refractive indices, after drawing the result is a nanostructured birefringent material. The glass slabs were created by patterning the initial 1-mm-diameter glass rods in alternating linear arrays before drawing down. In this case, the structure did not have to be reduced in size as much; the quarter- to half-wavelength period meant an easier draw-down procedure.

The researchers calculated the birefringence over a wavelength range from 500 to 2000 nm (the birefringence varies with wavelength as a result of dispersion) as a function of the nanostructure period; this allowed them to choose the best experimental period for a fabricated nanostructure. The birefringence of the fabricated structure was characterized, showing that the 10.77-mm-thick sample had a retardation (the phase difference at exit between the two orthogonal polarizations) between 5.3 and 5.7 radians.

The researchers note that the flexibility in positioning rods of different glass types, and arranging the metarods, could allow the fabrication of very interesting optics that include nonspheric index profiles and general diffractive optical structures. —*John Wallace*

ACKNOWLEDGMENT

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REFERENCE

1. M.R. Taghizadeh et al., *Adv. Opt. Technol.*, 1, 3 (2012).

ENDOSCOPY

Dual-wavelength method brings zoom capability to microendoscopy

Most optical endoscopes for light delivery and *in vivo* imaging of biological tissues have a fixed field of view (FOV) and resolution, primarily because they use a graded-index (GRIN) or other lensing method that typically prohibits the use of optomechanics to enable zoom capability, due to the overwhelming need for miniaturization. But researchers at Cornell University (Ithaca, NY) have developed a clever dual-modality 9X zoom optical endoscope with no moving parts that will significantly expand the usefulness of microendoscopy.[1]

By simply switching the wavelength of the excitation light, the user can switch between a high-magnification, high-resolution, small-FOV multiphoton fluorescence modality and a low-magnification, low-resolution, large-FOV one-photon reflectance modality. The device should prove extremely useful in a clinical setting where large-FOV imaging could be used to identify a tissue area for study, followed by immediate small-FOV and high-resolution imaging to reveal cellular details at sites of interest on the tissue, for example.

Zoom optics

The dual-modality microendoscope consists of a three-element optical system (see figure). The first element simply focuses the light slightly from the delivery/scanning optical fiber. The light then passes through the second element onto a multilayered, patterned dichroic coating at the center of the third element. Depending on the wavelength, the (800 nm) light is either reflected to the dichroic coating on the upper and lower portion of the second element and then focused to the sample with high numerical aperture, or the light (406 nm) is transmitted and focused through the third element to the sample with low numerical aperture.

This 3-mm-diameter "zoom" objective is then paired with a miniaturized resonant/nonresonant fiber raster scanner. The scanner is basically two scanning optical fibers glued together: 1) a hollow-core photonic-bandgap fiber that transmits light at 800 nm for high-resolution multiphoton imaging and 2) a standard singlemode fiber that transmits 400 nm light for large-FOV, one-photon imaging.

Imaging studies were performed by coupling 800 nm femtosecond pulses into the hollow-core fiber and continuous-wave 406 nm light from a laser diode into

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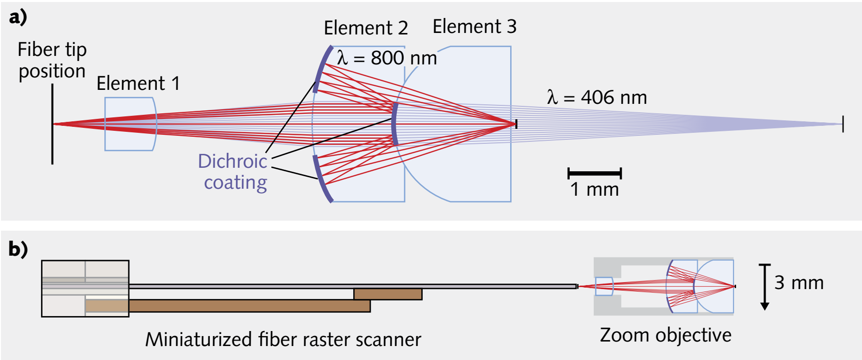

A three-element, dual-modality microendoscope (a) operates with effective 9X zoom capability simply by switching the excitation wavelength used. The zoom element is attached to two fibers for imaging (b).

the standard fiber. Using US Air Force test targets, the full-width half-maximum (FWHM) lateral resolution of the high-magnification mode was approximately 0.8 μm with a 150 μm FOV, while the FWHM lateral resolution of the low-magnification mode was approximately 4.5 μm with a very large 1.3 mm FOV. The dual-modality capability of this system has been experimentally demonstrated using unstained *ex vivo* mouse lung tissue, with excellent imaging results. —*Gail Overton*

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SEMICONDUCTOR LASERS

Green laser diode emits at 536 nm

Indium gallium nitride (InGaN) laser diodes have reached a new frontier in performance: continuous-wave (CW) emission at green wavelengths shorter than the 532 nm output of frequency-doubled Nd:YAG lasers. The previous long-wavelength record had been set by a 527 nm diode from Sumitomo Electric (Osaka, Japan). Now, a team from Sumitomo and the Advanced Materials Laboratory of Sony (Atsugi, Japan) reports diodes emitting more than 100 mW CW at wavelengths beyond 532 nm, and CW emission of unspecified power at 536.6 nm.

The success of these researchers could be a milestone in laser display and projector development. Doubled neodymium lasers can be used, but they require external modulation. Green laser diodes are more attractive, especially for mobile devices, because they can be directly modulated, are smaller, and can be more efficient. Laser-projector developers have been seeking 50 mW in the green with a wall-plug efficiency of 4.5%, according to Shimpei Takagi of the Sumitomo Semiconductor Technologies R&D Laboratories and colleagues.[1]

They also want diode wavelengths emitting in the 530–535 nm range, rather than the 515–520 nm of today's commercial green laser diodes. For most applications, a 10 nm shift in wavelength would be of little importance, but laser projection is an exception because of the importance of green light in human vision.

One reason for this is that color-sensing cones in the eye have their peak response at 555 nm in the green, matching the peak in the solar spectrum at Earth's surface. A second is that color perception depends on the relative response of the eye's color receptors, and the green and red receptors are closely spaced, peaking at 540 and 570 nm, respectively. That response makes the green wavelength used

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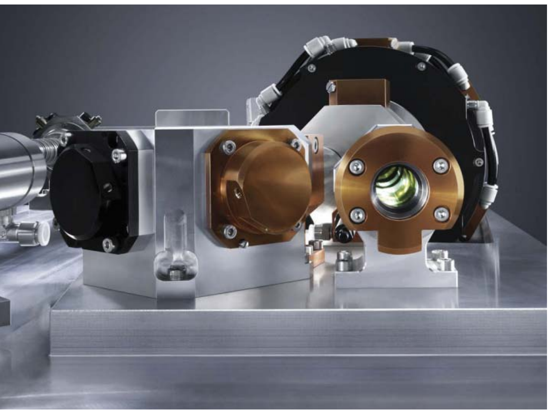

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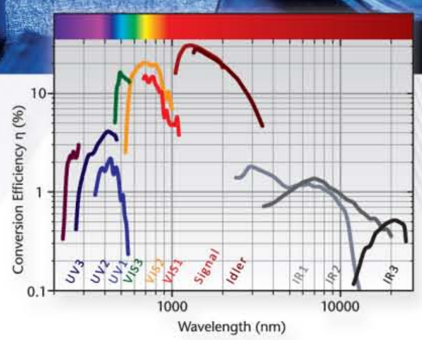

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info@continuumlasers.com | 1.888.532.1064 | www.continuumlasers.com in a laser projector particularly important in determining the gamut, or range of colors, that can be displayed. As shown in the International Commission on Illumination (CIE) diagram (see figure), the color gamut is largest for wavelengths of about 523 nm, but the optimum wavelength for displays is offset to 530–535 nm by the eye's higher sensitivity to longer wavelengths.

Semipolar planes

The challenge has been growing good-quality diodes containing the roughly 30% indium needed to reach the 520–530 nm band. Commercial InGaN laser diodes are grown on the substrate's hexagonal C plane, which is strongly polar, so electric fields separate electrons and holes. That increases emission wavelength without adding more indium but at the cost of reducing recombination rate and emission efficiency.

One alternative is growth on the nonpolar M planes orthogonal to the C plane, but diode fabrication has proven difficult. Sumitomo and other developers, including Corning (Corning,

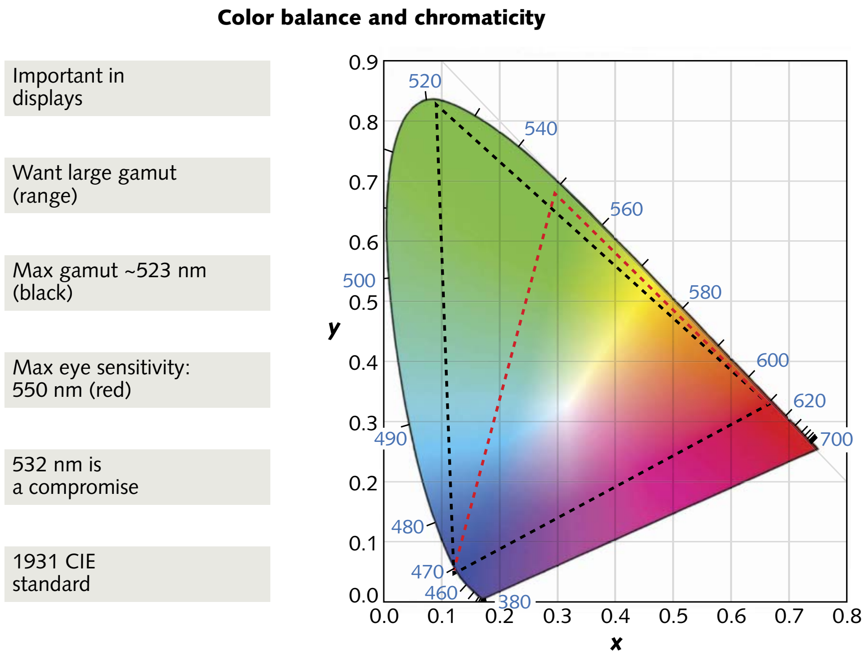
> Takagi and colleagues report reaching continuous-wave 100 mW InGaN diodes at record long wavelengths grown on semipolar GaN substrates.

NY), Soraa (Freemont, CA), and the University of California at Santa Barbara, have taken a compromise approach. They grow diodes on semipolar planes at a 45° angle to both the C plane and the crystal axis, where growth is easier and efficiency is higher, although more indium is needed.

Now Takagi and colleagues report reaching CW 100 mW InGaN diodes at record long wavelengths grown on semipolar GaN substrates. They fabricated a series of ridge waveguide lasers, 2 μm wide and 500 μm long, emitting at different wavelengths. They measured output of 167 mW at 525.1 nm, 107 mW at 532.1 nm, and 75 mW at 535.7 nm. They also observed CW operation at 536.6 nm but did not report the power, presumably because it was below the 50 mW they consider necessary for laser projectors.

High wall-plug efficiencies

The researchers report wall-plug efficiencies of 7.0% to 8.9% at 525 to 532 nm, well above the minimum goal for projectors, and improvement over their earlier semipolar lasers. "Improvement of the slope efficiency was the key factor for obtaining higher output powers," says Takagi. Reducing threshold voltages from 6.4 V in earlier laser diodes to 4.7 V also contributed to higher wall-plug efficiency. They also measured powers to 90 mW from a 528.1 nm laser operated at 80°C, indicating their lasers could be used in portable devices with limited heat-sinking and high internal temperatures.



A CIE chromaticity plot shows that the range of colors produced by a three-color laser display is largest when the green laser emits at 523 nm, but efficiency is higher with a green laser emitting at the 550 nm peak of eye sensitivity. (*Modified from original image: Wikipedia; User: PAR*)

Katsunori Yanashima of Sony's advanced materials laboratories and colleagues reported more good news: long lifetimes for similar semipolar InGaN laser diodes emitting at 527 to 530 nm.[2] Extrapolating from tests lasting about 1000 hr, they estimate that lasers emitting 50 mW should have lifetimes longer than 5000 hr, and lasers emitting 70 mW should have lifetimes of at least 2000 hr.

Those results "look pretty impressive, especially the reliability data," says Peter Zory, a veteran laser-diode developer at the University of Florida (Gainesville, FL). Soraa and Corning also are actively developing semipolar InGaN, although they have yet to report results matching Sumitomo's. The next challenge will be commercial production. —*Jeff Hecht*

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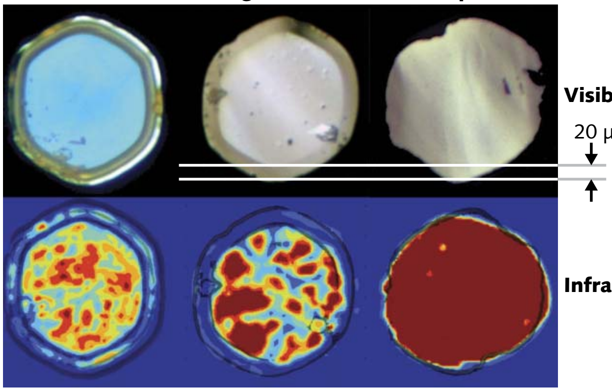
OPTICAL FIBER SENSING

Improved sapphire fibers raise prospects for harsh-environment-sensing

The thermal, mechanical, and structural stability of single-crystal sapphire makes it an excellent candidate for optical sensing applications in harsh environments, such as downhole temperature/pressure sensing for the petroleum industry or for use in combustion applications in gas turbines with temperatures greater than 800°C.

But for sapphire-based optical fibers to be used in harsh-environment temperature, pressure, or dynamics sensing applications, thin-film coatings or external cladding structures must be applied to the sapphire-fiber core to mitigate light transmission losses. Unfortunately, these cladding structures typically cannot withstand high-temperature thermal cycles



Visible and infrared images of light transmission are shown in sapphire fibers with cladding made by proton-ion implantation and annealing at 1700°C. An unimplanted fiber shows a uniform distribution of light. Fiber with a single ion-implanted barrier shows light confined to the core region 20 μm from the fiber surface, which was the target depth of the implant. When a second ion-modified barrier is added, light is confined to two separate regions in the fiber. (*Courtesy of CNSE, University at Albany–SUNY*)

without losing integrity. Furthermore, it is difficult to find cladding materials or any artificial structures that meet the low-refractive-index requirement and have a low thermal expansion to prevent thermal-stress-induced delamination of the cladding structure from the sapphire fiber surface under high-temperature conditions.

But a new method that uses ion implantation and annealing developed by researchers at the College of Nanoscale Science and Engineering (CNSE) at the University at Albany–SUNY (Albany, NY) is dramatically raising the prospects for using sapphire fibers as photonic sensing devices in harsh environments.

Inducing nanometer-scale voids

To avoid the need for applying a separate cladding material to the sapphire fiber, the ion-implantation and annealing process intrinsically alters the refractive-index profile of the sapphire through structural modifications in the form of nanometer-scale voids (typically 10–20 nm in diameter) that cause a decrease in material density and a subsequent decrease in refractive index of several percent.

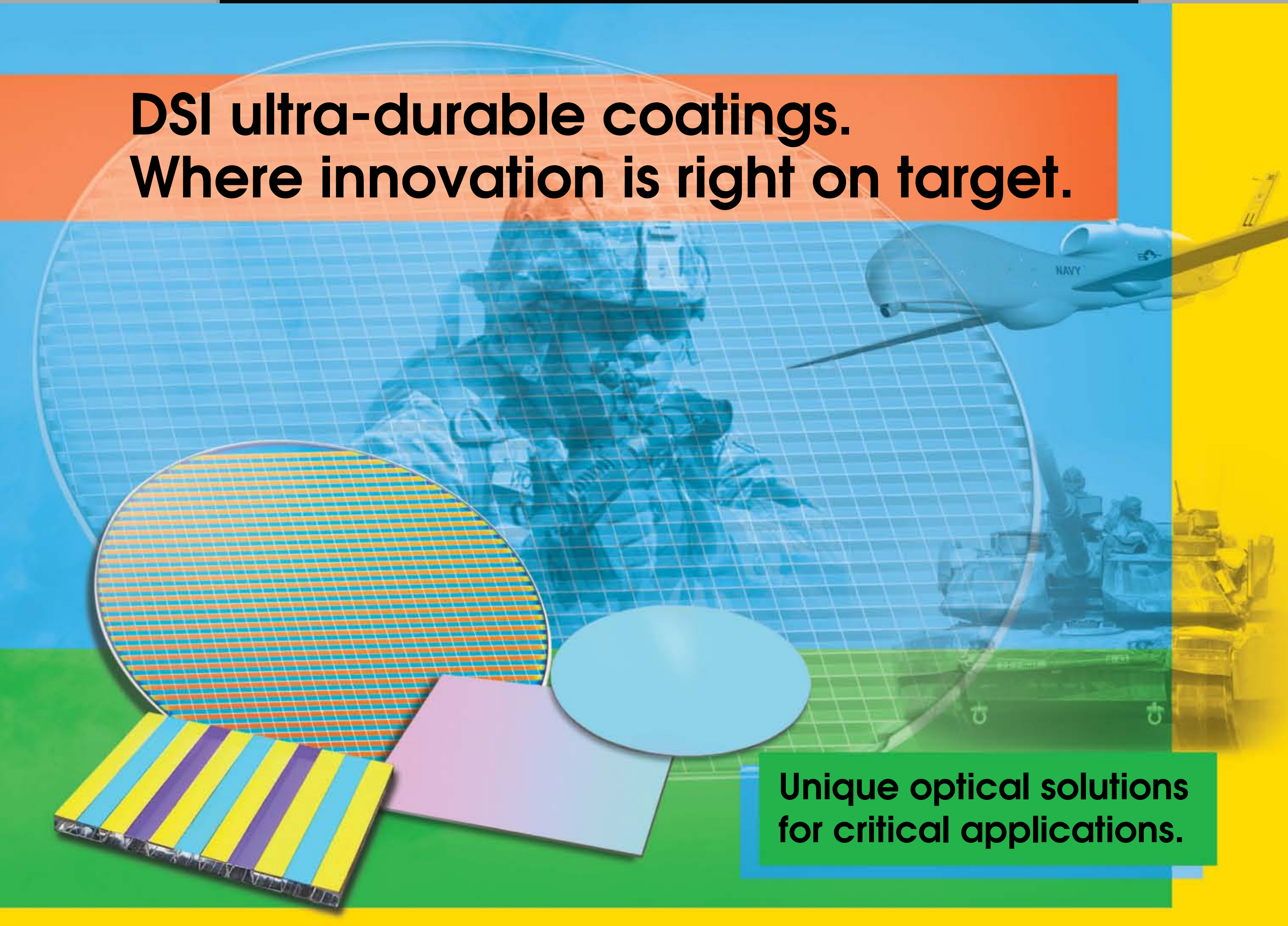
The proton-implantation step is performed on either sapphire wafers or sapphire optical fibers. The location and width of the optical-barrier (low-refractive-index) layer formed below the sapphire surface can be controlled by the proton energy. For example, implantation of 1 MeV protons in sapphire results in an optical barrier approximately 10 μm below the surface.

Prism-coupling measurements on a single-crystal sapphire plate processed by proton implantation and thermal annealing at greater than 1000°C show dips in the reflection curves, indicative of waveguide modes existing in the sapphire plate due to light confinement and propagation in the layer between the sapphire surface and the proton-implanted layer.

For fibers, a proton beam of an appropriate energy is rastered over the fiber surface while the sapphire fiber is continuously rotated about its axis, allowing a continuous, radially symmetric cladding layer to be created in the single-crystal sapphire fiber. Subsequent annealing at temperatures from 600° to 1800°C can induce refractive-index reductions ranging from 0.5% to nearly 4.0%, respectively.

When light is launched into sapphire fibers with cladding made by proton ion implantation and annealing at 1700°C, the resultant cladding structures strongly confine light to the core region of the sapphire fiber in similar fashion to conventional multimode-clad silica fibers (see figure). The research team has also used the method to fabricate a dual-core (or double-cladding) structure in single-crystal sapphire fibers whereby the light propagates in the thin core layer between two proton-implanted layers. This method is promising for production of single-crystal sapphire fibers with only a single or a small number of propagation modes—a crucial requirement for fiber-Bragg-grating (FBG)-based sensing applications.

"The lack of thermally robust cladding and the unavailability of singlemode or even few-mode light propagation due to the difficulty in growing small-sized single-crystal sapphire fiber have been the major hurdles to deploying such optical fibers for sensing applications in harsh environments," says Mengbing Huang, an associate professor at CNSE, University at Albany–SUNY. "The proton implantation method will provide a viable solution to these problems and help open up new opportunities for harsh-condition fiber-optic sensing." *—Gail Overton*



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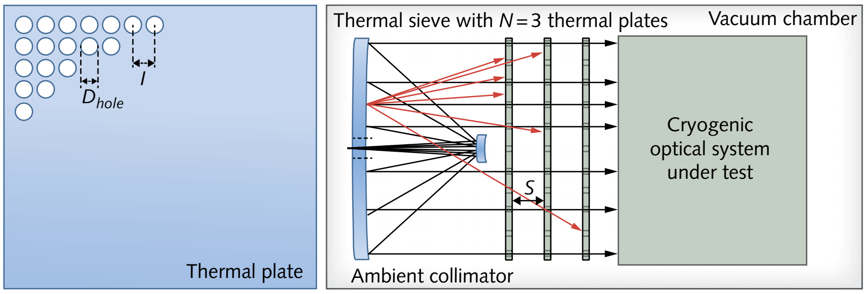
SPACE OPTICS

Thermal sieve isolates collimator from cooled test optics

Testing advanced space optics (which virtually all receive collimated light) before launch often requires cryogenic vacuum testing to simulate the space environment. Because apertures for some of these systems can be quite large (like the 6.5 m aperture of the James Webb Space Telescope's primary mirror), any reduction in complexity of the test setup helps cut costs.

Such a test setup needs to provide collimated light; the conventional way to do this in noncryogenic test is to include a collimator in the vacuum chamber. However, this is not ideal for cryogenic testing, as thermal radiation from the collimator is a problem unless the collimator is kept at the same low temperature as the test optics. Custom collimators designed to work at a precise cryogenic temperature are costly.

A collimator must have a diameter at least as large as the clear aperture of the optics under test. So how can a collimator be "hidden" in a cryogenic vacuum chamber so the optics under test don't thermally "see" it?



Three plates, each with an array of holes (left), form a "thermal sieve" that prevents most of the thermal radiation emitted by a collimator in a vacuum chamber at ambient temperature from reaching cryogenically cooled test optics (right) in the chamber.

Stacked sieves

A group of researchers at the University of Arizona (Tucson, AZ) has come up with an approach: a series of spaced plates, each with an identical square array of round holes, called a thermal sieve (see figure).[1] The setup, which is placed inside the chamber between the collimator and the optics under test, passes collimated light from the collimator but blocks most thermal radiation emitted by the collimator, since the thermal radiation usually takes paths angularly different from the path of the collimated light. The result is that the collimator itself can be kept at or near the ambient temperature outside the chamber.

Unavoidably, because the array of holes is in essence a 2D diffraction grating, the collimated beam received by the optics under test has multiple diffraction orders. However, all but the zero-order point-spread function produced by the test optics can be ignored.

By careful design and analysis, the thermal sieve can be optimized to reduce the remaining thermal load to the test optics: Parameters to be optimized include the thermal plates' temperatures and emissivity values, the hole size and spacing, and the number and spacing of plates. For example, the lateral spacing between holes must be small enough that the diffraction orders are separated at the image plane by a distance much greater than the Airy disk size.

An example modeled thermal sieve setup had an outside ambient temperature of 300 K, a cooled temperature of 35 K, a 6.5-m-diameter clear aperture, a 1 μm test-beam wavelength, three plates, 2-mm-diameter

world news

sieve holes, and 20 mm lateral hole spacings (for an obscuration ratio of 0.99). The plate nearest the collimator was held at 300 K, the plate nearest the test optics was at 35 K, and the temperature of the middle plate was varied from 150 K to 300 K.

In thermal-load calculations, the higher the emissivities of the two outer plates, the lower the thermal loads were. In contrast, the lower the emissivity of the middle plate, the lower the thermal load [for example, decreasing the middle plate's emissivity from 0.15 to 0.05 reduced the thermal load (with the middle plate at 280 K) from about 0.6 W/m^2 to about 0.2 W/m^2].

The relation of thermal load to the plate temperatures was complicated, but the researchers learned that if the middle plate's temperature was fixed, tweaking the temperatures of the other two plates could optimize the performance of the thermal sieve. Conversely, letting the middle plate's temperature float showed a best performance point; in both cases, this was when the middle plate reached a temperature of about 252 K.

Analysis showed that the hole-alignment tolerance was more important than the hole-size tolerance for achieving lowest test-beam phase errors. For the assumed tolerances, the rms phase error due to the thermal sieve was under 0.006 waves. —*John Wallace*

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BusinessForum

Persistence and playing 'truth or dare'

MILTON CHANG

Q *I have been working on a solar concentrator concept that is ideal for urban places. Do you have any suggestions on what I could do now that this area is out of vogue?*

A It is difficult to beat (mega) trends. Sound technical ideas sometimes languish because they cannot be developed into viable business propositions. Even established solar companies are having a hard time staying profitable at this moment and in the foreseeable future. To get to a somewhat objective decision, persist if you feel there is greater than 50% likelihood that you will be able to get the funding you need; abandon ship if your gut tells you the odds are greater than 80% against you. There is no point in banging your head against the wall just because entrepreneurs are supposed to be persistent.

You may be able to realize some value out of your work by partnering with an established solar company, especially if you have valuable proprietary know-how. Not all is lost if you learned from this experience. Many of us had to pursue multiple ideas before we came upon a good one to hit the ground running.

Q *I was asked by my CEO to state my observations of the operation as CTO and senior VP at an all-hands strategic planning meeting. I sensed great resentment afterwards. What can I do to recover from this misstep? FYI, both the CEO and I are new on the job, and the CEO agrees with my opinion that the culture of keeping information close to the vest must change.*

A I am sure many of us have had regrets after speaking up. Words once spoken cannot be taken back! You have three options now that you have spilled the milk. Apologize, hang tough and be unrepentant, or find a way to make lemonade out of lemons. What I mean is that you might as well turn what you did into a positive by minimizing the negative.

Apologizing would negate any positive impact you have made; instead, it would create a negative image that you are indecisive and prone to flip-flopping. And playing tough would only harden any negative feelings to isolate you. What I would suggest is to send out an e-mail blast to solicit input. You may be able to position what you have done, putting your strong opinion out there as a stalking horse to stimulate intellectual debates between groups. Giving people permission to speak up will also relieve resentment, calming people down and thereby making it possible for them to put their energy to constructive use. All of this could make you appear open-minded, approachable, and receptive; you might just be able to get meaningful bottom-up feedback to fine-tune your viewpoint.

The issue behind this question is how you can put forth an honest opinion when giving advice. This is something I have struggled with frequently. Should I speak my mind to be most helpful at the risk of hurting someone's feelings, or should I only accentuate the positive? The problem is that an honest opinion may not be a correct opinion. You have to challenge your viewpoint and get behind the reasons why people do what they do. Come to a good understanding by doing your homework; then present your opinion tactfully by discussing the pros and cons of each approach from multiple points of view. This will allow people to come to their own conclusions. It is analogous to what people in marketing do to create a pull: Provide enough information for an individual to come to his or her own conclusion, which by definition is the right decision (for that particular individual).

A side comment I can offer is that you may want to develop a better understanding of the way your CEO operates. One can question whether he was using you as a trial balloon or a mouthpiece to take the heat. ◄

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.

Thinking about R&D at photonics companies

JAN MELLES

The critical R&D question for a photonics company is: Are the funds reserved for this really bringing the return that the owners and management expect? To answer this question, we must understand the nature of research and development at photonics companies, what it should be, and what should be avoided.

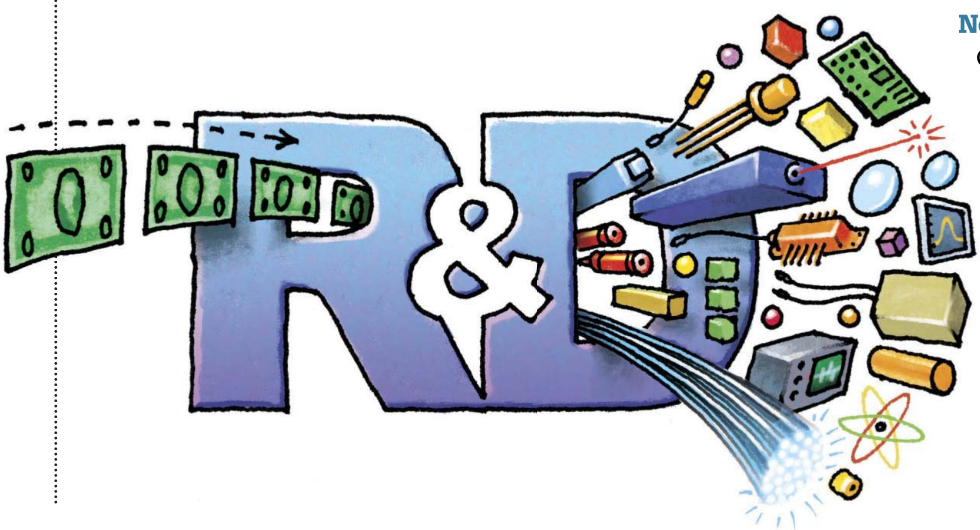
First, I should define what I mean by R&D, because there is a clear distinction between the concepts of "research" and "development." With research we commonly refer to the investment an organization makes in developing new technology from which new products or services can be generated. Development has a broader meaning, which may include new product development, improvement of existing products, and/or satisfying specific customer needs.

For many smaller companies, there is no distinction between these two elements, and R&D as shown in financial statements is rarely broken down between them. Although market research is also a category of research, I will emphasize research for the purpose of improving and expanding a company's product line.

Research usually takes place in large organizations—sponsored by the government and/or academia, or corporate laboratories. Much of this kind of research can be classified as "basic" as compared to "applied" because it covers primarily the development of advanced new technologies, which tend to be very expensive and beyond the means of most photonics companies. In the highly fragmented world of photonics, where companies with less than 100 employees represent 90% of the entire industry, R&D represents a combination of the two concepts, with more emphasis on product development.

No one in business will disagree that investing in new product development is essential for growth, if not survival. Without new products in the pipeline, product lines will become obsolete and market share taken over by competitors.

However, the owners and management of photonics companies face a variety of problems that stress human and financial resources, varying from meeting delivery times and solving last-minute technical issues, to customers who first delay placing new orders then suddenly demand fast delivery of a large order. Facing these kinds of issues, new product development—particularly in smaller companies—frequently receives less attention in a company's development.



No short-term thinking

Curiously enough, there are also examples of companies purposely lowering their investment in R&D, mainly driven by short-term financial considerations. It is not uncommon for companies facing acute cash shortages to cut back on R&D or for companies that are for sale to reduce R&D to improve their bottom line, which they believe would make them more attractive to potential buyers.

This is short-sighted and unwise as the opposite is often the case. Buyers will clearly see this as a sign of weakness, valuing their target in a direction that is opposite of what the seller hopes to achieve. It also needs to be stated that pumping more capital in R&D is no assurance of better results. Although this may be true in many cases, there is no guarantee. An example is Apple, by market capitalization the world's most valuable business. Apple invests only a third of what Microsoft invests in R&D, but no one would accuse Apple of not being innovative.

Investing for returns

Investment in R&D by photonics companies runs from 5% to as high as 20% of sales, with 8% to 12% the more common choice. There is no good or bad number; there are enough examples of companies justifiably investing less than 5% at any given time in their development, and spending more than 20% may not represent an unacceptably high number.

With the possible exception of very small businesses, just about all photonics companies generate an annual budget, which usually includes a line entry for R&D. This number is often based on an in-house practice that has been in place for some time. Unfortunately, after setting this number many photonics companies fail to follow up and develop an operating plan on how to invest these funds for maximum yield.

Like any other investment a company makes, it does so with the objective of generating a rate of return that it has committed itself to achieve. R&D is only one element in the process of bringing new or improved products or services to market. The money set aside for R&D should be based on a careful analysis of what is required to sustain and improve the company's market position. R&D should not be a reserve pot of money that can be used for any need that happens to come along.

I have observed over many years that mature product lines normally get about 20% of available R&D funding, while 50% goes to upgraded products and 30% goes for totally new products.

A company's product line usually can be categorized in three stages: 1) mature products, 2) new products that are generally upgraded versions of mature products, and 3) totally new products often serving new markets based on new technology and targeting customers who differ from the company's traditional customer base. Each stage requires the support of R&D activities to maintain its market share, improve its market share, or acquire share in new markets based on using existing products or developing new ones.

There is no golden rule about how R&D funding should be allocated among these stages as it depends a great deal on a company's corporate objectives. But I have observed over many years that mature product lines normally get about 20% of available R&D funding, while 50% goes to upgraded products and 30% goes for totally new products.

Quantifying the return on a company's investment in R&D has proved to be extremely difficult because it is very different from other investments that a photonics company may make such as investing in physical assets or making acquisitions. These are "hard targets," the return on which can be more easily calculated. Not so with R&D.

The most common method still is based on sales, but even that does not make it easy to define the return on R&D because so many other factors play a role in generating new products. One thing is assured: When a photonics company loses market share on the sale of its product line—be it a mature product or a new product—the cause indeed could be a lack of effective R&D.

Successful photonics R&D—the essentials

1. The team responsible for R&D must be the best the company has to offer in terms of intellectual and creative talent, having intimate knowledge of the company's technology base and markets served. Without this information, the team will work in a vacuum and cannot be effective. Market research is essential, especially to learn what key customers need in terms of future products and services, and what the competition is doing.
2. The R&D team needs to interact continuously with the staff at sales and manufacturing to ensure that efforts will be guided in the right direction.
3. Sufficient funds must be made available to allow the hiring and functioning of an effective R&D team. Such funds should not be reallocated to other needs to solve short-term problems.
4. Milestones must be set for the three key stages of development: a) concept, b) prototype, and c) final design.

Jan Melles is president of Photonics Investments and was the co-founder and later chairman of Melles Griot. He is currently on the board of numerous public and private photonics companies, and invests in and brokers the mergers and acquisitions of photonics companies. E-mail: jmelles@photonicsinvestments.com; www.photonicsinvestments.com.

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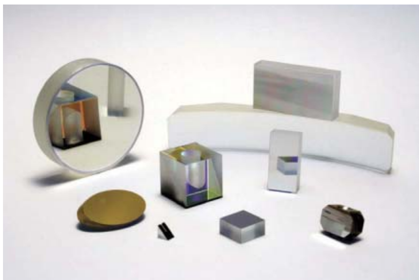

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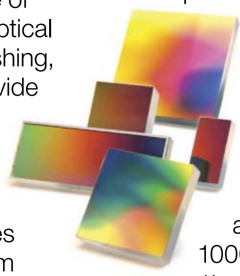

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Gradient field microscopy allows label-free disease diagnosis

TAEWOO KIM, SHAMIRA SRIDHARAN, and GABRIEL POPESCU

Intrinsic contrast methods that rely on the passage of light through a transparent sample promise to change clinical pathology as we know it. Without requiring labels such as fluorescent dyes, these are valuable techniques due to their noninvasive nature, allowing for unperturbed study of biological specimens and diagnosing diseases such as cancer.

Imaging unstained live cells and thin slices of tissues (biopsies) is extremely challenging because these structures are transparent and, as a result, the images lack contrast. Over the past four centuries, much of the development in light microscopy has been driven by this challenge of obtaining high-contrast images of translucent structures.[1]

Contrast-generating microscopy methods fall into two classes: extrinsic and intrinsic, depending on whether the approach requires exogenous contrast agents or not, respectively. In the first category we find methods that involve stains—such as those used in standard clinical pathology—and fluorescence dyes, used extensively in cell biology. Intrinsic methods include phase contrast microscopy and differential interference contrast (DIC) microscopy.[2] These approaches exploit the particular interaction between light and tissue rather than attaching absorbers or emitters to the structure of interest. Therefore, intrinsic contrast methods have the advantage of studying the cells and tissues in their unperturbed conditions.

Quantitative phase imaging (QPI) is emerging as an intrinsic contrast method that measures how much the light is delayed through the specimen at each point in the field of view.[3] This optical path length or phase information relates to both the refractive index and thickness of the specimen and therefore enables new biological studies—especially of cell structure and dynamics.[4-6] Recently, our group at the University of Illinois at Urbana-Champaign discovered that QPI holds valuable potential for clinical pathology; that is, the optical path-length map associated with the biopsy can be used for cancer diagnosis using spatial light interference microscopy, or SLIM.[7]

The SLIM method combines Zernike's phase contrast microscopy and Gabor's holography to render quantitative phase images, and is sensitive to path-length changes of 0.3 nm spatially and 0.03 nm temporally.[8] We obtained images of prostate biopsy cores that were diagnosed by the pathologist as high-grade prostatic intraepithelial neoplasia (HGPIN) using a 40X/0.65 numerical aperture (NA) objective (see Fig. 1).

Gradient field microscopy

Remarkably, we found that the spatial fluctuations of the path length and *not* its average values hold the true diagnosis

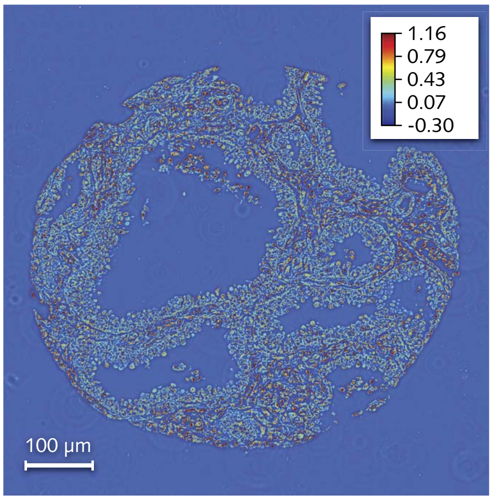

FIGURE 1. A quantitative phase image of a prostate biopsy is stitched together from 100 (10 × 10) smaller field-of-view images. The quantitative data is indicated in different colors with red being a long optical path length and blue being a short optical path length. The color bar indicates phase shift in radians. The data show that the basal cell layer is clearly visible in the high-grade prostatic intraepithelial neoplasia (HGPIN) cores.

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power for this microscopy method. In other words, while the average phase shifts in the tumor and normal tissue have similar values, the statistics of the spatial fluctuations (such as the variance) are completely different. Specifically, we found that the architecture of the prostate tumor is more disordered and characterized by higher variance as compared with the normal tissue, which is smoother. These results may form the basis for a new, label-free, quantitative approach to cancer diagnosis.

From an optical point of view, the fact that only relative changes in the phase shift and not absolute values are relevant to tissue diagnosis is quite significant. It suggests that new, simpler methods can be developed that do not necessarily quantify phase shifts but instead measure some spatial differential of the phase map. One such method is gradient field microscopy (GFM), a technique recently developed at our Quantitative Light Imaging Laboratory (http://light.ece.illinois.edu/).[9] The GFM method provides high-contrast images of transparent specimens, including cells and tissues. In GFM, the spatial change of the optical path length is measured by taking the first- or second-order derivatives of the phase information that is carried by the light.

Currently, GFM is built as an add-on module to a commercial brightfield microscope. The aperture stop is closed down for the highest possible spatial

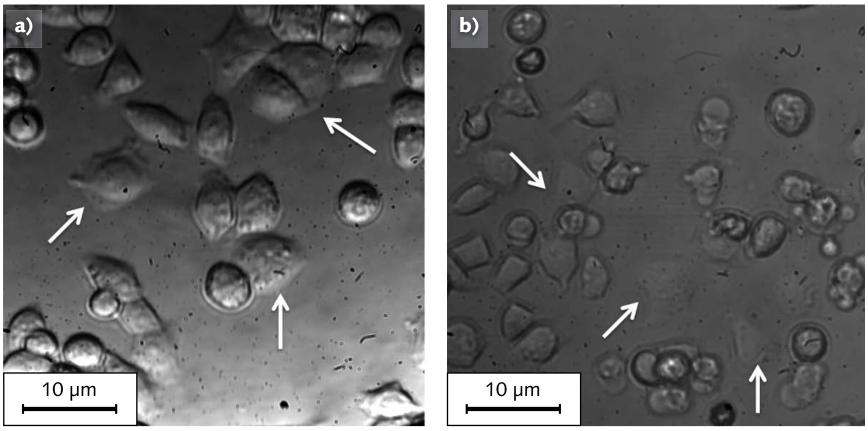

FIGURE 2. Images of a HeLa cell culture in a plastic petri dish are taken (a) using gradient field microscopy (GFM) and (b) conventional differential interference contrast (DIC) microscopy. White arrows indicate the flat cells, which show increased contrast only under GFM because of the birefringent material.

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coherence of the illumination. The system consists of a series of two lenses forming a 4*f* system to provide access to the Fourier transform of the image field. At this Fourier plane, spatial amplitude modulation is provided through a spatial light modulator. Depending on the modulation mask given at this plane, the type (and order) of the phase derivative obtained at the image plane changes. There are three different modes of GFM that we have implemented to obtain different phase derivatives: a first-order derivative along one direction (one gradient component), the amplitude of the first-order derivative (gradient intensity), and a second-order derivative (Laplacian).

GFM advantages

The GFM setup brings many advantageous features such as fast acquisition speed and stability along with the flexibility of using the different modes of operation. Since GFM is a single-shot technique and does not require any image processing after acquisition, the acquisition speed of this system is as fast as the camera allows. Furthermore, the spatial modulation can be changed electronically, without moving mechanical parts of the system. This contrasts with the conventional DIC microscopy technique in which the physical movement of a birefringent prism is required. The absence of the prism in the imaging system also allows GFM to image through birefringent materials such as plastic-bottom dishes, which is generally difficult using DIC (see Fig. 2). Cells exhibiting low contrast under common DIC microscopy are rendered visible via GFM.

One exciting feature of GFM is that it can image unstained tissue biopsies, indicating the HGPIN condition in which the epithelial cells of the prostate glands have morphological characteristics associated with prostate cancer such as prominent nucleoli and Roman bridge formation (see Fig. 3).[10] Further studies have shown that HGPIN glands also show genetic and immunohistochemical changes associated with carcinoma.[11] However, the basement cell membrane is still present in these glands and presence of patchy basal cells excludes the diagnosis of carcinoma. Currently, basal cells are detected using antibodies against cytokeratin 34BE12 and p63 markers. By zooming in to a more specific region of the GFM tissue images, the biopsy can be successfully diagnosed by showing the existence of basal cells without staining. Furthermore, because of the fast imaging of GFM, it is possible in principle to obtain diagnosis information in real time.

Our current work focuses on identifying "optical markers" for diagnosis and automating the process. We anticipate that based on such advanced imaging principles, "smart microscopes" could be developed in the near future that are capable of yielding knowledge rather than images. That is, we believe it is possible to have an imaging system that performs real-time analysis and diagnosis without ever saving the images. The combination of advanced optical imaging and parallel image processing shows the promise of revolutionizing standard pathology, allowing for faster, label-free diagnosis—affordable at the global scale.

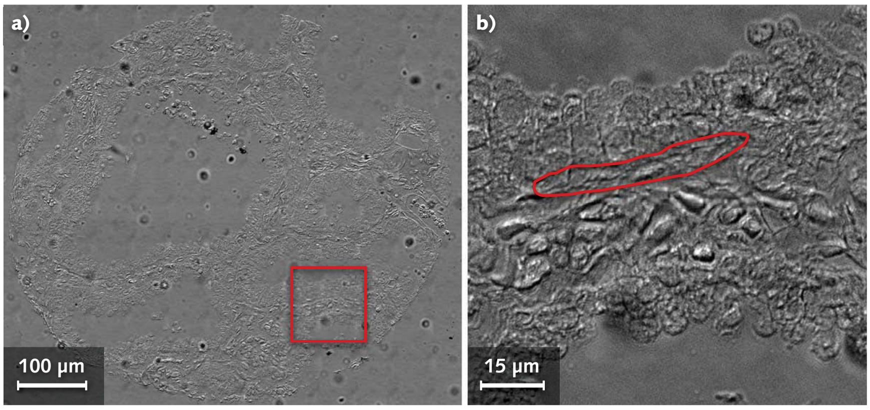

FIGURE 3. A GFM image (a) shows the same biopsy tissue as in Fig. 1. The image is constructed by stitching together 225 individual images (a 15 × 15 array) taken with a 100X/1.4 NA brightfield objective. The gland area (b) is zoomed in to show the basal cell layer, indicating the HGPIN condition.

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Taewoo Kim and **Shamira Sridharan** are graduate students, and **Gabriel Popescu** is an assistant professor in the Department of Electrical and Computer Engineering & Bioengineering and the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign, 405 North Mathews Ave., Room 4055, Urbana, IL 61801; e-mail: gpopescu@illinois.edu; http://light.ece.illinois.edu.

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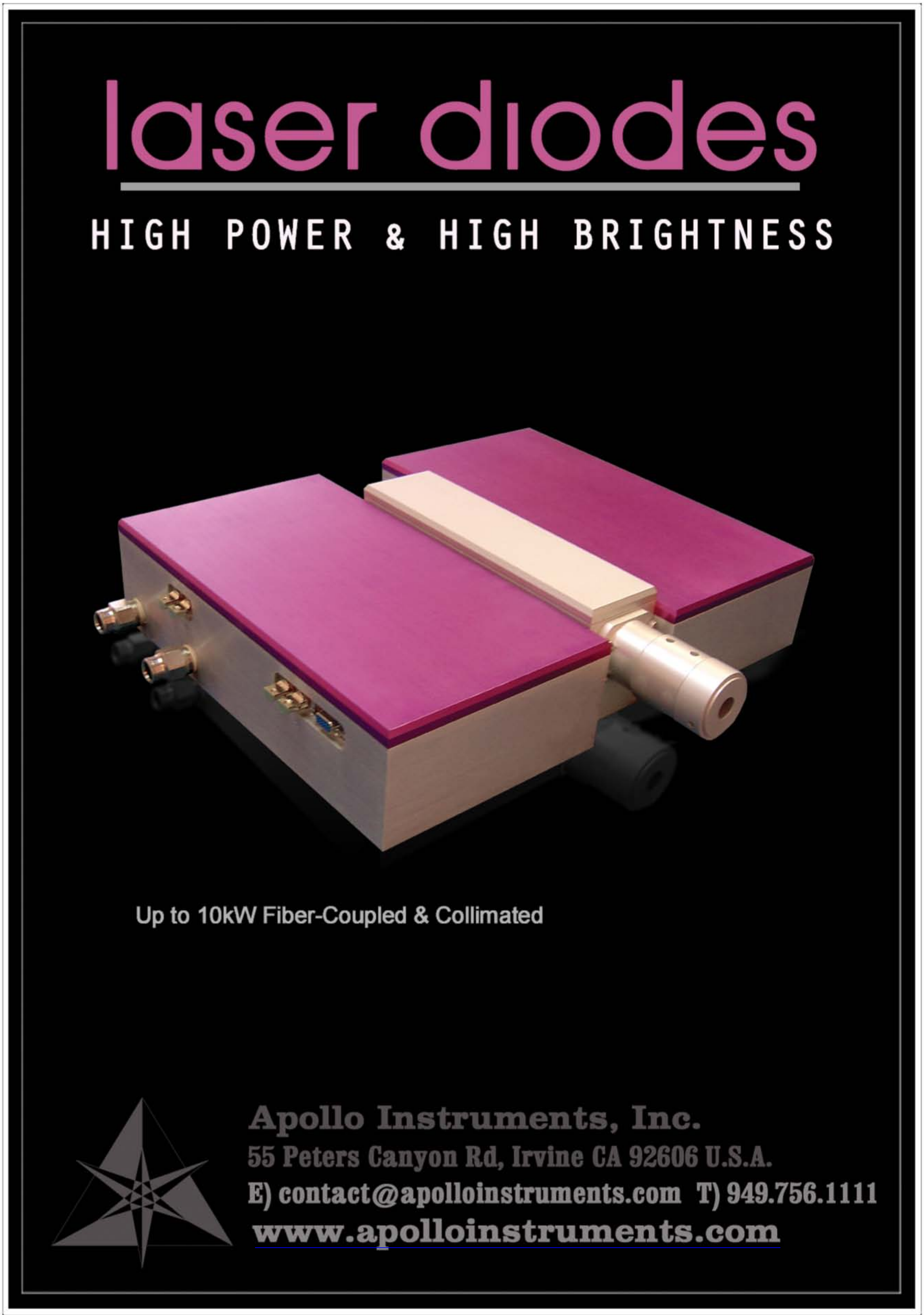
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Holmium-doped silica fiber designs extend fiber lasers beyond 2 μm

BRYCE SAMSON, GEORGE OULUNDSEN, ADRIAN CARTER, and STEVEN R. BOWMAN

A 140 W, 2.13 μm mid-infrared (mid-IR) fiber laser operating with 60% slope efficiency is possible using holmium-doped silica fibers operating at the long-wavelength limit of silica optical fiber transmission.

Fiber lasers operating at high power levels (greater than 100 W) with high efficiency have historically been limited to devices made from silica fibers doped with ytterbium (Yb; 1 μm operating wavelength), erbium (Er; 1.5 μm), or more recently thulium (Tm; 2 μm). In fact, Tm-doped fiber lasers operating at 2 μm have been demonstrated with as much as 1 kW of singlemode-beam-quality output power from a large-mode-area fiber.[1] But more recently, research has focused on holmium (Ho)-doped silica fibers that operate at longer wavelengths (greater than 2.1 μm) than Tm and with higher efficiency when resonantly pumped at 2 μm, offering the potential to scale to higher power levels than the currently available Tm-doped fibers.[2]

Glass optimization

The design and fabrication of Ho-doped fibers is still largely in the research phase and is being investigated by several groups worldwide.[2-4] One of the topics currently under investigation is optimization of the pumping scheme for power scaling to kilowatt levels. The challenges associated with operating this latest family of rare-earth-doped fibers at high power level are numerous and include operating at the long-wavelength transmission limits of silica glass around 2.1 μm, where the multiphonon absorption edge of the silica glass becomes problematic. In addition, the role of extrinsic losses, such as hydroxide (OH) contamination, is also far greater at this operating wavelength.

Optimization of the spectral parameters of Ho-doped silica glass requires mitigation of concentration effects, including up-conversion quenching processes and optimization of co-dopant species in order to minimize clustering and concentration quenching effects on the radiative lifetime (see Fig. 1). The intrinsic nonradiative multiphonon quenching of the holmium $^5I_7$ upper state lifetime is also important and from our measurements is around 0.6 ms at room temperature for fibers doped with 0.5 wt% Ho. This measured lifetime corresponds to a radiative quantum efficiency of approximately 10% for Ho-doped silica. Although much lower than the values associated with Er-doped or Yb-doped silica fibers, this is not a major factor in determining the slope efficiency for high-power lasers and amplifiers.

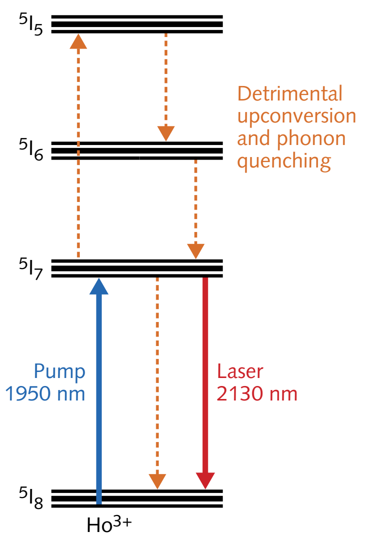

FIGURE 1. The energy level diagram is shown for holmium (Ho)-doped glass.

A major factor in limiting the slope efficiency is the background loss of the fiber and in particular the level of OH contamination from the preform fabrication process. This is particularly important because the overtone of the fundamental OH absorption that occurs around 2.2 μm in silica is relatively close to the lasing wavelength of 2.13 μm in these Ho fibers.[5] By resonantly pumping the Ho at 1.95 μm, the goal is to reduce the quantum defect in the fiber laser and hence lower the thermal load on the fiber as compared with 790 nm pumping of Tm-doped fibers. The deleterious effect of small amounts of OH contamination on the thermal load stresses the need for high purity levels in these fibers to increase efficiency and enable high-power laser operation (see Fig. 2).

Novel processes have been developed to minimize OH contamination during the fiber preform manufacturing process. The key is in understanding the various sources of OH contamination and minimizing their impact in a stepwise, controlled fashion. The sources can range from the preform manufacturing process itself, to the purity level of the raw starting chemicals, and to the manner in which the glass is handled during processing. Manufacturers of Ho-doped fibers have developed their own proprietary methods for minimizing OH contamination. These processes include additional drying steps, elimination of the handling of the glass during manufacturing, and strict control of atmospheric conditions. In all cases the additional steps add process time and increase the complexity of manufacturing Ho-doped fibers.

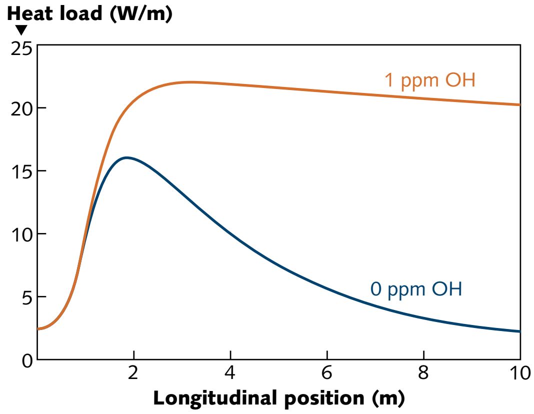

FIGURE 2. Thermal modeling shows the effects of hydroxide (OH) contamination on a high-power Ho-doped 2.13 μm fiber laser.

Fiber waveguide design

In addition to glass optimization, fiber waveguide design has also been investigated over the past few years. Early research into Ho-doped fiber lasers typically involved a 1.15 μm pump wavelength and relatively small-core, singlemode fibers. In order to power scale this laser system, many groups have chosen a pump wavelength around 1.95 μm corresponding to direct excitation into the Ho $^5I_7$ metastable level. This pump wavelength is readily available from high-power, singlemode Tm-fiber lasers that now operate at power levels exceeding 100 W and are, in turn, pumped by high-power 790 nm laser diodes.

Modifications of the waveguide design to lower the numerical aperture (NA) of the core with respect to the silica cladding have also been investigated and a range of commercially available singlemode and large-mode-area (LMA) Ho-doped fibers are now starting to emerge. The development of LMA designs for Ho fibers has been far more straightforward than Er:Yb and Tm-doped fibers that both require pedestal fiber designs to obtain a core NA in the range of 0.1. Cladding diameters for the Ho fibers are typically smaller than Yb-doped fibers because of the high brightness of the available Tm-fiber laser pump sources.

One complication of the fiber design is the desire for an inner glass waveguide for the pump light rather than the glass/polymer waveguide often used in Yb-doped fibers. This inner glass waveguide offers a lower loss for the 1.95 μm pump light (see Fig. 3). Despite the use of a fiber laser as the pump source, the

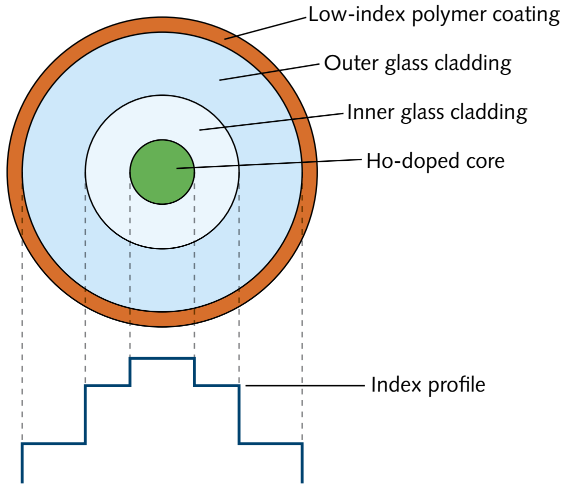

FIGURE 3. The latest generation of Ho-doped fibers for high-power fiber laser operation are based on triple-clad designs with glass inner cladding for the 1.95 μm pump light.

overall electrical-to-optical conversion efficiency of this pump scheme is still high due to the high pump conversion efficiency of the Tm-fiber lasers—which is typically 60–65%.

It is worth noting that although double-clad Ho-doped fiber designs operate with lower efficiencies than their triple-clad counterparts, they are often preferred during early stages of device development to more easily optimize the fiber design for the given application. Once the fiber design has been optimized (composition and geometry) in the double-clad version, further optimization into a triple-clad fiber design is relatively straightforward.

Experimental results and future directions

Recently [6], a Ho-doped fiber from Nufern was used to create an efficient 2.13 μm fiber laser source. The Ho-doped fiber was fabricated to be singlemode at 2.1 μm, with a doped core of diameter of 18 μm and 0.08 NA corresponding to a V-number of 2.2. The core was surrounded by a standard octagonal-shaped silica glass inner cladding of 112 μm flat-to-flat diameter. A low-loss 1.95 μm pump waveguide for the inner cladding was achieved using a 180 μm diameter all-glass fluorine-doped outer cladding, providing an NA of 0.22. The fiber was then overclad with silica glass to produce an outer fiber diameter of 250 μm.

The free-space-pumped fiber laser made using this Ho-doped fiber recipe operated at 140 W continuous wave (CW), delivering a singlemode beam at 2.13 μm and a slope efficiency of 60% with respect to the launched pump power (see Fig. 4). A second LMA fiber with 40 μm diameter core was also fabricated and the resultant fiber laser operated at 140 W, pump limited in the same experimental configuration. In addition to CW laser cavities, a gain-switched Ho-doped fiber laser was demonstrated that produced more than 5 W average power at a 600 kHz repetition rate, 85 ns pulse duration (8 μJ) with stable linearly polarized output.

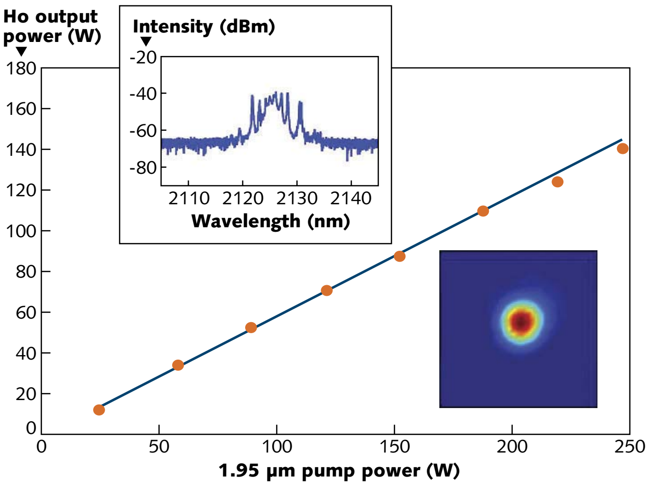

FIGURE 4. A cladding-pumped Ho-doped silica fiber laser operating at 2.13 μm with 60% slope efficiency is pumped by a Tm-based fiber laser at 1.95 μm.

A broad range of applications require laser sources in the 2 μm spectral region including remote sensing, light detection and ranging (lidar), and nonlinear frequency conversion, as well as future high-power laser weapons systems that would all benefit from high-power, mid-IR sources with excellent beam quality.

The atmospheric windows at wavelengths greater than 2.1 μm are of particular interest in military and sensing applications. There are also a variety of scientific, military, and medical applications involving nonlinear frequency conversion into the mid-IR range that often use commercially available zinc germanium phosphide ($ZnGeP_2$) or ZGP crystals. However, defect-related absorption in ZGP below 2.1 μm hinders power scaling due to the associated thermal lensing and degradation of beam quality. This limits the use of Tm-based fiber lasers as pump sources for high power and is an ideal application for a new generation of Ho-doped fiber lasers.

In order to scale CW power and pulse energy, further work is needed to mature the LMA fiber designs as well as the matching support fibers and components required to make monolithic all-fiber devices for robust, compact lasers that could be commercialized. Work by several groups is now focusing on these monolithic devices at high power levels and wavelengths greater than 2.1 μm. It is envisaged that as Ho-doped fiber designs mature, multikilowatt fiber lasers operating beyond 2.1 μm will become readily available.

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Bryce Samson is vice president of business development, **George Oulundesen** is a product line manager, and **Adrian Carter** is chief technology officer at Nufern, 7 Airport Park Rd., East Granby, CT 06026; e-mail: bsamson@nufern.com; www.nufern.com. **Steven R. Bowman** is section head, Advanced Laser Concepts, at the US Naval Research Laboratory, 4555 Overlook Ave., SW Washington, DC 20375; e-mail: steven.bowman@nrl.navy.mil.

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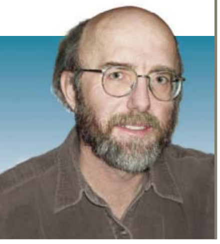

New designs expand capabilities of quantum-cascade lasers

JEFF HECHT contributing editor

Advances include watts of power and wall-plug efficiency above 20% at room temperature, shorter wavelengths, narrowband output, and new competition from interband cascade lasers.

Performance of quantum-cascade lasers (QCLs) "has improved to a point I could never have dreamed of," Jérôme Faist of the Swiss Federal Institute of Technology (Zurich, Switzerland) told CLEO 2012 attendees during an invited talk in May. In 1994, while working in Federico Capasso's group at Bell Labs (Murray Hill, NJ), he was lead author on the first reported demonstration of a QCL.[1] Performance of that first device "was pretty bad," he recalled; it emitted a feeble 10 mW at cryogenic temperatures.

Now a professor at ETH Zurich, where he heads the FIRST Center for Micro- and Nanoscience and the Institute for Quantum Electronics, Faist said he never expected to see QCLs operating at room temperature with watts of output or wall-plug efficiency above 20%. Yet sophisticated design and fabrication tools have made those high-performance devices possible and made QCLs vital tools for infrared (IR) applications ranging from sensors and delicate measurement devices to military countermeasures.

Cascades through quantum wells

The basic concept that led to QCLs was proposed by Russian physicists R.F. Kazarinov and R.A. Suris in 1971, just a year after the first continuous-wave, room-temperature operation of diode lasers.[2] They proposed cascading electrons through a stack of quantum wells to excite laser action on transitions between quantum-well sub-bands.

At first, the idea didn't seem very promising. Inter-sub-band transitions have very narrow absorption peaks and sub-picosecond radiative lifetimes, so their spontaneous emission is much weaker than that of the interband transitions used in diode lasers. However, Faist said, "an inefficient LED does not make an inefficient laser." Electrons cascading through a series of quantum wells produce stimulated emission far more efficiently than spontaneous emission. That realization, and Albert Cho's use of molecular beam epitaxy to grow very thin layers with very good interfaces, led to Bell Labs' development of the QCL.

Their initial demonstration produced only milliwatt pulses at cryogenic temperatures, but it opened the door to further advances. Electrons can cascade through 20 to 200 quantum wells, and in the mid-IR they lose only small increments of energy on each transition.

FRONTIS. A packaged thermal laser pointer from Daylight Solutions. Models emitting 100 mW at wavelengths from 3 to 20 μm are available for use as pointers, illuminators, or beacons. (*Courtesy of Daylight Solutions*)

Applying voltage across the entire stack offers an important economy of scale by reducing the fraction of the voltage lost to overcoming contact resistance, improving device efficiency.

Design flexibility has become a major attraction of QCLs. Their properties depend largely on their structure rather than on the semiconductor compound, with operating ranges from the mid-IR to the terahertz band, roughly spanning 3 to 300 μm. Designers can incorporate structures used in other semiconductor lasers, such as buried heterostructures and distributed feedback. External cavities allow tuning ranges well above 10% of the center wavelength.

Optimizing QCL design has been a complex process because it requires balancing a number of tradeoffs. Faist said that new simulation tools can automate the process using genetic algorithms that evaluate effects of changing design parameters.[3]

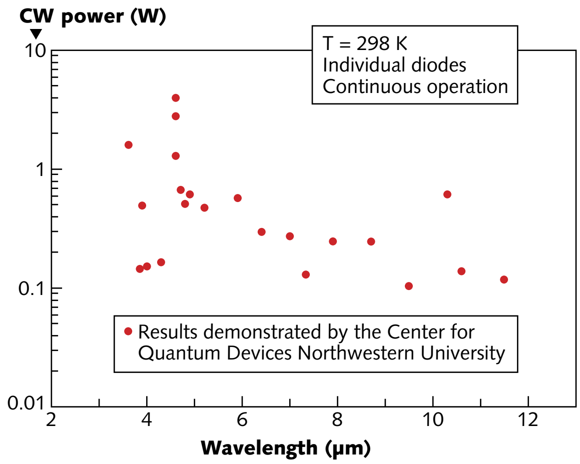

FIGURE 1. Highest continuous-wave powers in single QCLs operating at room temperature in experiments at Northwestern University's Center for Quantum Devices. (*Courtesy of Prof. Manijeh Razeghi*)

Power and efficiency

Military interest in higher-power mid-IR sources has led to development of watt-class QCLs. In 2009, a DARPA-funded team at Pranalytica (Santa Monica, CA) reported a then-record CW room-temperature output of 3 W at 4.6 μm. Their novel design allowed simultaneous optimization of several design parameters, reducing threshold current density to 0.86 kA/cm^2 and increasing wall-plug efficiency to 12.7%.[4]

Last year, Manijeh Razeghi's group at the Center for Quantum Devices at Northwestern University (Evanston, IL) claimed the CW power record with 5.1 W at 4.9 μm in a near-diffraction-limited beam from a buried-ridge QCL with a cavity 5 mm long and 8 μm wide. Their shallow-well design allowed them to reach record CW power efficiency of 21%, with pulsed efficiency reaching 27%.[5] They earlier reported peak power of 120 W at 4.4 μm in 200 ns pulses at 0.2% duty cycle from a QCL with 400-μm-wide ridge waveguide.[6] Figure 1 shows the highest CW powers they recorded from room-temperature QCLs at a range of wavelengths.

Commercial QCLs can generate diffraction-limited power to 2 W at 4 to 5 μm in the mid-IR atmospheric window, says Erik Takeuchi of Daylight Solutions (San Diego, CA). The maximum available power depends on wavelength. From a physical standpoint, he says, the sweet spot for high power from QCLs is around 6 μm, but that wavelength has attracted little interest because of poor atmospheric transmission. Somewhat lower power, around 1.5 W, is available in the 8 μm band.

By far the best efficiencies are possible at cryogenic temperatures, where internal quantum efficiencies can exceed 80%. However, the best wall-plug efficiencies were less than half that level until 2010, when Razeghi's group reached 53% wall-plug efficiency in a pulsed 5 μm laser cooled to 40 K. That was the first QCL to generate more (IR) light than heat.[7]

Wavelength and interband cascade lasers

One important limitation of QCLs has been their poor performance at wavelengths shorter than 4 μm, arising from limitations of the arsenide quantum well system. One approach has been to add antimonides to the QCL structure, and at CLEO 2012, a group from the University of Dundee (Dundee, UK) described a room-temperature antimonide QCL tunable across an 85 nm range near 3.2 μm.[8] But antimonides require special fabrication techniques, and Faist's group reported pulsed antimony-free QCLs tunable across a 450 nm range near 3.3 μm.[9,10]

Meanwhile interband cascade lasers (ICLs), which had dominated the 3-to-4-µm band, are pushing to longer wavelengths. As shown in Fig. 2, these are hybrids of QCLs and conventional diodes, in which electrons cascade through a series of quantum wells, but they emit light on transitions between conduction and valence bands, like in diodes, and the electron then tunneling through to the next quantum well, as in QCLs.

In 2011, Jerry Meyer's group at the Naval Research Laboratory (Washington, DC) showed that heavily *n*-doping electron injectors can increase electron populations in quantum wells, reducing ICL room-temperature threshold current density to as low as 170 A/cm^2 and raising wall-plug efficiency to as high as 13.5%.[11] That allows pushing ICLs to longer wavelengths than previously possible, where their low input power requirements might be attractive for applications that require low power consumption, such as sensing. "There is no reason we can't have interband cascade lasers beyond 6 µm," Meyer said at CLEO. His group has demonstrated room-temperature CW operation near 5.6 µm and pulsed operation at 9.4 µm at temperatures to 190 K.[12]

A team from the University of Oklahoma (Norman, OK) reached even longer wavelengths with ICLs containing plasmon waveguides. At CLEO they reported CW lasing at 10.3 µm in one laser at up to 166 K. Curiously, that device had emitted near 9.0 µm at 125 K, then hopped to the longer wavelength at 150 K for reasons not yet understood.[13]

> Interband cascade lasers are hybrids of QCLs and conventional diodes, in which electrons cascade through a series of quantum wells, but they emit light on transitions between conduction and valence bands, and the electron then tunneling through to the next quantum well.

Frequency combs and broad bandwidth

Mid-IR spectroscopists have used weak teeth from frequency combs as injection seeds for QCL amplifiers to produce precisely calibrated wavelengths. But QCLs are difficult to modelock because their gain recovery time is only 0.3 ps—much shorter than the tens of picoseconds round-trip time of a high-performance QCL cavity. That might seem to block producing femtosecond frequency combs with QCLs.

However, at CLEO Faist said that there are other ways to generate frequency combs besides circulating an ultrafast pulse in the cavity of a modelocked laser. What's essential is that the laser emission is periodic and repeats at the cavity round-trip frequency. Thus the spectrum of a perfectly frequency-modulated laser with low group velocity dispersion could be seen as a series of discrete, equally spaced frequencies—a frequency comb.

At CLEO, Faist's student Andreas Hugi reported getting a free-running broadband QCL to emit a comb spanning 490 nm at 7 μm. Beat-note linewidths of individual comb teeth were as narrow as 10 Hz.[14]

Outlook and applications

Quantum-cascade lasers have become a commercial technology, both for sensing in the milliwatt range and for higher-power applications such as mid-IR countermeasures and pointers for use with mid- and thermal-IR cameras (see frontis) A new trend is extending sensing applications to the 14-to-16-μm window, where the signatures of hydrocarbons are much more distinct than in the mid-IR, where there is much more overlap, says Takeuchi. "You can tell benzene, toluene, and xylene apart very nicely" at the longer wavelengths, an excellent commercial application.

Even without a "killer app," commercial markets look encouraging. Component costs have dropped an order of magnitude in the past six years, Takeuchi says. Manufacturers also have built up the reliability data that equipment makers want before committing to a new technology. "We haven't seen a failure yet" in run-time testing of nearly 100 devices over a total of 550,000 hours at Daylight, he adds. So far, it looks very good.

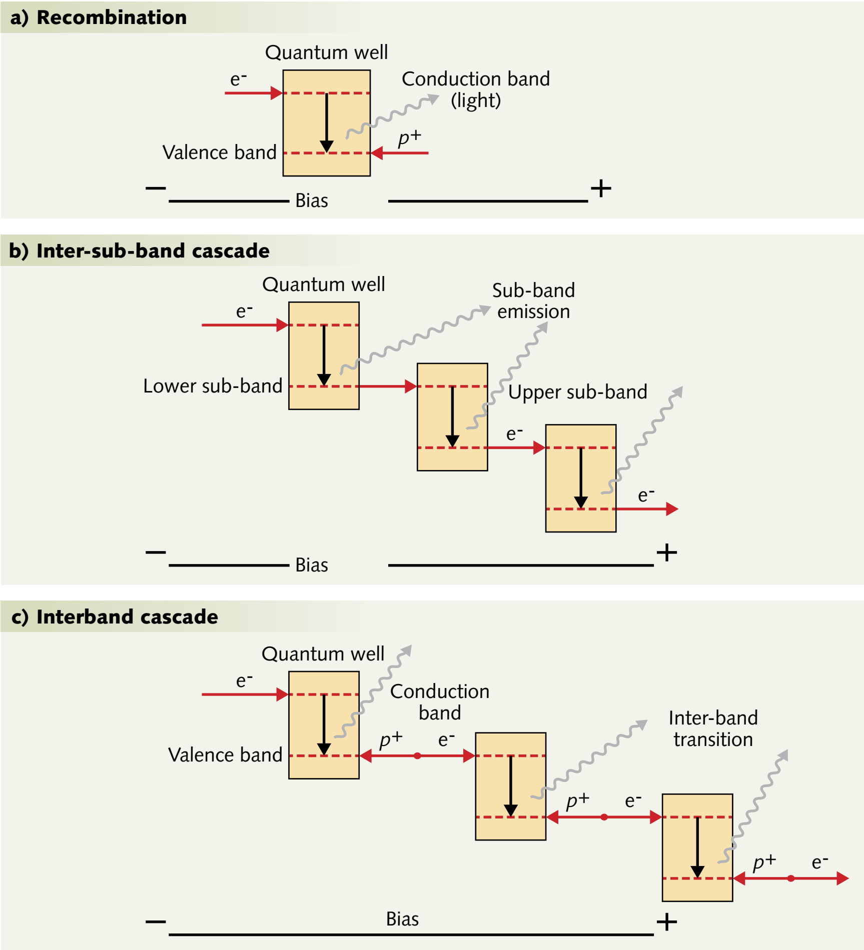

FIGURE 2. Comparison of laser diode emitting on an interband transition (a) with QCL (b) and interband cascade laser (c). In the laser diode, a conduction electron recombines with a hole in a single quantum well, emitting on the interband transition. In the QCL, a single electron falls through a series of quantum wells, in each case emitting light on transition between sub-bands in the quantum well. In the interband cascade laser, electrons travel to the right and combine in quantum wells with holes moving to the left. New electron-hole pairs are generated for each quantum well. A high voltage bias is applied across both types of cascade lasers, but the QCL is doped only to produce electrons, and the interband cascade includes *p*-doping to produce holes.

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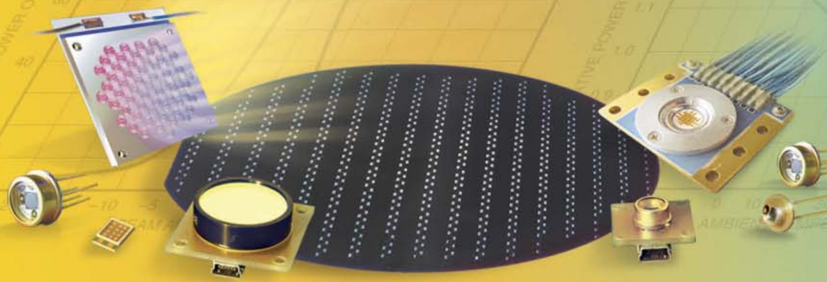

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Plasmonic perfect light absorber has a wide IR spectral band

JOSHUA HENDRICKSON and JUNPENG GUO

By multiplexing two or more plasmon-resonance perfect-absorber structures together, wideband performance in the infrared is achieved.

Anomalous light absorption in metal structures was first observed by R.W. Wood a century ago.[1] Interest in strong light absorption in metallic structures resurfaced in the 1960s.[2-9] Metamaterial-based perfect light absorbers are metal plasmonic-resonance structures that completely absorb incident light at specifically designed wavelengths.

Because light absorption in structured metals is due to surface-plasmon resonance, perfect absorption typically occurs at a specific wavelength with a very narrow spectral range. In many applications, however, it is desirable to have perfect light absorption over a broad spectral band.

Multiplexed structures

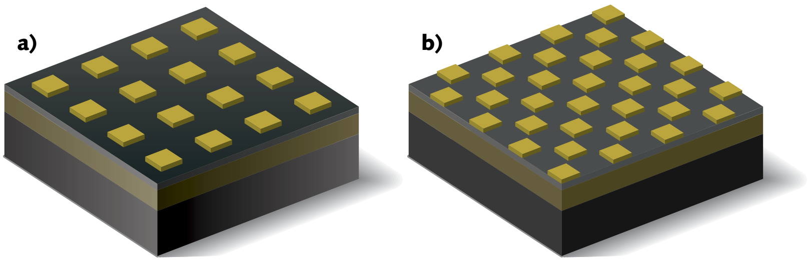
Recently, a wideband perfect light absorber in the midwave IR was proposed and demonstrated by using multiplexed metal structures.[10,11] In the multiplexed plasmon-resonance structure, several gold metal squares of different sizes are multiplexed in the unit cell. The multiplexed-structure perfect absorber can completely absorb photons falling onto the surface over a certain spectral band due to the multiple resonance modes and the coupling between these resonance modes.

The regular-structure (narrowband) perfect light absorber can be seen in Fig. 1a. Gold thin-film squares are periodically patterned on the top of a thin dielectric layer deposited on top of a thick gold metal layer. The gold layer is thick enough so that no transmission can occur. Due to the plasmonic resonance in the structure, optical reflection from the surface can be eliminated.

The multiplexed metal-structure perfect light absorber is shown in Fig. 1b. The period of the multiplexed structure is the same as the period of the nonmultiplexed structure; but in the multiplexed structure, there are two different-sized metal squares in the unit cell that generate two plasmon-resonance modes at different frequencies. In both of these structures, the periods of the unit cells are identical in both lateral dimensions to ensure polarization-independent absorption for normal incidence.

Wideband performance

In one example, a multiplexed perfect-absorber structure has a unit cell in which two gold film squares of 815 nm



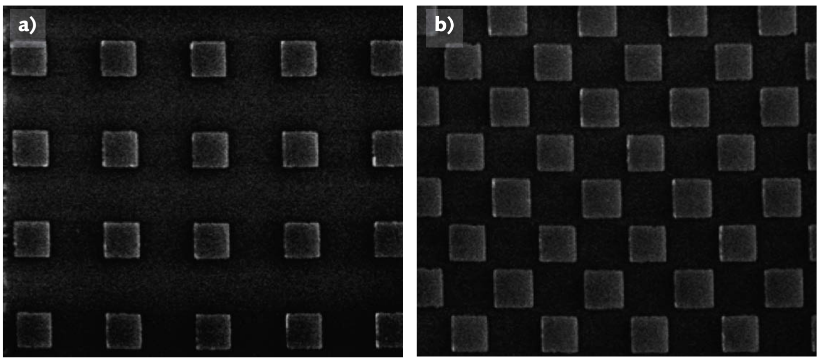


FIGURE 1. A regular perfect-absorber metal structure (a) is compared to a multiplexed perfect-absorber structure (b).

FIGURE 2. A scanning electron micrograph (SEM; bottom) shows a multiplexed-structure perfect-absorber surface with two different sized gold film squares in the unit cell.[11]

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and 865 nm sizes are multiplexed (see Fig. 2). Optical power reflectivities from perfect absorbers with a multiplexed metal structure and with a nonmultiplexed structure are shown in Fig. 3. The dotted blue line is the reflectivity from the nonmultiplexed regular structure perfect absorber with an

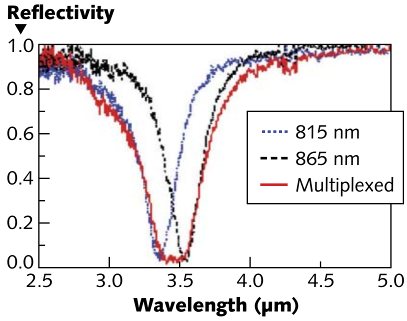

FIGURE 3. The measured optical reflectivities from the multiplexed structure perfect absorber (red line) and nonmultiplexed structure perfect absorbers with different perfect-absorption wavelengths (dotted blue line and dotted black line).[11]

815 nm gold square in the unit cell. The device has near-perfect absorption of 96% at a 3.36 μm wavelength. The dotted black line shows the optical reflection from the regular nonmultiplexed-structure perfect absorber with an 865 nm gold square in the unit cell. This device has near-perfect absorption of 96.7% at a 3.55 μm wavelength.

The solid red line in Fig. 3 shows the optical power reflectivity from the multiplexed structure perfect absorber with both 815 nm and 865 nm gold metal squares in the unit cell. The multiplexed-structure absorber reaches above 97% over a wide spectral band centered at a 3.45 μm wavelength. The multiplexed structure's absorption band has been expanded significantly due to the two gold metal squares of different sizes in the unit cell.

This absorption-band expansion is not a simple linear superposition of two absorption bands of the regular nonmultiplexed metal-structure perfect absorbers. The coupling of two resonance modes may also contribute to broadening of the absorption spectral band.

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Joshua Hendrickson is a research physicist at the Wright Patterson-Air Force Research Lab (Dayton, OH) and **Junpeng Guo** is a faculty member of optics at the University of Alabama (Huntsville, AL); e-mail: guoj@uah.edu.

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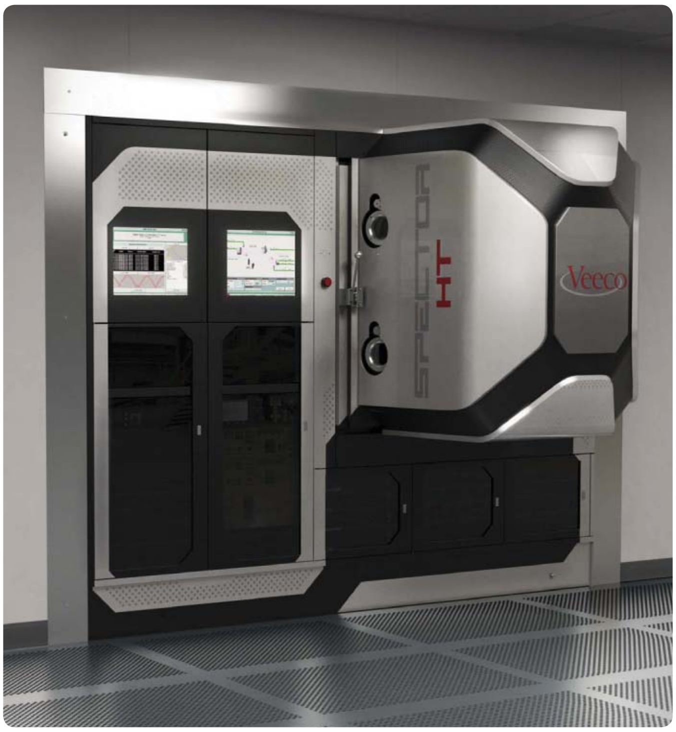

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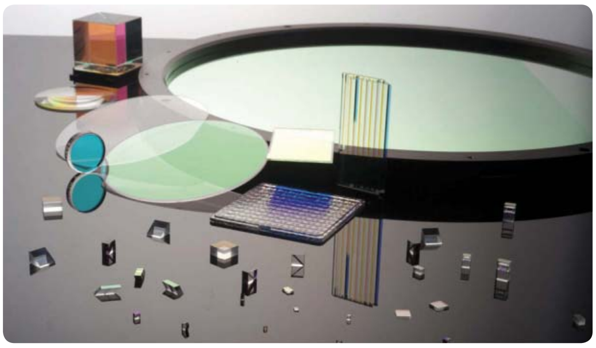

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SWIR InGaAs FPA enables photon emission failure analysis

RAF VANDERSMISSEN and PATRICK MERKEN

Cooled, very sensitive detectors are critical for low-light-level measurements in spectroscopy, fluorescence imaging, and photon emission measurements, including semiconductor failure analysis.

Specially designed focal plane arrays (FPAs) are required to obtain the lowest possible noise and highest sensitivity in applications such as high-resolution spectroscopy, nanotube fluorescence imaging, and especially for photon emission measurements such as in semiconductor failure analysis (see frontis). Such a design may also be critical in other very low-light-level, short-wavelength infrared (SWIR) and visible-to-near-infrared (VisNIR) imaging tasks.

To meet requirements for low dark current, low noise, and sensitivity in the SWIR range, Xenics developed an indium gallium arsenide (InGaAs) detector, the XFPA-1.7-640-LN2, optimized for 77 K operation. The circuitry is based on a source-follower detector (SFD) read-out, which provides high sensitivity at a resolution of 640 × 512 pixels and a pixel pitch of 20 μm.

The frame rate is 2.5 Hz (in 4-output mode), which can be increased when a smaller region of interest is selected. Nondestructive read-out mode simplifies operation when long integration times are used. Liquid nitrogen (LN_2) cooling allows for very low noise (<20e-). A low dark current (<5e-/s/pixel) can also be achieved at these low temperatures. The sensitive wavelength band of the device covers the region from 0.9 to 1.6 μm (optional 0.4 to 1.6 μm).

Sensor design

The light detectors are integrated along with the silicon-based ROIC, which utilizes Xenics' in-house hybridization technology (see Fig. 1). Pixel topology is based on an SFD stage, which is known for its excellent noise performance. The basic (simplified) pixel schematic is shown in Fig. 2a.

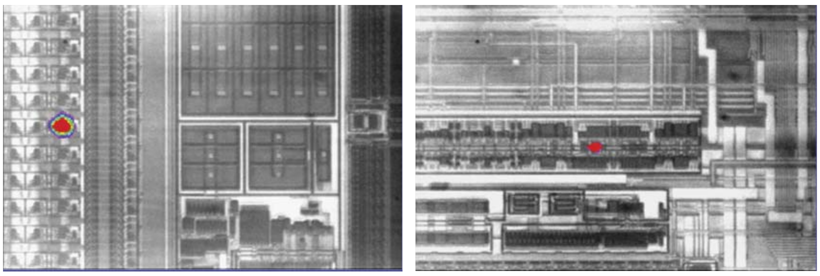
The SFD's main advantage is design simplicity and the ability to integrate charge without the need to be powered. Therefore the SFD is a good choice for large-format arrays with small pixel dimensions. Another advantage is the fact that very few elements are present in the pixel that will reduce the so-called Narcissus effect, which can substantially degrade detector performance in low-temperature applications.

The main disadvantage of the SFD is the change in the input node voltage that occurs as charge is collected on the input node capacitance of the circuit. However, this is not a serious drawback because the intended use is low-temperature operation, where the impact of unstable bias is greatly reduced, if not completely absent.

All pixels are interconnected via a common column bus and sequentially read out through an analog multiplexer circuit. Interconnect and signal paths are laid out in a low-complexity fashion to optimize noise performance (see Fig. 2b).

Operational modes

The sensor device offers two distinct modes of operation: NDR (nondestructive readout, also known as integrate while read) and ITR (integrate



FRONTIS. Backside images of memory devices, with photon emission overlay for fault localization were taken with SWIR InGaAs cameras. *(Courtesy of SEMICAPS Pte Ltd., Singapore)*

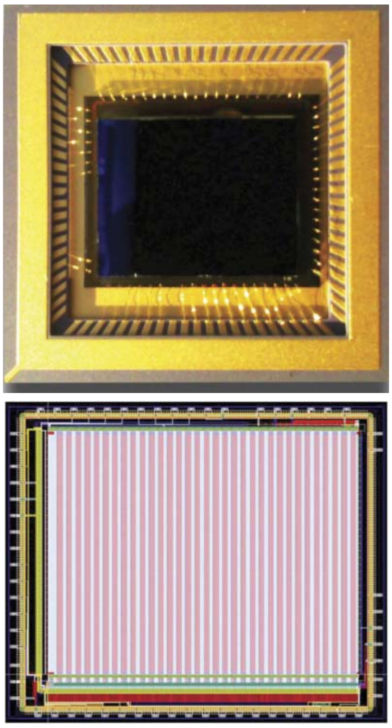


FIGURE 1. The Xenics XFPA-1.7-640-LN2 is an LN_2 cooled high-resolution SWIR detector.

then read). Timing diagrams for both modes of operation are shown in Fig. 3.

NDR mode operation starts with a simultaneous global reset of the entire array. All pixels begin simultaneously with the integration of IR induced carriers. However, the pixels are not read out simultaneously in this mode (the integration time of first and last pixel is different). Therefore, the external electronic circuitry always uses the first frame read-out as reference for the subsequent frames. As leakage is very low and integration times are long, several

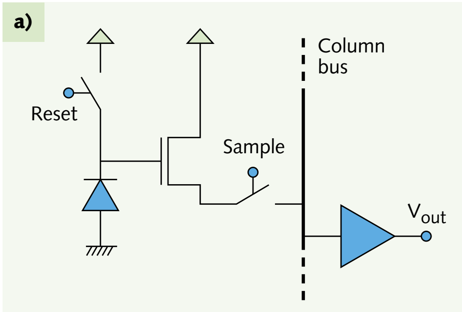
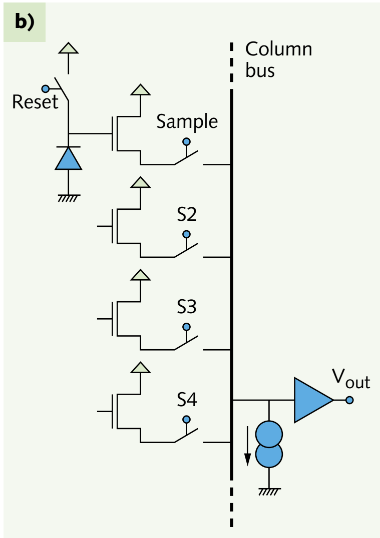


FIGURE 2. Pixel topology of the XFPA-1.7-640-LN2 is based on a source-follower detector stage (a), and column multiplexer circuitry (*simplified;* b).



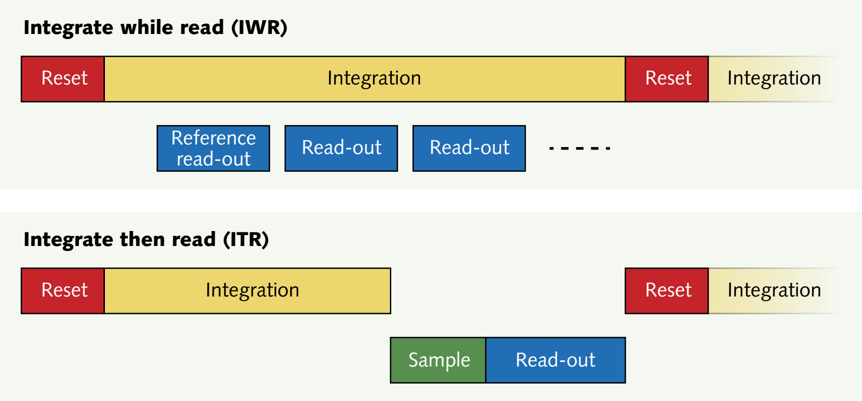


FIGURE 3. The sensor device offers two distinct modes of operation: nondestructive readout (or integrate while read) and integrate then read. Timing diagrams are shown for both modes of operation.

frames can be used to build up the resulting image using advanced multisample signal-acquisition techniques.

In ITR mode all pixels start integration at the same time and then are sequentially read out. Integration time here is simply the time between Reset and Sample moments.

The sensor device has four different (selectable) outputs, which can drive capacitive loads. The sensor allows operation in a window-of-interest (WOI) or Windowing mode. To ease cooling measures and device operation, a temperature sensor was integrated. The chip consists of the actual FPA and the ROIC detector interface combined with a digital circuit for multiplexing and signal transfer, as well as an analog interface and test topologies.

Nanotube imaging

Nanotube fluorescence is typically investigated in nanotechnology imaging research. The ultimate goal is to create faster nanoelectronic devices as well as ultrastrong and extremely lightweight materials with advantageous structural features. Of particular interest are nanotubes, which are formed when carbon atoms bond to one another to establish planar hexagonal rings.

The formation of nanotubes is widely investigated with the aim of improving production processes. When produced on a perfect molecular level, fullerene tubes offer revolutionary electrical, thermal, and mechanical properties at the nanometer scale. Researchers are also interested in the optical properties of nanotubes as they have potential applications as fluorescent tags in chemical and biological systems.

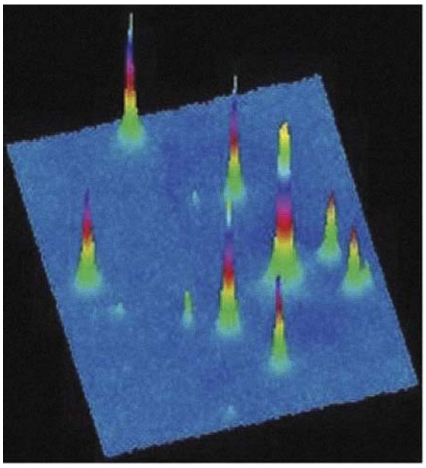


FIGURE 4. 3D fluorescence plot is captured from single-walled nanotubes using an LN_2-cooled InGaAs camera. *(Courtesy of R.B. Weisman, Rice University)*

The availability of LN_2-cooled InGaAs cameras with high sensitivity can now enable researchers to capture low-light fluorescence events in the SWIR region (900 to 1600 nm) stemming from nanomaterials (see Fig. 4).

Quantum dot research

Quantum dot research is a relatively new field that targets new applications in optoelectronics and quantum information processing. Sensitive SWIR cameras are used here to investigate and better understand the physical properties of quantum dots.

The quantum dots can be regarded as "artificial atoms." The photoluminescence of quantum dots is tunable by changing the dot size over a wide range, from the far infrared to deep ultraviolet.

Photon emission microscopy

Photon emission microscopy (PEM) can be used as a failure-analysis technique for the localization of defects in semiconductor devices. System sensitivity (in other words, InGaAs detector sensitivity) is key in such photon emission applications.

If the very faint emissions—in the 900-to-1600-nm wavelength band—that are typically caused by failure effects can be detected, then this technique can be used to quickly locate leaky junctions and other current leakage phenomena that generate light emissions.

Very sensitive InGaAs detectors, when equipped with LN_2 cooling, have an extremely low dark current and low noise. They enable operation modes with long integration times and excellent signal-to-noise ratios.

Semiconductor failure analysis

In semiconductor failure analysis, photon emission microscopy has the potential for high-volume applications. High-end photon emission microscopes based on LN_2-cooled InGaAs cameras can be used for fault localization in component fabs and foundries for production quality control, return merchandise authorization (RMA) control, and electronic design debug purposes.

Fault localization is the manufacturing step that attempts to isolate the defective areas on the die of failed units. It is a critical step since it dramatically reduces the area required for the analysis. Moreover, after characterizing a localized defect, the underlying failure mechanism can be further investigated.

Two main categories of fault localization exist: passive and active. Active techniques

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typically use a scanning ionizing beam (e.g., a laser beam) to stimulate the failure source. The most common passive technique is photon emission microscopy by means of sensitive (appropriately cooled) cameras. It relies on the fact that various types of failures will emit small amounts of light (photon emission, or also electroluminescence) when the failure is occurring.

Frontside chip or wafer analysis through a photon emission microscope faces limitations due to the growing use of multilevel metallization. This prevents photon emissions of the defects from reaching the detector. Backside chip or wafer analysis can benefit from the fact that silicon, the most common material in microelectronics, is fairly transparent for near-infrared light at wavelengths longer than 1100 nm (see frontis).

This is exactly the area where SWIR InGaAs cameras show an advantage based on their high quantum efficiency (QE) between 1000 and 1600 nm. Moreover, the lower operating voltages that characterize the ongoing miniaturization of microelectronic devices are causing a shift toward longer photon emission wavelengths, typically peaking between 1300 and 1500 nm.

FPAs vs. CCD for PEM

Silicon-based CCD detectors have been used extensively for photon emission microscopy. Especially scientific-grade, back-illuminated, cooled CCD detectors are used for backside chip and wafer analysis. However, CCD cameras at a wavelength between 300 and 1100 nm are effective only for observing photon emissions with energy transitions above the silicon bandgap. They do not allow the observation of intraband emissions above 1100 nm, where this emission is most intense.

Also, sub-bandgap emissions involving chemical impurities, physical defects, deep traps, and other recombination centers cannot be observed with CCD detectors. Furthermore, backside analysis requires a transmission through the silicon substrate, which is opaque to wavelengths below 1100 nm.

Consequently, InGaAs-based cameras are the best candidates for high-sensitivity photon emission applications in the 900-to-1600-nm band because of their QE. Especially with LN_2 cooling, they exhibit very low dark current and noise levels, making them the most sensitive detectors in this band.

Spectral analysis of photon emission in the SWIR is a very promising field if one takes into account that each semiconductor failure mechanism may have its own spectral signature. This, however, requires the use of very sensitive detectors in the SWIR band in combination with high-end diffraction optics or, alternatively, a wavelength-tunable filter.

Raf Vandersmissen is CEO of sInfraRed–a Xenics company, Singapore, and **Patrick Merken** is with RMA Brussels and Xenics, Ambachtenlaan 44, BE-3001, Leuven, Belgum; patrick.merken@xenics.com; www.xenics.com.

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Swept fiber laser uses dispersion tuning to target OCT imaging

YUYA TAKUBO and SHINJI YAMASHITA

A fast and wide-wavelength swept fiber laser based on dispersion tuning sweeps the wavelength without using wavelength-tunable filters. This enables a 200 kHz sweep rate over a 140 nm range and offers tremendous potential for optical coherence tomography (OCT) imaging.

Fiber lasers are widely used in many telecom, medical, and industrial applications, and wavelength-tunable fiber lasers are very useful for dense wavelength-division multiplexing (DWDM), optical fiber sensing, and test and measurement applications. Conventional wavelength-tunable fiber lasers change wavelength through adjustments to a wavelength-tunable filter (a diffraction grating or fiber Fabry-Perot tunable filter, for example) in the laser cavity. Even though Fourier domain modelocking (FDML) introduced by R. Huber et al. is a strong method for swept-source OCT (SS-OCT) imaging, all these conventional techniques have fundamental limitations of wavelength sweep rate and range as they rely on some kind of mechanical tunable filter.[1]

Our group at the University of Tokyo has developed a wavelength-tunable fiber laser based on dispersion tuning, a method that enables wavelength sweeping without using any tunable filters. In this method, we apply a modulation signal in a highly dispersive laser cavity and choose the wavelength by controlling the modulation frequency, enabling a sweep rate of more than 200 kHz over a 140 nm sweep range. This performance is significantly better than conventional wavelength-swept fiber lasers.

An important application for tunable fiber lasers is SS-OCT, a noninvasive cross-sectional imaging technique using infrared light that has shallower imaging depth but much higher resolution than competing x-ray tomography and magnetic resonance imaging (MRI) techniques.[2] The OCT method is also capable of real-time imaging and is expected to be applied to endoscopic systems and intravascular catheters using optical fiber delivery.

For SS-OCT systems, wavelength-swept fiber lasers with high sweep rate and sweep range are needed. We have applied our dispersion-tuned fiber laser to an SS-OCT system and obtained OCT images at up to 50 kHz, demonstrating the promising potential of these lasers for high-performance OCT imaging applications.

Dispersion tuning

The principle of the dispersion tuning method is modelocking of a dispersive laser cavity. Highly dispersive devices (such as dispersion-compensating fibers) are inserted into the laser cavity and the light in the cavity is intensity modulated. The lasing wavelength changes corresponding to the intensity modulation frequency.[3, 4]

When the light in the laser cavity is intensity modulated at the integral multiple frequency of the free spectral range (FSR), the light is actively modelocked. The FSR of the laser

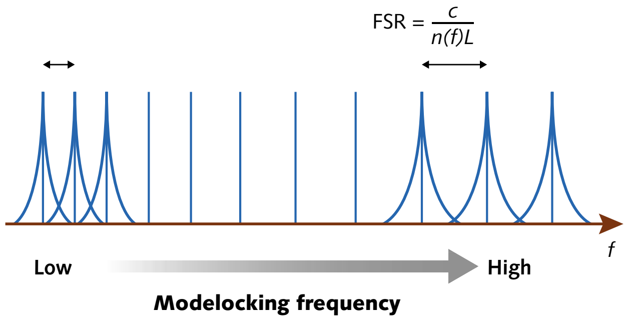

FIGURE 1. In dispersion tuning, the free spectral range (FSR) is a function of wavelength or frequency in a highly dispersive laser cavity. The light is actively modelocked when the light in the laser cavity is intensity modulated at the integral multiple frequency of the FSR.

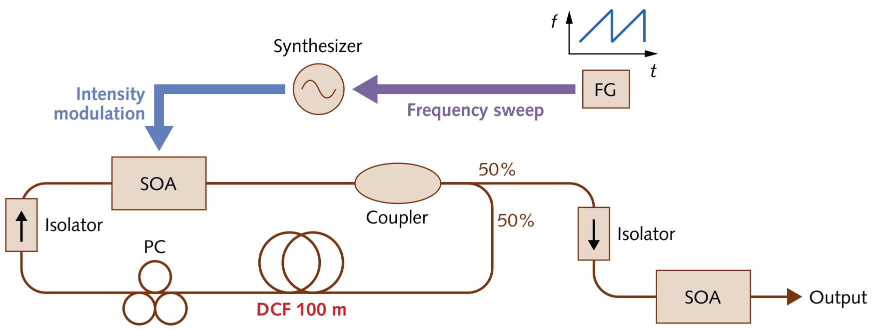

FIGURE 2. A schematic shows the components of a dispersion-tuned fiber laser, where SOA is the semiconductor optical amplifier, DCF is dispersion-compensating fiber, PC is the polarization controller, and FG is the function generator.

cavity F can be expressed as $F = c/nL$ where L is the cavity length, n is the refractive index in the cavity, and c is the speed of light in a vacuum. When the cavity contains chromatic dispersion, the FSR is a function of wavelength λ or frequency f (see Fig. 1). Ignoring higher-order dispersion, the relationship between the wavelength and the FSR F is expressed as $\lambda = -(n_0/cDF_0)(F - F_0) + \lambda_0$ where n_0 is the refractive index at λ_0 and D is the dispersion parameter.

Active modelocking is a technique to generate short pulse trains by applying modulation to the laser cavity. For stable active modelocking, the modulation frequency f_m applied to the cavity must match with an integer (N) times the FSR ($N \times F$), where N is the order of harmonic modelocking. That is, when we apply a modulation at f_m to the dispersive cavity, the laser is forced to operate at the wavelength λ_m to meet the harmonic modelocking condition, which can be expressed as $\lambda_m = -(n_0/cDf_{m0})(f_m - f_{m0}) + \lambda_0$ where $f_m = N \times F$. Therefore, the light oscillates at the specific wavelength corresponding to the modulation frequency.

The change of lasing wavelength $\Delta\lambda$ can be expressed as $\Delta\lambda = -(n_0/cDf_{m0})\Delta f_m$ where D is the dispersion parameter, f_{m0} is the center of the modulation frequency, and Δf_m is the change of the modulation frequency. This equation indicates that the lasing wavelength can be swept linearly by sweeping the modulation frequency, and that a smaller f_{m0} and D are needed for a wider tuning range. However, a smaller f_{m0} increases the instability of the lasing wavelength and a smaller D means the difference of the FSR between wavelengths is smaller—both facts leading to linewidth broadening. Therefore, a tradeoff between parameters is needed to optimize a dispersion-tuned fiber laser.

Laser setup and characteristics

In our dispersion-tuned swept fiber laser, a semiconductor optical amplifier (SOA) is directly modulated for modelocking and a 100-m-long dispersion-compensating fiber (DCF) is inserted to increase the dispersion of the cavity (see Fig. 2). The dispersion parameter D is about -120 ps/nm/km. The cavity includes the polarization controller and isolator, and half of the light in the cavity is output via a 50:50 coupler. In order to sweep the lasing wavelength, the modulation frequency f_m is linearly swept around the center frequency by the function generator (FG).

> Active modelocking generates short pulse trains by applying modulation to the laser cavity. For stability, the modulation frequency applied to the cavity must match with an integer (the order of harmonic modelocking) times the FSR.

In consideration of the radio fre-

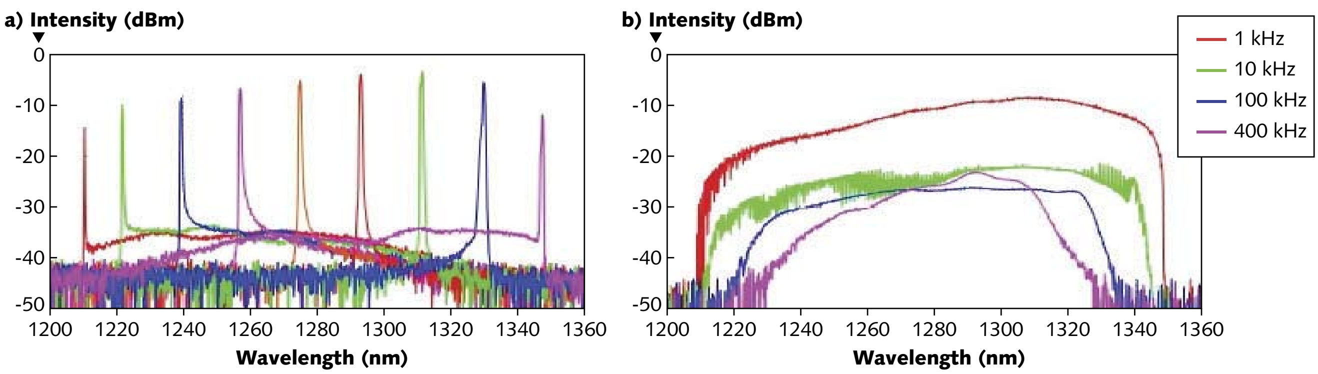

FIGURE 3. The dispersion-tuned fiber laser as observed by an optical spectrum analyzer shows several oscillation spectra when the modulation frequency is manually controlled (a). The peak-hold spectra are shown (b) at sweep rates of 1, 10, 100, and 400 kHz.

quency (RF) modulation characteristics of the adopted SOA, we set the center modulation frequency f_{m0} at 461 MHz. The SOA drive current is 80 mA and the AC modulation signal from the synthesizer is 28 dBm after amplification. When the modulation frequency is manually controlled, the laser output shows several oscillation spectra as observed by an optical spectrum analyzer (see Fig. 3). The lasing wavelength shifts corresponding to the change in modulation frequency. As the SOA used in this setup emits O-band light (1260–1360 nm), the oscillation wavelength of the laser is tuned over 140 nm around 1300 nm.

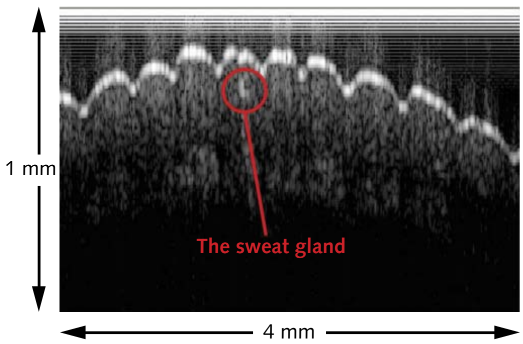

FIGURE 4. An optical coherence tomography (OCT) image of the human finger is obtained at 1 kHz by a swept-source OCT system that uses a dispersion-tuned fiber laser.

OCT imaging

By replacing the light source in a Santec Corp. (Komaki, Japan) Inner Vision OCT system with our dispersion-tuned wavelength-swept fiber laser, we were able to perform SS-OCT imaging.[5] An image of the human finger at a 1 kHz sweep rate does show a stripe pattern near that surface that derives from system noise (see Fig. 4). With a resolution of 16 µm and a sensitivity of about 87 dB, the depth at which the signal has a 6 dB drop-off is 0.38 mm. Although this depth range is not sufficient for OCT imaging, the sweat gland under the surface of the finger can be observed near the center of the image.

At sweep rates greater than 100 kHz for this initial SS-OCT system, the laser output power decreases and the instantaneous linewidth broadens mainly because the laser cavity length is too long and the wavelength is shifted before the light perfectly oscillates at higher sweep speed. In order to shorten the laser cavity and solve this problem, we replaced the 100 m DCF with a chirped fiber Bragg grating (CFBG). The cavity length is reduced by a factor of ten and performance is dramatically improved. Furthermore, we tried a reflective SOA (RSOA) as the gain medium and made a linear cavity instead of the existing ring cavity. The laser length in this case was approximately 2 m and performance was further improved.

Using the CFBG configuration, we successfully obtained OCT images of adhesive tape at 50 kHz, clearly identifying several layers of the tape. Additional images at a 125 kHz sweep rate—although with more limited depth range than the 50 kHz images—clearly indicate the potential of filter-free, dispersion-tuned fiber lasers as real-time OCT imaging sources. ◂

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Yuya Takubo is a master's degree student and **Shinji Yamashita** is a professor in the Department of Electronic Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan; e-mail: takubo@cntp.t.u-tokyo.ac.jp; www.u-tokyo.ac.jp.

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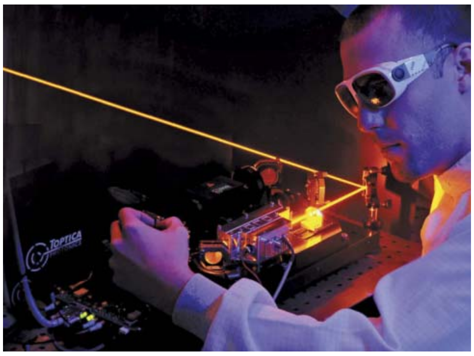

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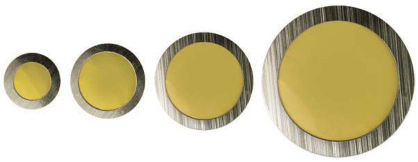

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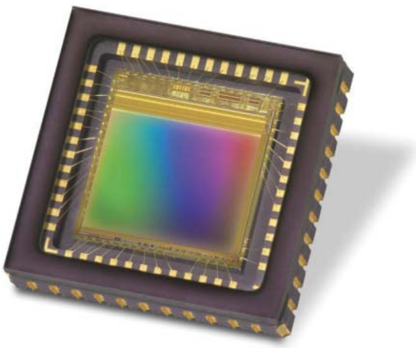

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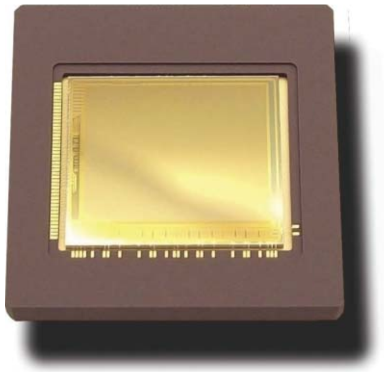

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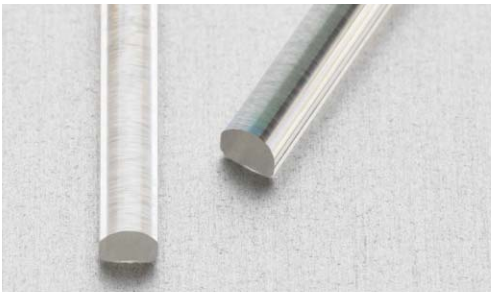

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Taiwan Diana Wei
886-2-2396-5128 ext. 270; fax: 886-2-2396-7816
diana@arco.com.tw

For all other international sales, please contact:
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(see contact info. above)

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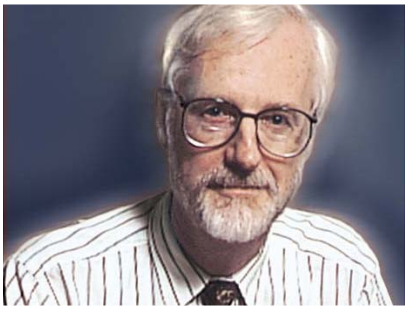
IN MY VIEW

BY JEFFREY BAIRSTOW

Now this really is rocket science

Here's a short take on an innovative research program for which several teams of engineers, scientists and astronomers deserve to get an appreciative tip of the hat. It's a program that ought to get more attention from both the technical and consumer media. I don't have much space to cover this exciting project but, as usual, Google will soon get you moving in the right direction. In my view, this really is rocket science. Let's take a look.

Back in mid-June this year, several teams of rocket scientists and engineers working at the California Institute of Technology (Caltech) Jet Propulsion Laboratories (JPL) in Pasadena, CA—and sponsored by NASA—successfully launched an orbital x-ray telescope slung under a specially modified Lockheed L-1011 jetliner flying at 39,000 feet. This was truly a low-cost launch, a harbinger, perhaps, of other cost-effective ventures to come.



NASA and Caltech/JPL deserve credit not only for the conception of NuSTAR but also the management of project teams around the world. If all goes well, NuSTAR will become a model for unmanned research deep into the cosmos.

Known as the NuSTAR satellite (Nuclear Spectroscopic Telescope Array), the project is intended to peer into black holes and other explosive events in our galaxy and others. This is projected to cost about $170,000 over two years, or about one-tenth of the cost of similar orbital observatories to date.

Sounds easy enough, you might think, but I must repeat, this really is rocket science. The first target for NuSTAR is Cygnus X-1, the black hole nearest to Earth, a mere 6100 light-years away. By the end of June, the NuSTAR was busily sending images to JPL. "Today we obtained the first-ever focused images of the high-energy x-ray universe," said Fiona Harrison, the mission's principal investigator at Caltech. Harrison first conceived of NuSTAR about 15 years ago. "It's like putting on a new pair of glasses and seeing aspects of the world around us clearly for the first time," she said.

At the time of this writing (in early July), the NuSTAR satellite had successfully extended its 33-foot antenna and JPL scientists were starting to test its array of 133 mirrors. The NuSTAR was expected to begin regular operations by the end of July. If you would like to follow the NuSTAR's progress, you should Google the satellite or go directly to either the NASA (www.nasa.gov/nustar) or the JPL web sites (www.nustar.caltech.edu/). There are videos and slide shows galore at these sites. While satellite launching is hardly a walk in the park, these videos ooze with confidence in a successful launch.

As I said earlier, NASA and Caltech/JPL deserve credit not only for the conception of NuSTAR but also the management of project teams around the world. If all goes well, NuSTAR will become a model for unmanned research deep into the cosmos. Way to go, NuSTAR people!

By the way, in poking around in the media files for NuSTAR, I came across this lengthy list of collaborative organizations that ought to be given an honorable mention for their participation in the venture.

NuSTAR is a Small Explorer Mission led by Caltech and managed by JPL for NASA's Science Mission Directorate in Washington, DC. The spacecraft was built by Orbital Sciences Corporation, based in Dulles, VA. The instrument was built by a consortium including Caltech; JPL; the University of California–Berkeley; Columbia University (New York, NY); NASA's Goddard Space Flight (Greenbelt, MD); the Danish Technical University (Lyngby, Denmark); Lawrence Livermore National Laboratory (Livermore, CA); and ATK Aerospace Systems (Goleta, CA). NuSTAR will be operated by the University of California–Berkeley, with the Italian Space Agency providing its equatorial ground station located at Malindi, Kenya.

I can imagine that keeping so many diverse groups in line across several continents will be no mean feat for Dr. Harrison!

Jeffrey Bairstow
Contributing Editor
inmyview@yahoo.com