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July 2012
LaserFocusWorld®
International Resource for Technology and Applications in the Global Photonics Industry
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Modeling optimizes thin-film coating PAGE 28
Real-time digital holography arrives PAGE 53
Portable lens-free on-chip microscope PAGE 59
Broadband OPO spans mid-IR PAGE 62
Multicore fiber becomes lantern filter PAGE 22

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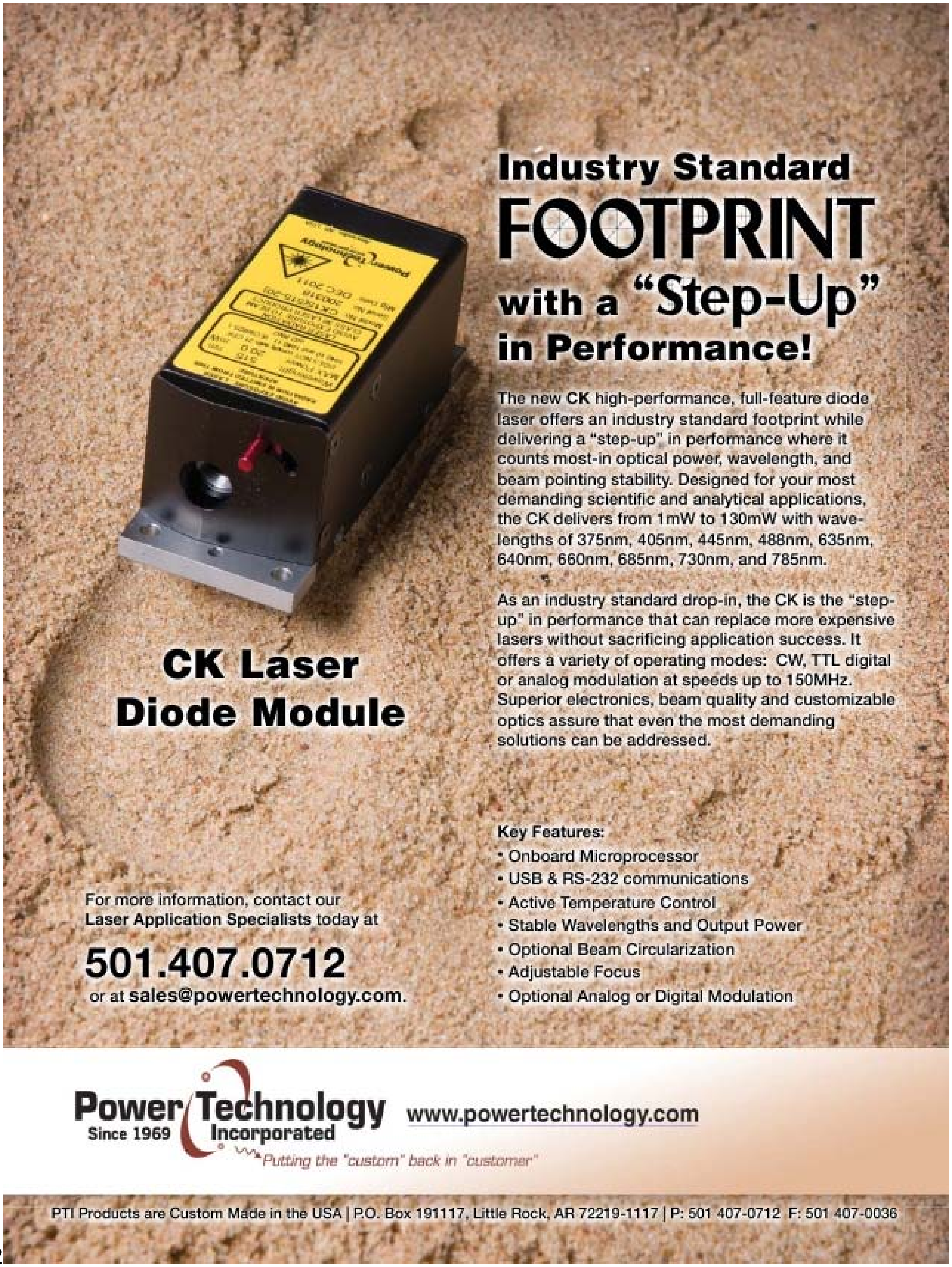
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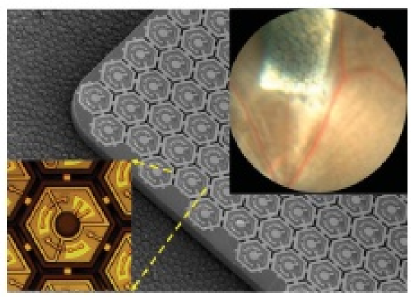
newsbreaks

world news



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features

36 COVER STORY

Two miniature spectrometers were launched on the STS-129 shuttle mission to evaluate more than 700 new optical and electronic materials. As part of NASA's Materials International Space Station Experiment (MISSE), MISSE 7 instrumentation was mounted to the ISS to test the optical properties of the materials when exposed to the extreme environment, and digital data were transmitted down to ground stations for real-time processing. *(Courtesy of NASA)*

Coming in August

Market Insights: Thoughts on R&D in photonics companies

Jan Melles, president of Photonics Investments and former founder and chairman of Melles Griot, contributes some thoughts on the role and importance of research and development in photonics companies. Are the funds reserved for R&D really bringing the return that the company owners and management expect?

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More Features, News & Products

cool content

New Blog: Photonics Education Corner

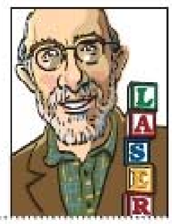
Optics workforce pipeline

The changing face of the American economy and education present US optics companies with a major barrier to growth: lack of trained workforce. Here in Rochester, a university town for sure and the only city in the world that offers an associate's, bachelor's, master's, and doctorate in optics, lack of talent is still the single top challenge named by manufacturers. http://bit.ly/LjblXP

Blog: Photonics Building Blocks

QCL—Defining the quantum-cascade laser

Did you know the first steps toward QCLs took place in 1971? Jeff Hecht spells out the meaning and development back-story of quantum-cascade lasers. http://bit.ly/L8vYPU



Blog: Larry's VC View

What kills tech startups

I have heard visionary or highly technical founders blamed repeatedly for the failure of a company because the technology didn't work—in some countries, they are blacklisted for life for this "failure." I don't believe I have ever seen a company fail because of bad technology (although I have seen one where the founder simply but unintentionally fooled himself). http://bit.ly/NnOkkP

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trending now

Automotive fiber

Automobiles make the 'MOST' use of plastic optical fiber

Plastic optical fiber (POF) has been used in automotive networking systems since 1998, spurring introduction of the Media Oriented Systems Transport (MOST) standard. Today, car makers and component suppliers cooperate to enable the adoption of the latest MOST standard. *Masahiko Otake*
http://bit.ly/MNyR9m

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editor's desk

Space is still the place

Whether you surrendered control of your TV to "The Outer Limits" or voyaged to the final frontier with "Star Trek," space has held a vivid grip on our imaginations—and spectroscopy has been along for the ride. A decade after these television shows first aired in the mid-1960s, Voyager 1 was launched with infrared and ultraviolet spectrometers on board. Thirty-five years later the UV spectrometer is still functioning as the spacecraft heads out beyond the solar system.

As senior editor Gail Overton writes in our cover story, such planetary and deep-space applications of spectroscopy have demanded rugged designs to survive the environment and capture the data. The resulting spectrometers have been delivering invaluable information that ranges from the makeup of heavenly bodies to the performance of optical materials, sensors, and electronics in space (see page 36).

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

Highly scalable

Photonics has also been exploring the microcosm and three articles in the issue illustrate the technologies available to explorers at this end of the scale. Aydogan Ozcan and his colleagues at UCLA describe their work to develop a lens-free, on-chip microscope that should find many uses in field applications (see page 59). Christopher Cotton at ASE Optics shows how creative thinking about optical system design can improve the capture of fluorescence light in a commercial microscopy system used for microbiology testing at pharmaceutical manufacturing (see page 47). And contributing editor Jeff Hecht writes about developments now leading to digital holographic microscopes that can display 3D images of living cells in real time (see page 53).

Whatever the scale, photonics clearly continues to enhance existing applications while enabling new ones.

LaserFocusWorld

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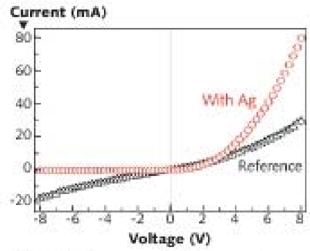
newsbreaks

Silver-enhanced silicon nitride LED is efficient integrated-photonics source

One of the more difficult problems in creating silicon (Si) photonic circuits with active components is that no practical and efficient silicon-based light sources exist (hybrid circuits containing germanium-based or III-V light sources can be used instead). One possible approach, introducing nitrogen (N) to create SiN integrated LEDs, does result in light production but is still not very efficient. A group at Zhejiang University (Hangzhou, China) is working to remedy this by adding a layered structure that contains silver (Ag) islands 50–80 nm in size, resulting in the formation of efficiency-raising localized surface plasmons.

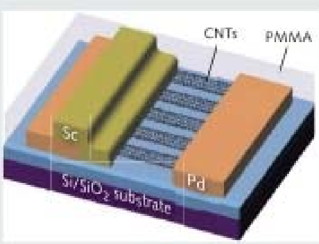
The researchers created an LED containing such a structure and compared it to a similar SiN LED that lacked the structure. Both LEDs emitted broadband electroluminescence from 400 to 700 nm, but the Ag-island LED had an output at 550 nm that was enhanced by a factor of 14 at a 25 mA current. In addition, the Ag-island device could be driven at a current of more than 40 mA, while the control device burned out at 25 mA. The applied voltage was higher for the control device in these experiments but when the voltage was made the same (6 V) for both devices, the new LED had an integrated



electroluminescence 480 times greater than the control device. The current-voltage characteristics of the new device were quite different, too. *Contact Dongsheng Li at* mselds@zju.edu.cn.

Parallel single-walled CNTs form high-performance IR photodetector

While carbon nanotubes (CNTs) have some properties (high infrared absorption, picosecond response, and ballistic electron transport) that could make them excel for IR photodetection, they are difficult to handle and fix in place in large quantities. Researchers at Peking University (Beijing, China) and Duke University (Durham, NC) have come up with a geometry that allows for large numbers of single-walled CNTs to be both held in place and easily electrically contacted at both ends of the nanotubes. In the setup, many parallel semiconducting CNTs lay flat in a position normal to the incoming IR light direction on a silicon (Si)/silicon dioxide (SiO_2) substrate; the CNTs are contacted *en masse* on one end by a palladium (Pd) electrode and the other end by a scandium (Sc) electrode, then encased in PMMA polymer for durability. The two metals have different work functions, making ohmic contacts with the valence and conduction bands of the CNTs, respectively.



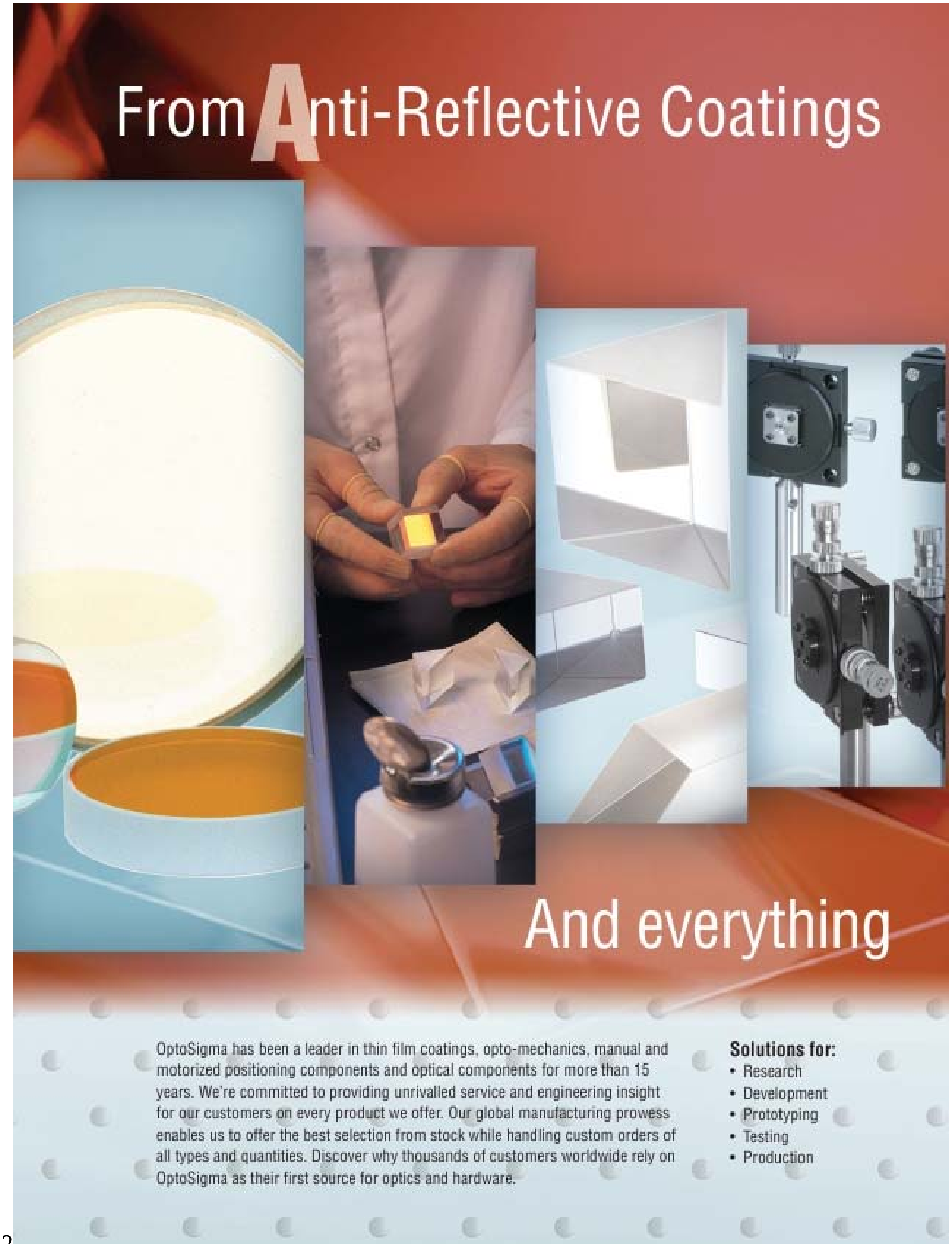
Many parallel interdigitated electrode fingers can allow the creation of a larger detector area; for example, 10×20 µm. The prototype detector had a responsivity of 9.87×10^{-5} A/W and a detectivity greater than 10^7 cm·Hz$^{1/2}$/W for light at 785 nm. Increasing the CNT count and the quality of the CNTs could boost these numbers to 10 mA/W and 10^8 cm·Hz$^{1/2}$/W, respectively, say the researchers. *Contact Sheng Wang at* shengwang@pku.edu.cn.

Femtosecond-laser wet etch forms low-cost microlens arrays

Polymer micro-optical elements or microlens arrays are typically fabricated using photoresist reflow, photolithography, and LIGA methods that require expensive masks and complex processing steps, or by maskless inkjet and self-assembly processes that limit lens quality.

A modified laser-direct-writing process creates glass microlens masters.

And while laser-direct-writing processes such as two-photon-polymerization (TPP) produce high-quality arrays, the point-by-point fabrication process is extremely slow. Researchers at Xi'an Jiaotong University (Xi'an, China), however, have created a modified laser-direct-writing process that rapidly creates high-quality glass Femtosecond continued on page 12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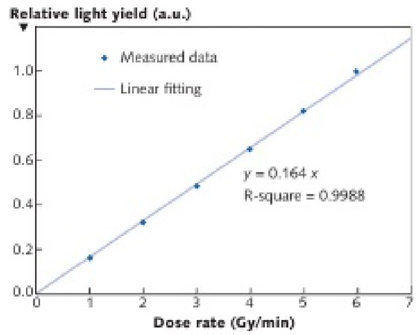
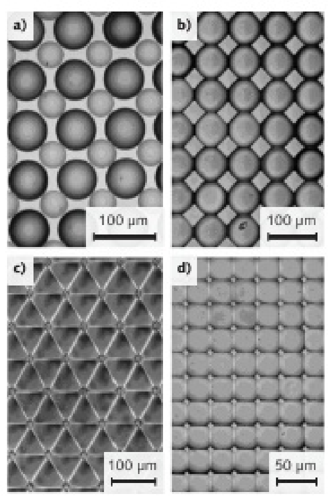
2

Fiber-optic Cerenkov radiation sensor gets dose for proton cancer therapy

In proton therapy, a beam of protons is used to irradiate cancerous tissue, damaging its DNA and ultimately eliminating the cancer cells. Conventional dosimetry for proton therapy involves a scintillator, which is less than ideal because protons can temporarily damage (quench) the scintillator's organic molecules; the result is that complicated formulas must be used to correct for the scintillator's output errors. As an alternate approach, researchers at Konkuk University (Chungju, South Korea) and the National Cancer Center (Goyang, South Korea) are using the Cerenkov radiation produced in plastic fibers as a signal.

Cerenkov radiation occurs when a charged particle travels through a medium at a speed faster than the speed of light in the medium. It is not generated from scintillation, and is not quenched (in this case, it is actually generated by secondary electrons produced by the proton's passage). The resulting fiber-optic Cerenkov radiation sensor, with the Cerenkov radiation measured by a photomultiplier tube, has a linear dose measurement as a function of dose, as determined using a 7-cm-diameter, 180 MeV proton beam measured at a depth of 15 cm in water (1 Gy = 1 J/kg). The researchers are working on using shorter lengths of fiber for higher spatial resolution, and note that the technique can be used for dosimetry of other heavy particles used in cancer therapy. *Contact Bongsoo Lee at* bslee@kku.ac.kr.





Femtosecond continued from page 9

microlens masters that can be used to replicate polymer arrays.

In the process, an 800 nm ultrafast laser delivers intensity- and time-controlled, carefully arranged, individual pulses to a glass slide that is then subjected to wet-etch processing. The laser pulses change the physical and chemical properties of the glass in the focal spots, and the wet-etch processing that follows carves out a unique microlens array pattern. An 80-µm-diameter glass mold with more than 16,000 concave structures can be fabricated in less than three hours, improving significantly on TPP processing and enabling a variety of different glass "master" shapes such as circular, rectangular, diamond, and octagonal designs. *Contact Feng Chen at* chenfeng@mail.xjtu.edu.cn.

A*STAR Exploit Technologies

Flexure-Based Electromagnetic Linear Actuator (FELA):

A breakthrough in precision technology that eliminates the millimetre-range barrier

Travelling range from 1mm to 20mm, positional resolution from ±10 nm, good force sensitivity of up to 120N/Amp

A big challenge for industries such as the electronics, semiconductor, and biomedical sectors is precision over a large workspace. Applications such as wafer positioning or cell-manipulation require fast and accurate positioning within a working range of a few millimetres to hundreds of millimetres.

Currently, Piezoelectric (PZT) actuators have been the most popular choice among the nano-positioning actuators due to its large actuating force and high stiffness. Yet, limited displacement makes it unsuitable to drive a high-precision manipulator targeted for a few millimetres of workspace.

Other nano-positioning actuators that adopted displacement-amplification techniques such as "inchworm" clamping through solid-state PZT or magnetostrictive materials etc., suffer from poor repeatability, low speed, and low payload.

What is FELA?

The Flexure-Based Electromagnetic Linear Actuator (or FELA) revolutionizes the industry as a unique nano-positioning actuator that combines an electromagnetic driving scheme with flexure-based supporting bearings.

FELA breaks through the millimetre-range barrier encountered by state-of-the-art nano-positioning actuators and provides superior nano-metric positioning, large force generation, and high actuating speed.

The Singapore Institute of Manufacturing Technology (SIMTech), a research institute of Agency for Science, Technology and Research (A*STAR), has developed a series of FELAs with different sizes that offer a travelling range from 1mm to 20mm, positional resolution from ±10 nm, good force sensitivity of up to 120N/Amp, fast actuating speed of at least 100mm/sec and high stiffness at all non-actuating axes. The smallest diameter of FELA is about 49mm, and can be used to work on bio cells. That is how precise its movements are designed to be.

Overall, FELA offers an all-in-one solution to overcome the current limitations of nano-positioning actuators such as low payload, repeatability, displacements and speed.

Precise yet cost efficient: The FELA advantage

FELA consists of an Electromagnetic (EM) translator, which is supported by flexure-based bearings. Taking advantage of the elastic deflection, such bearings provide frictionless motion that preserves the contact-less nature of the EM scheme.

Generally, a combination of the Lorentz-force actuation and the frictionless bearings is inadequate as Lorentz-force actuation is well-known for delivering a low driving force. FELA uses a new magnetic configuration to enhance the force generation by almost 40 percent. Such configuration makes FELA more efficient in comparison to a conventional single-phase Lorentz-force actuator of similar size since only half the amount of energy is needed to generate a similar force.

The linear characteristic and high repeatable motion of a FELA is governed by the frictionless nature of flexure-based bearings. Unlike other frictionless bearings such as the air bearing, the magnetic bearing, and the hydrostatic/hydrodynamic bearing, these flexure-based bearings do not require any air/electrical/fluid source, sensors, or complex control algorithm to function.

High energy efficiency with simple construction as well as maintenance-free and low cost bearings make FELA a cost-effective solution to precision engineering industries.

Flexibility of reconfiguration

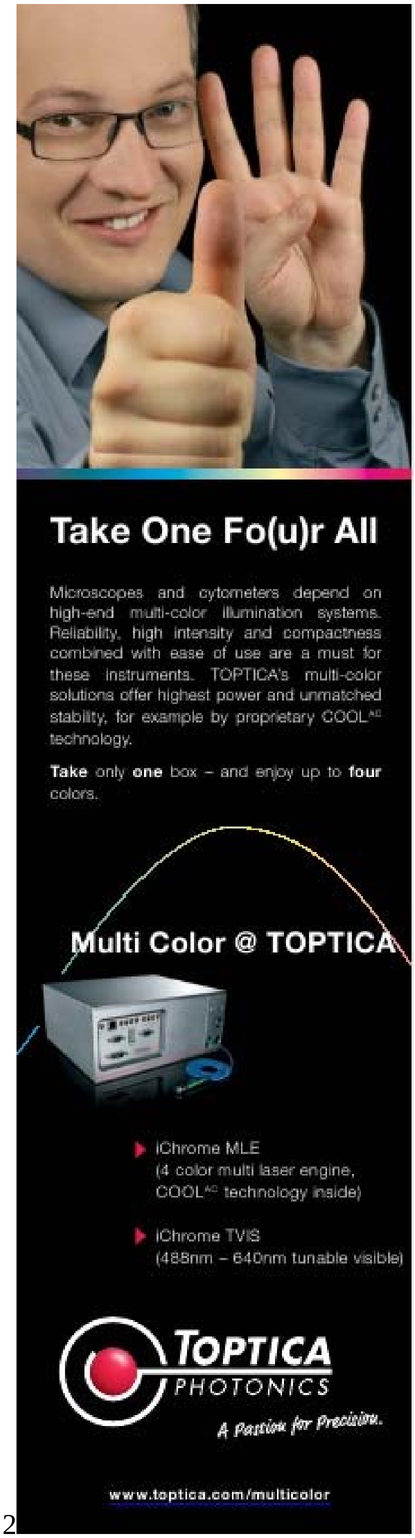
Because Lorentz-force actuation has a linear current-force characteristic while the flexure-based bearings offer a linear force-displacement characteristic, FELA is designed with the flexibility to re-configure its open-loop positioning resolution (i.e. minimum controllable input current versus output displacement).

Reconfiguration can be realized either by increasing the force-displacement characteristic of the bearings or by reducing the current-force characteristic of the Lorentz-force actuation.

Because it can be used across a number of industries, for instance in the electronics, semiconductor, and biomedical sectors, flexibility of reconfiguration becomes a key advantage, surpassing existing nano-positioning actuators by displaying advantages such as predictable performance, non-hysteresis and linear characteristics.

In summary, FELA delivers superior performance on a single platform, crucial for next-generation high-precision systems such as nano-imprint lithography systems, micro-/nano-scale positioning systems, micro/nano-metrology systems, micro/nano-machining systems, micro/nano-manipulation systems, and bio-medical instruments.

Developed by SIMTech and commercialized by Exploit Technologies, the tech transfer arm of A*STAR, FELA is now available for customization and licensing. For more information, please contact Jason Sim at tech-offer@exploit-tech.com.

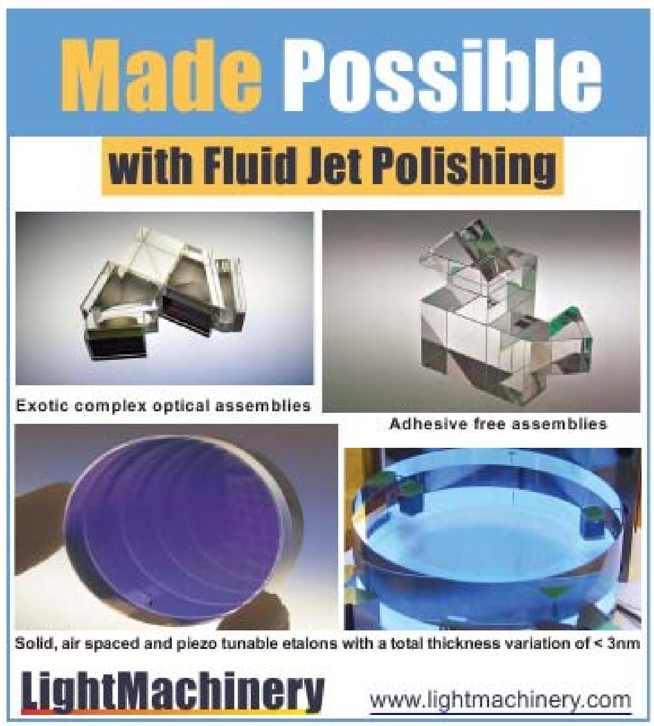


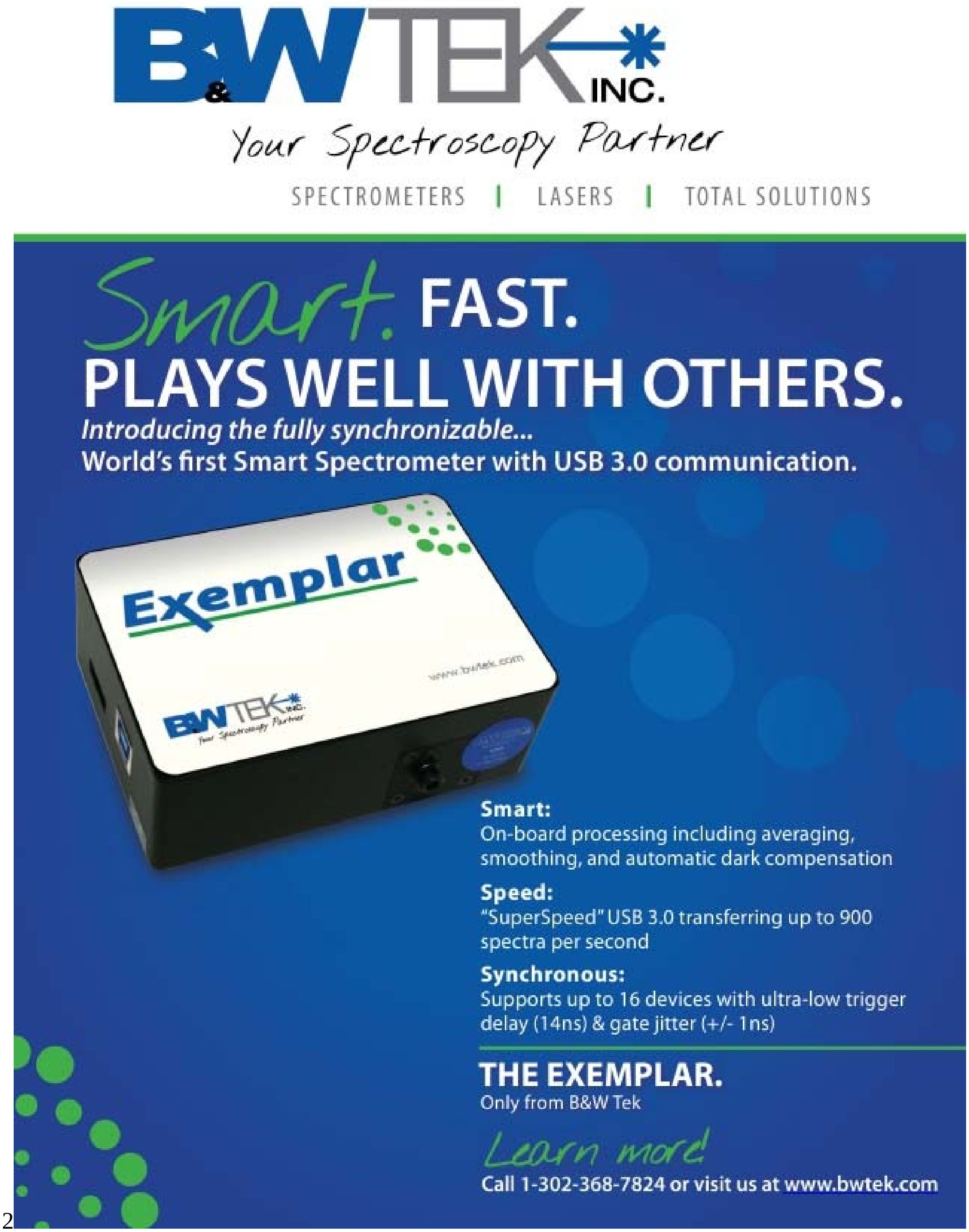
newsbreaks

Time-reversal of light could improve focusing and imaging in scattering media

University of Twente (Enschede, the Netherlands), FOM Institute of Atomic and Molecular Physics (Amsterdam, the Netherlands), and Langevin Institute at École Supérieure de Physique et de Chimie de la Ville de Paris (Paris, France) researchers are developing new techniques to improve imaging and focusing in scattering media. A wave (sound or light) emanating from a point source in a scattering medium will spread and develop a speckle pattern due to interference of different scattering pathways. The time reverse—a speckled wave converging toward a point and becoming a single bright spot—is also possible due to reciprocity. In ultrasound such a wave can be created by electronically recording the outgoing wave and playing it backward, a method that is not possible in optics. However, for light it is possible to directly create a wave that converges to a focus by shaping the incident wavefront using spatial light modulators. In this case, feedback from a detector at the target point is used to shape the wavefront properly.

In the past few months, the researchers say that groups worldwide have demonstrated many of the extraordinary possibilities of wavefront-shaped light, including focusing and imaging in and through turbid media, pulse compression, and spectral selection. Remarkably, both in ultrasound and light the focus obtained through a scattering medium can in some situations be much smaller than a focus made without scattering, an effect that is being exploited for microscopy. *Contact Allard P. Mosk at* a.p.mosk@utwente.nl.

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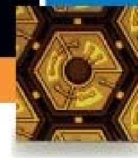
world news

PV retinal prosthesis
See page 18



Technical advances from around the globe

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INTEGRATED PHOTONICS

Integrated F-P laser array solves 100G problems

A primary challenge in the 100 Gbit/s or 100G optical interconnect space is the design and manufacture of high-speed, low-cost lasers that can support the several-kilometer distances of a large data center. Although widely used at 1 and 10 Gbit/s, vertical-cavity surface-emitting lasers (VCSELs) are not an option for 100G systems since their distance is limited to 100 m on OM3 fiber (multimode, 50 μm core/125 μm cladding)—much too short to span a large data center.

"The IEEE 802.3 specification for 10 km reach, 100GBase LR (100 Gbit/s, baseband modulation, long reach) would span almost any data center and more; but this specification requires four directly modulated distributed feedback (DFB) or electro-absorption (EA) lasers with wave-division multiplexing (WDM) to combine all four channels onto a single fiber," says Arlon Martin, VP of marketing at Kotura (Monterey Park, CA). "The problems with this approach are cost, power, and size. Due to complexity, these transceivers cost one hundred times 10G transceivers of similar reach."

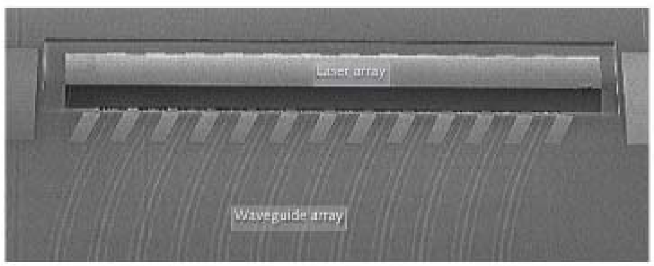
Martin says that customers expecting next-generation transceivers to transmit more bits at a lower cost are disappointed, and cost is not the only concern: Power consumption is also way too high—20–24 W compared to 1–2 W for 10G. Finally, the 100G C form-factor pluggable (CFP) package is so large (larger than an iPhone) that only four of them fit across the face plate of a 19 in. switch, making density worse than using 10G transceivers.

Martin says 100G transceivers are expensive because of the stringent requirement for the lasers, which are specified to an 800 GHz grid (corresponding to roughly 4.5 nm spacings) in the 1310 nm region, meaning the laser wavelengths must center exactly at 1295.56, 1300.05, 1304.58, and 1309.14 nm. In addition, to allow for multiplexing and system interoperability, only 2.1 nm of the 4.5 nm window can be used by the laser. Not only does the laser manufacturer have to develop high-performance 25 GHz lasers to match this unusual grid, they also have to throw away the distribution of perfectly good lasers that don't match the grid.

A better way

Fabry-Perot (F-P) lasers—one of the easiest to manufacture—have a broad lasing spectrum without the complicated, DFB-style grating and not requiring the EA stage of a multisection EA laser. These lasers are so small that 10,000 or more fit on a single indium phosphide (InP) wafer at high yield. However, F-P lasers usually cannot be used for high-speed data-center applications because their modulation speed is far too slow and their lasing modes cannot meet the requirements of a WDM system.

But Kotura has developed a new approach that converts a low-cost, F-P style laser to a high-speed WDM laser for data-center applications. A laser array is flip-chip bonded onto a silicon photonics chip using an automated pick-and-place machine and passive alignment (the lasers are not powered on). Using physical features and alignment marks, the entire array is soldered into place, precisely aligning each laser with its corresponding waveguide on the silicon photonics chip (see figure).



An array of 12 lasers on a single bar are flip-chip-bonded onto a silicon photonics chip and lined up against waveguides.

Conversion of the broadband laser spectrum to the precise WDM wavelength requires a grating on each of the waveguides of the silicon chip. The gratings are imprinted simultaneously using a photolithographic mask so that each laser has its own exact grating defined by the silicon process, not by the InP process. This means that every laser can be used to generate the required wavelength and almost any wavelength plan can be accommodated. If more channels are required, then a larger array is used and additional waveguides and gratings are added to the silicon chip, allowing expansion from 4 WDM channels to 12 or even 40 channels on a single chip.

Because Kotura uses a 3-µm-diameter waveguide that roughly matches the beam profile of the laser and special waveguide facets and coatings on the array, the need for collimators, lenses, and double-stage isolators is eliminated, lowering costs and simplifying assembly. And to accomplish the increased modulation speed of 25 GHz or more, the laser is operated in CW mode and modulators are integrated into the silicon chip—fast enough for 100G with four encoded data streams at 25 Gbit/s each.

The Kotura WDM 100G engine fits inside a compact quad small-form-factor pluggable (QSFP) package, increasing front-panel density by more than a factor of 10 to more than 4.4 Tbit/s, all while consuming far less power than many CFP solutions at data-center reach lengths of 2 km and more. —*Gail Overton*

ARTIFICIAL RETINAS

PV retinal prosthesis has high pixel density

Even though age-related macular degeneration and retinitis pigmentosa cause loss of ocular photoreceptors, most of the inner retinal neurons typically survive for a long time. In addition to optogenetic-based therapies, methods to restore sight to the visually impaired typically involve external cameras and implanted wired electrode arrays to stimulate these neurons; however, the required components are bulky, pixel density is low, and the delivered image cannot be scanned naturally by the eye.

Pixel density is much improved in devices that use photosensitive pixels such as those from Retina Implant AG (Reutlingen, Germany); but again, external power delivery makes the device very bulky and greatly complicates implantation and maintenance.

In response to these drawbacks, researchers at Stanford University (Stanford, CA) and the University of California, Santa Cruz have developed wireless, photovoltaically driven, subretinal arrays of photodiodes to stimulate the inner retinal neurons that transmit signals to retinal ganglion cells when illuminated with pulsed near-infrared (NIR) light.[1] The scheme eliminates the need for complex electronics and wiring and preserves the natural link between image perception and eye movement.

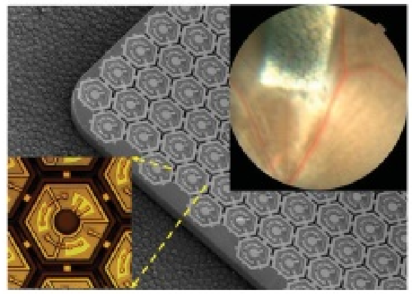
NIR goggle projection

The retinal prosthesis basically consists of a miniature video camera to capture images that are processed by an external computer and projected into the eye via a near-to-eye goggle projection system using pulsed NIR (880–915 nm) illumination. The image is focused on the retina, and the subretinal photodiode array, like any photovoltaic device, converts the light into pulsed photo-

2

current for neural stimulation at each pixel location (see figure).

Because ambient light is much too dim (by at least a factor of 1000) to photovoltaically stimulate neurons, the NIR laser image projection system produces more intense pulsed illumination that drives the photodiode array. The light-induced temperature rise is kept within the physiological range of ocular safety regulations (less than 1°C) by limiting the average irradiance to 5.2 mW/mm^2 at the 905 nm wavelength used in this part of the study.



The photovoltaic retinal prosthesis array is shown implanted under the retina in a rat eye. Higher magnification views show the array itself and a single pixel of the implant. (*Courtesy of Stanford University*)

High-pixel-density arrays

Each 70 μm pixel contains a photodiode connected to a 20-μm-diameter iridium oxide electrode. Each pixel converts the received light into a charge-balanced stimulation pulse. Corresponding pixel density is about 180 pixel/mm^2.

In order to limit the amount of cross-talk between pixels caused by the common return electrode in current array designs, one solution is local return electrodes for each pixel. Three diodes per pixel are connected in series to achieve a higher current density. The triple-diode pixels produce up to 1.5 V at physiologically safe light intensities and require 3X illumination levels for the same current output compared to single-diode pixels.

Laboratory testing using both healthy and degenerate rat retinas implanted with both single- and triple-diode arrays confirmed successful stimulation of the inner retina, with retinal response influenced by the illumination levels and pulse durations. Stimulation threshold (peak irradiance) with 4 ms pulses was 0.3 mW/mm^2—more than two orders of magnitude below the ocular safety limit.

The thin (30 μm) and wireless retinal implant drastically simplifies the complexity of subretinal surgery. Multiple modules can be implanted side-by-side to cover a larger field of view. Furthermore, the array is amenable to fabrication on a flexible silicon substrate for easier conformity to eye curvature. —*Gail Overton*

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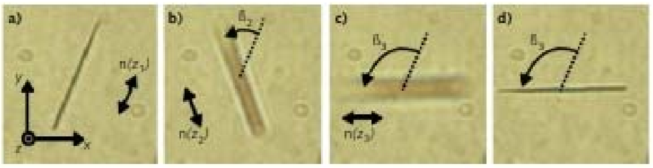
OPTICAL TWEEZERS

LC allows optical trapping of high-index nanowires

Optical trapping, which allows trapping and manipulation of microscopic particles using light alone ("optical tweezing"), has been a boon to biologists, who can trap and sort cells, and materials scientists, who can, in just one example, move microspherical lenses for direct-write nanopatterning. But the required optical gradient forces typically are of the right magnitude only when the refractive indices of the particles to be manipulated are only modestly higher than the refractive index of the surrounding medium.

A team of scientists from the University of Colorado, the National Renewable Energy Laboratory, and the National Institute of Standards and Technology (all in Boulder, CO) and the University of Gothenburg (Göteburg, Sweden) is pursuing an approach that allows optical manipulation of microparticles with a much higher refractive index, such as gallium nitride (GaN) nanowires, which have a very high along the LC direction (which minimizes elastic energy), with a small tilt due to influence from the surface-rubbed LC alignment layer. Focusing a low-power (less than 25 mW) laser beam near a nanowire attracts the wire to the beam; then, once the wire is trapped, it pushes



A nanowire is pushed by an optical trap along the *z*-axis (perpendicular to the plane of these images), also causing the nanowire to rotate (a through c). The trap light is then blocked, the microscope refocused, and the trap light unblocked (d). *(Courtesy of the University of Colorado)*

refractive index of about 2.4 for light at 587 nm.[1] To achieve this, the surrounding medium is liquid crystalline (LC); the interaction of laser light with the liquid crystal (which has a relatively low index of about 1.5) leads to a number of effects that can be exploited for manipulation.

The experimental setup includes holographic optical tweezers and a fluorescence confocal polarizing microscope (FCPM). To form the optical tweezers, a 512 × 512 spatial light modulator (SLM) is imaged onto the back-aperture of the microscope objective. Two objectives were used, 60X and 100X, both with a numerical aperture of 1.42.

The GaN nanowires were fabricated using molecular-beam epitaxy, which creates wires with a typical length of about 10 μm and a hexagonal cross-section with a width of about 300 nm. Experimental LC hosts included nematic and cholesteric LCs doped with a very small amount of fluorescent dye to allow FCPM imaging without altering the properties of the LC. Optical manipulation was done at a 1064 nm wavelength, while imaging relied on excitation at 488 nm and detection in the 505–525 nm wavelength range.

Nematic LC host

Left by themselves, nanowires in a nematic LC host tend to align themselves the wire along the beam.

Placing the optical trap at one end of a nanowire places a torque on the wire due to scattering, which rotates the wire out of plane until the torque is balanced by the LC's elastic torque; removing the torque causes the wire to rotate back to its initial position.

Higher optical powers (around 35 mW or more) cause the local direction of the LC itself to change, which changes the elastic forces on the nanowire. The result is a repelling force as the wire moves to minimize elastic free energy. As a result, a nanowire that stays parallel to the LC direction can be translated in a perpendicular direction using a single trap; with two traps, one stationary and one moving, the wire can be rotated (at least until the added elastic energy becomes large enough to overcome the torque).

Cholesteric LC host

In a cell with two surfaces having parallel-rubbed alignment, a cholesteric LC falls into a helical form that produces a coupling between a nanowire's position along the *z*-axis and its in-plane rotation angle. As a result, as an optical trap at the center of a nanowire pushes it, the wire also rotates as it passes along the helical structure (see figure).

Conversely, two traps positioned at the nanowire's ends that cause the wire to rotate also force the wire to move, screwlike, along the *z*-axis. The nanowire remains parallel in the *x-y* plane as it rotates, even if a trap is positioned at the end of the wire; this is due to elastic forces preventing the wire from tipping toward the *z*-axis. Such manipulations actually allow the researchers to determine the local "pitch," or amount of helicity, in the cholesteric LC.

These types of nanowire manipulations also enable probing discontinuous cholesteric LC samples, with wire motions helping to locate discontinuities and characterize the twists and turns within complex defects. —*John Wallace*

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ASTRONOMY

Multicore fiber becomes 'photonic lantern' filter

When fiber Bragg gratings (FBGs) are written into all 120 cores of a multicore optical fiber, great things can happen, as researchers from the University of Bath (Bath, England), Universidad de Valencia (Burjasot, Spain), and the Waterford Institute of Technology (Waterford, Ireland) know. Specifically, such an arrangement can become a "photonic lantern" filter that serves as an ultranarrowband line blocker for astronomy.[1]

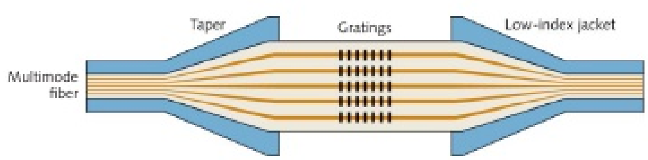
Photonic lanterns couple the functions of single-spatial-mode optical devices (in this case, FBGs) to multimode fiber inputs and outputs. To do this, they combine many singlemode fibers together (or in some cases, rely on integrated photonics). Photonic lanterns based on the combination of many singlemode fibers with FBGs have been constructed with as many as 61 identical FBGs, with at least one already under test with a telescope.[2]

But these existing photonic lanterns consist of many identical devices fabricated separately and then placed in parallel, spliced to singlemode fiber pigtails. The new device avoids all this trouble, being made instead as a single large fiber with many singlemode cores, all with individual FBGs that are written in one process. The two ends of the large fiber are then tapered to match the input and output multimode-fiber ports (see figure).

Mode-number matched

For low loss, the fiber device must contain at least as many singlemode cores as there are modes in the input multimode fiber (note: the singlemode cores are nonpolarizing, so each actually supports two polarizations). For low loss at the outgoing end, the output fiber must support at least as many modes as there are singlemode cores in the fiber device. As a result, for input and output fibers with identical diameters (thus supporting identical numbers of modes), there is a certain number of single-mode cores that minimize mismatch losses: This is called a mode-number-matched design.

The experimental design, which operates in the 1550 nm spectral region, con-



A photonic-lantern notch filter intended for astronomy contains 120 germanium-doped singlemode fiber cores in a silica fiber. Fiber Bragg gratings are written into the cores in a single process.

tains 120 germanium-doped, 3.9-μm-diameter cores with a 0.22 numerical aperture and a hexagonal grid spacing of 16.9 μm, all encased in a 230-μm-diameter silica fiber.

Single-spectral-notch FBGs were created in a single operation using a 244-nm-wavelength, 100 mW laser beam passed through a phase mask with a 1067 nm period to perpendicularly illuminate the multicore fiber, which had been hydrogen-loaded for two weeks beforehand under a 20 bar pressure.

The resulting single spectral-loss notch was at about 1549.1 nm. Because the line-center wavelength for each single-mode fiber core depends on the core's diameter, the diameter tolerance of the cores was kept at 1.3%, which results in a wavelength spread of 160 pm or less.

The researchers fabricated numerous multicore-fiber samples and tested the FBG notch depth and notch wavelength for every core in every sample, with two of them having a wavelength-spread standard deviation of 100 and 67 pm, respectively. Samples with stronger gratings had more wavelength spread, showing that the spread was due more to imperfect FBG fabrication than to differences in core diameters.

Because the fabrication process tended to result in some singlemode cores not having FBGs, a new multicore fiber was made with a larger uniform silica outer cladding, which ensured that the UV light used to write the FBGs did indeed reach every single-mode core, although some cores were shadowed by other cores, thus reducing the quality of some FBGs.

Finally, the multicore fiber was tapered at both ends to transition to the input and output multimode fibers. At a small enough taper, the light leaves the single-mode cores and bounces around in the cladding; thus, a lower-refractive-index additional outer cladding was added to the tapers to keep the light confined.

After mounting, a spectral scan was taken across the region of interest, showing a spectral notch with a depth of about 7 dB. The relatively small size of the dip was chalked up to the fact that not all FBGs were of good quality in these first experimental prototypes. The coupling loss between the test device and the corresponding input and output multimode fibers was tested and found to be less than 0.5 dB.

In an interesting side note, the researchers found that a similar device, but with no FBGs, can serve as an effective mode scrambler, being far more effective than an equivalent length of simple multimode fiber. —*John Wallace*

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BIOMEDICAL IMAGING

Random laser produces speckle-free images

Random lasers may have a future in imaging. A team at Yale University (New Haven, CT) who last year made random lasers with low spatial coherence has now used those low-coherence lasers for speckle-free imaging. The demonstration could open the door to new laser applications in biological imaging, picoprojectors, and cinema projectors.

A byproduct of coherence, laser speckle is a shifting pattern of bright and dark zones produced when a laser beam passes through a scattering medium. It's tolerable in many laser applications, but speckle degrades images recorded in laser light or displayed by laser projectors.

"Speckle is a random grainy pattern, which is really bad for human perception because you tend to focus on it," says Yale physicist Hui Cao. Speckle is a particular problem for medical imaging, because it hides details that doctors need to see. Even superluminescent sources generate speckle, so most imaging systems use incoherent lamps or LEDs despite their lower brightnesses.

The first to demonstrate random lasing in a disordered material, Cao has worked on random lasers for more than a dozen years. What is unusual about random lasers is that they lack cavity mirrors, and rely on light scattering from particles distributed through the laser medium to sustain oscillation. They have been demonstrated in a variety of materials, including laser dyes and semiconductors, but until last year they always produced coherent output.

Speckle and OCT

Cao began exploring ways to reduce coherence after talking with Michael Choma, an imaging specialist at Yale's medical school, about the problems speckle noise caused in his work on optical coherence tomography (OCT). "That led us to wonder if a random laser could be used," Cao says.

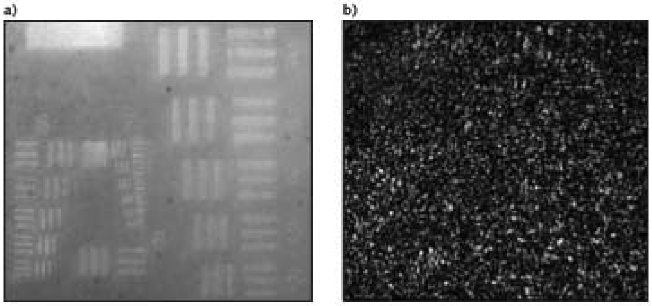
With postdoctoral researcher Brandon Redding, Cao and Choma explored ways to reduce coherence of random lasers. Working with 240-nm-diameter polystyrene spheres dispersed in a laser-dye solution, they explored effects of varying the density of the light-scattering

A byproduct of coherence, laser speckle is a shifting pattern of bright and dark zones produced when a laser beam passes through a scattering medium.

spheres and the size and shape of the laser medium pumped with 532 nm pulses. They found that increasing the pump area and decreasing the distance between scatterers increased the number of laser modes, reducing spatial coherence. The study, published last year, also showed how to design random lasers to reduce their coherence.[1]

After demonstrating incoherent imaging with the random laser, Cao says they want to show they can remove coherent artifacts from a coherent imaging process, OCT, Choma's original goal. She also wants to develop more practical low-coherence random lasers, such as a semiconductor with quantum dots and random air holes, or a

a) b)



An Air Force resolution chart is imaged through a scattering film (placed on the detection side of the target) using a random laser as a source (a) and a conventional laser as a source (b). *(Courtesy of Yale University)*

Now they report achieving speckle-free imaging by tuning their random laser to emit with low spatial coherence.[2] A series of experiments compared images of objects illuminated by their low-coherence random laser to images recorded with illumination by LEDs, amplified spontaneous emission, a broadband laser, and a narrowband laser. In all cases reported, sharpness of the random laser image was second only to that of the LED image, and markedly better than those recorded with amplified spontaneous emission or other laser sources.

The results are good news for biomedical imaging because brighter laser sources open new options, such as imaging objects that are moving or changing. "Your light source really defines the boundaries of what you can do—how fast you can image," says Choma. "And you always want to go faster." Speckle-free lasers also are attractive for laser projection. Laser movie projectors now require moving optical elements to average out speckle; random lasers could avoid that complexity.

photonic-crystal fiber. And she is thinking about ways to adjust random lasers so they are coherent enough to make a hologram, but not so coherent that they produce speckle.

Chris Dainty of the National University of Ireland (Galway, Ireland) calls the demonstration "an impressive achievement," but cautions that reducing laser coherence comes at the cost of increasing beam divergence and reducing brightness. Joseph Goodman of Stanford University (Stanford, CA) agrees the speckle-free laser is newsworthy, but adds that it will have to compete with other speckle-reduction techniques such as moving diffusers. Goodman has just described how a stationary multimode fiber could reduce speckle in large laser projectors.[3]

—*Jeff Hecht*

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Patents, projects, and prototypes pose problems

MILTON CHANG

Q *A big competitor has filed a frivolous patent infringement lawsuit against us. Should I file a petition for summary judgment to dismiss the case, or file a countersuit for unfair business practices?*

A It is very hard to sue someone for filing litigation; you have to prove malicious prosecution and to do that you first have to win the suit. And it is extremely unlikely you'll get a summary judgment without significant work because, in layman's terms, that's like saying you have an argument to end all arguments. Not everyone will agree with your opinion when different points of view are involved. Even though the likely outcome is a settlement before it goes to trial, be prepared to spend quality management time to deal with this thorny issue for the next 12–18 months.

Q *My group completed a small research project for a startup company a few months back. Now the company wants me to spend time talking to investors to help them raise capital. How could I get compensated without being taken advantage of?*

A The real issue is that you feel you were not adequately compensated for the research project. But what is in front of you is an unrelated issue. The contract is history and frankly you went in with your eyes wide open. A professor asking for compensation for sharing knowledge or opinion would be considered bad form because that is expected to be *pro bono*. Consider talking to the investors as a favor to this company; hopefully the goodwill might return some financial benefits to you at a later time. It is customary for professors to get stock options in addition to monetary compensation when they engage in a long-term advisory role, and you can also do consulting work or take on another research project, which you can price appropriately.

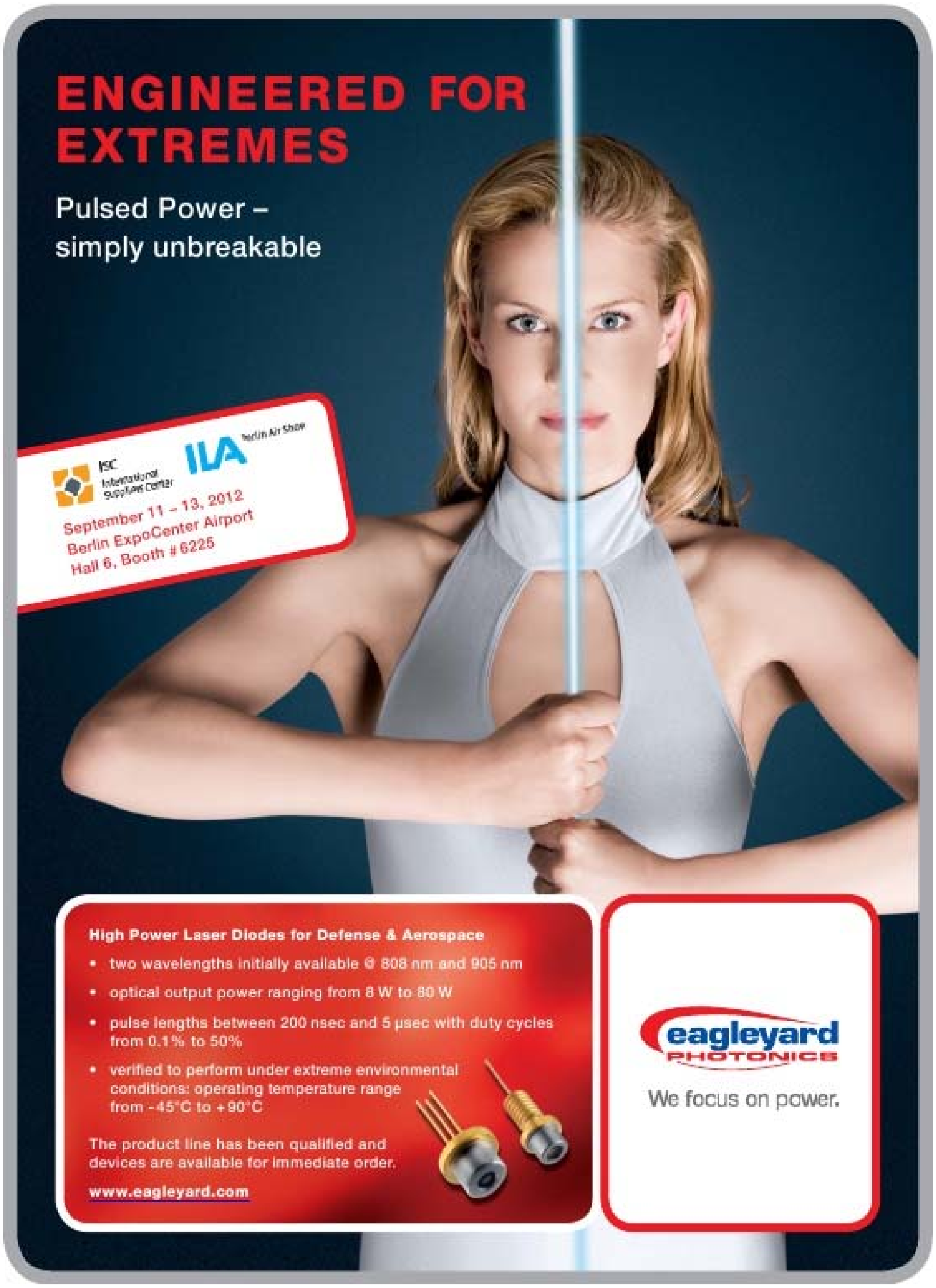
Q *We have spent close to $5 million to develop a working prototype of an unconventional solar energy system. The current investor will fund if and only if we can raise half of the capital we need from other sources. We will be running out of funds in four months and so far no takers. Any suggestions?*

A Based on the performance and cost goals you provided, this could be a breakthrough product to serve a number of niche markets. I am not sure how you can get through the "valley of death" given the unfavorable funding environment. You got your initial funding five years ago, when investors were hot on energy generation. Today, even existing solar companies with substantial revenue are not faring well on Wall Street because the price of solar panels has plummeted. Investors now are putting money in web and mobile application startups.

I believe the lack of validation is a major concern. Investors are defensive; they tend to not believe everything you say. And when in doubt, they don't invest. It would provide great comfort to investors if you had a major development contract from a government agency, a leading investor in the energy field who is a strong advocate, a few orders from knowledgeable customers, or strong recommendations from opinion leaders in the energy space. You have none of that aside from half-hearted support from your current investor.

Given your time constraint, my recommendation is for you to engage at least one energy industry insider who is an opinion leader to provide credibility. You have to act fast. Given the short runway, your opportunity is diminishing rapidly with passing time. You may want to also make an incredibly good offer to an interested investor to get money that will buy time. One other option you might want to plan for is an orderly liquidation. Assuming your technology is viable, trading what you have developed for some upside in an established energy company may yield some benefit for you and your investors. ◄

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.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Computer modeling optimizes thin-film coating uniformity

WILLIAM H. SOUTHWELL AND JOSEPH E. PEEPLES

Coating uniformity is vital for high yields in thin-film coating fabrication processes, especially as coating requirements become tighter and as production volumes increase to reduce costs and remain competitive. A new software utility tool has been developed that models and predicts coating uniformity for various sources and planetary motions. When chamber configuration geometry design is insufficient for adequate uniformity, masks may be designed and optimized to improve coating uniformity as a function of source position, planetary gear ratios, and other chamber parameters.

Thin-film coating basics

The fabrication of multilayer optical interference coatings is a particularly difficult task. All of the layers must have uniform thickness over a single part and over all the parts being deposited in a single coating deposition step, especially to obtain the desired spectral response of a thin-film filter, for example.[1] Most deposition sources will deposit on surfaces with a direct line-of-sight view of the substrate being coated. The increment of deposition thickness in an incremental time element depends on the length of the line-of-sight ray and the angle this ray makes with the source normal and substrate normal.

Thin-film coating chambers come in various sizes and shapes, but many are characterized by boxes with evaporative sources near the floor and planetary mounts rotating above them, bringing the substrates in and out of the depositing plume. Rotating the parts greatly improves the thickness uniformity across all filters attached to the planetary.[2] Just how uniform the various parts on the planetary become is a function of the chamber geometry and the planetary motion (see Fig. 1).

Achieving good coating uniformity is typically a lengthy iterative process. Quantitatively determining uniformity involves populating the planetary with small samples, performing a single-layer deposition with enough thickness to have some ripples in the transmittance or reflectance spectra, and then spectrally measuring each part. The shift in the wavelength positions

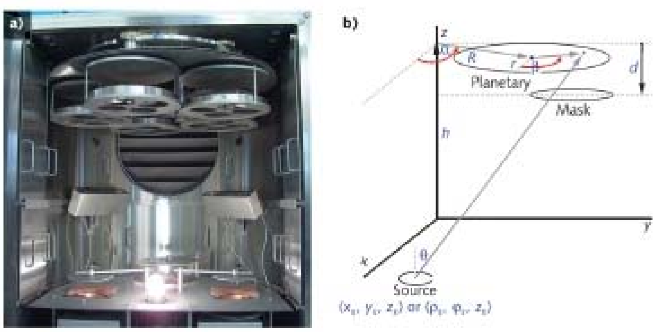


FIGURE 1. An optical coating chamber (a) includes one or more plasma sources (here, two copper-colored structures in lower part of the chamber) with one or more planetaries (five are shown near the top of the chamber) for holding the coating substrates. The masks—often proprietary—are not shown, but would typically be placed up high just below the planetaries. (*Courtesy of Denton Vacuum*) The chamber geometry (b) is based on a coordinate system with origin in the center of the chamber floor. (*Courtesy of Table Mountain Optics*)

of the ripple peaks or valleys is a measure of the coating uniformity.

With rapidly rotating planetary motion, the uniformity is fortunately radial regardless of the source distribution. Uniformity is usually normalized to the center of the planetary; that is, thickness across the planetary divided by the thickness at the center forms the uniformity curve. With the uniformity known, a mask is configured (usually by experience and trial and error), installed, and the uniformity measurement is repeated.

A common mask shape looks like a leaf and is fixed in place under the moving planetary. The purpose of the mask is to block some of the deposition in regions where the coating is too thick; however, the mask cannot add thickness, it can only reduce deposition. Since generally all points on the planetary will pass over the mask, the trick is to find the mask shape that will retard the deposition in the high spots to improve uniformity. Furthermore, since the mask reduces deposition, the deposition will take longer. Thus, mask efficiency as measured by how much less is being deposited as compared to the case without a mask is an important parameter in mask design.

In the next step for improved uniformity, the mask is trimmed. This step is difficult because the mask is only decreased in size and it is hard to know where and how much to trim to change the material distribution in a certain region. In addition, this mask-trimming process typically results in residual nonuniformity because the convergence of this technique depends too much on the shape of the starting mask and its position in the chamber. Source position is also a factor for convergence.

A software tool from Table Mountain Optics called *UniformityPro* enables the calculation of coating uniformity for given chamber configurations, including the presence of one or more masks. The software also allows for optimizing the shape and position of the mask to improve uniformity. In addition, it can improve uniformity while maintaining good efficiency.

Plume distribution

Of foremost importance in this new software modeling process is knowledge of the plume distribution. The most widely used model is the cosine to the *m*th power, or $\cos^m\theta$. The value $m = 0$ has no angular dependence and hence the evaporant behaves as a point source. More commonly, $m = 1$ represents an extended source emulating from a small region. Higher values of m show a more peaked distribution, and noninteger values of m are also used.

When the plume distribution is not known, then it should be measured in order for the modeling to have validity. It is this

measurement that anchors the code to reality. The plume distribution may be measured by positioning several small parts on a nonrotating and stationary planetary above the source. Then, deposit a single layer on known substrates and measure the layer thickness of each part, which has been identified by its *x*, *y*, *z* position relative to the source. Then fit the value of *m* to best fit the measurements, properly accounting for the source and substrate normal angles and radial (*R* squared) effects in the calculation.

The *UniformityPro* software has a menu option that opens a data grid allowing these measurements to be entered manually or pasted from a spreadsheet. The height of the planetary and the *x*, *y* positions and the corresponding thicknesses are entered. When the *Fit m* button is clicked, the best fit value of *m* is displayed.

Modeling parameters

The inputs to the *UniformityPro* software code are the geometric chamber parameters: *h* is the height of the planetary plane above the chamber floor; *x*, *y*, and *z* is the position of the source relative to the center of the chamber floor (optionally the source position may be entered as ρ and φ polar coordinates); *R* is the radial position of the center of the planetary; *r* is the radius of the planetary; and *g* is the gear ratio of the planetary (optionally, this may be entered as the *number of sun gear cogs* divided by the *number of planetary cogs*). For convenience, the chamber units are in inches.

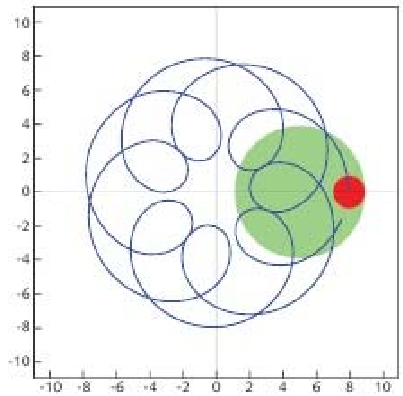
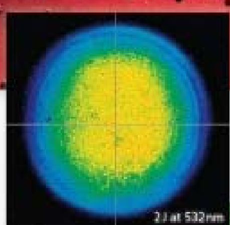


FIGURE 2. The trajectory of a point on a planetary as it makes two full rotations is shown in blue, while the red represents the position of the source and the green shows the size of the planetary in its starting position.

For plots of the trajectory of a point on the planetary, one inputs r_p, the radial position on the planetary to show in the trajectory plot, and N_p, the number of rotations of the center of the planetary. These numbers are also used in the computation of the uniformity.

Masks

Currently there are three shapes used for optimization masks: a leaf, conic,



Low Divergence Beam

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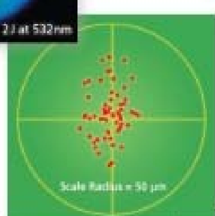

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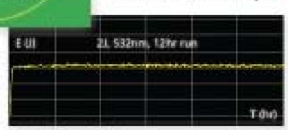

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and an arbitrary form constructed from a table of general coordinates. Any number of masks may be modeled.

The leaf mask looks like a leaf but is a symmetrical parabola. Its parameters include the radial position of the inner tip of the leaf (r_L), ψ_L the angular position of the inner tip of the leaf (in degrees), L or the length of the leaf mask, and the full width of the leaf mask W.

The conic mask is defined by a set of parameters as a parabola, circle, ellipse, or hyperbola in ray-tracing terminology. The parameters include the curvature c, which is 1 divided by the radius of curvature at the vertex, the conic coefficient k (k = -1 for a parabola; k = 0 for a circle; other values are ellipses and hyperbolas), and the coefficients A_4, A_6, A_8, and A_{10} for the r^4, r^6, r^8, and r^{10} general aspheric terms, respectively.

The arbitrary form of the mask is constructed from a table of parameters that define the x,y coordinates of points on the upper and lower edge of the mask. This allows arbitrary mask shapes to be entered.

Code features and optimization

The software allows any number of sources to be used. When more than one is used, then relative deposition rates need to be assigned to each one. Each source has its own position and plume distribution, and the code also accepts any number of masks, each with its own position and size parameters (see Fig. 2).

The software also has an optimizer that allows uniformity and mask efficiency to be improved by adjusting the parameters that affect it. For example, source position and planetary height may be adjusted to maximize uniformity for any given plume distribution m. The user may click on a check box to have the code also improve the efficiency while improving the uniformity. Without this feature, excellent uniformity may be achieved at the expense of a very large mask requiring much longer deposition times.

Example mask design

To demonstrate how *UniformityPro* can optimize coating uniformity, consider a coating chamber with the source x-position at 8 in., h = 12 in., R = 5 in., and with a planetary radius of 4 in. (8-in.-diameter). The computed uniformity of this configuration

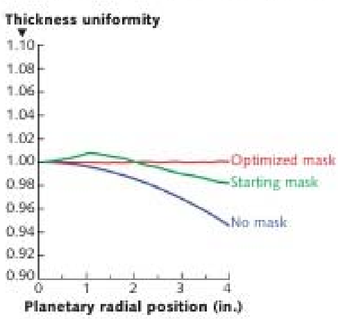

FIGURE 3. Using the *UniformityPro* software, the thin-film coating uniformity is 2.46% with no mask (blue), 0.81% with a starting mask (green), and 0.08% with the optimized mask (red).

is 2.46% (see Fig. 3). Next, a leaf mask is added with a 4 in. starting position, 5 in. length, and 2 in. width. The addition of this mask improves the uniformity to 0.81%. This mask shape was determined by manually adjusting the mask width, length, and noting the uniformity curve as these changes are made. The user can fairly easily obtain 1% uniformity in this fashion. We then let the optimizer software adjust the position, length, and width of the mask, which dramatically improved the uniformity to 0.08%.

Adding a mask reduces the deposition efficiency, which means it takes longer to deposit coating layers. In this example, the starting mask decreased the deposition efficiency to 92.4% from 100% for the no-mask case. Although the final optimized mask deposition efficiency is 84.8%, the user can—if they feel the value is too low—check the efficiency optimization box and the program will find a balance between efficiency and uniformity. The user can fine-tune the efficiency and uniformity by adjusting the user-controlled weight on the efficiency.

Furthermore, when the starting mask is compared to the optimized mask, it becomes obvious that trimming the mask would never have produced its final optimized form (see Fig. 4). In short, the *UniformityPro* software eliminates the long process of guessing at mask shapes and positions and iteratively trimming them after depositions; the optimized mask shape can even be printed out with real dimensions. The details of the selected mask can also be exported to a .SCR (AutoCAD) file.

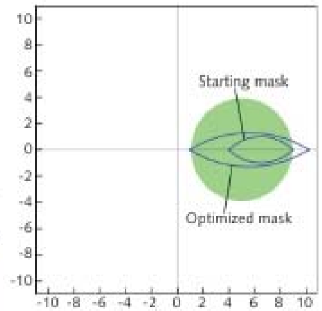

FIGURE 4. An optimized coating chamber mask is compared to the starting mask, illustrating how simple mask trimming is not always the best way to optimize coating uniformity.

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Planetary and deep-space applications push spectroscopy to the outer limits

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Deep-space and planetary instruments are challenged by extraordinary temperatures, vibration, radiation, space debris, and other performance-threatening conditions that require engineers to develop rugged optical and photonic components that push spectroscopy to extremes.

With NASA's Voyager 1 spacecraft now well outside our solar system at more than 11 billion miles from the sun, it is amazing that its onboard ultraviolet spectrometer (UVS) instrument is still functional. As if the minus 31°F temperatures for which it was designed weren't bad enough, NASA turned off the heaters on the part of Voyager 1 that houses the UVS to conserve energy and extend Voyager's life into 2025. Despite its current temperature below -110°F, the Voyager 1 spectrometer—which was very active during its Jupiter and Saturn encounters—continues to transmit data.

Clearly, deep-space and planetary spectral instruments such as the spectrometers that measure our Sun and even the ALICE spectrometer from Ocean Optics (Dunedin, FL) that confirmed the presence of water ice on the moon are challenged by extreme temperatures, vibration assaults, space debris, and a host of other performance-threatening conditions, requiring scientists to develop new techniques supported by novel optical and photonic components.

Since Voyager

More than 35 years have elapsed since the launch of Voyager 1. "The Voyager UVS experiment revolutionized our understanding of the outer solar system," says Roger Yelle, professor in the Department of Planetary Sciences in the Lunar and Planetary Laboratory at The University of Arizona (UA; Tucson, AZ). "But more than that, it

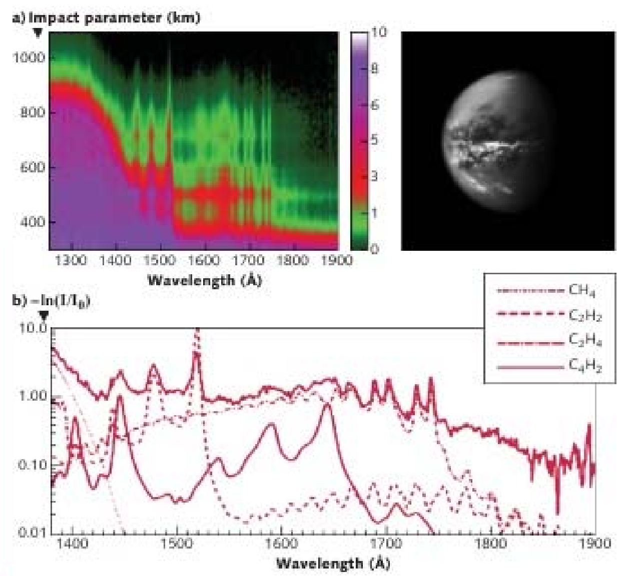

FIGURE 1. Optical depth contours from Titan (inset shows image of Titan; *Courtesy of NASA JPL*) show extinction layers (layers of higher optical depth) marked by enhanced absorption due to both aerosols and other species (a). The spectrum of optical depth (b; solid line) is averaged over the 700–750 km atmospheric range; other broken lines show contributions from different absorbers based on best-fit column densities. *(Courtesy of University of Arizona)*

showed the power of UV spectroscopy—especially UV occultations."

In cooperation with the Université Paris (Paris, France) and NASA's Jet Propulsion Laboratory (JPL) at the California Institute of Technology (Pasadena, CA), the University of Arizona is using data from stellar occultations observed by the Cassini/UVIS instrument to probe the mesosphere and thermosphere of Titan—the largest moon of Saturn—at altitudes between 400 and 1400 km.[1] Cassini/UVIS refers to the Ultraviolet Imaging Spectrograph (UVIS) built by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado (Boulder, CO) and launched into space aboard the Cassini-Huygens spacecraft by JPL in 1997.

Spectral information about Titan's atmosphere is obtained when a star is imaged above the limb of a planet. Comparison of the known spectra of the unocculted star and the spectra of the star transmitted through the atmosphere of the planet reveals the composition of the planet itself.

The Cassini/UVIS instrument consists of a telescope, a toroidal grating spectrograph, and a two-dimensional pulse counting microchannel plate detector with 1024×64 (spectral × spatial) "pixels," each with dimensions of 0.025×0.1 mm. The entrance pupil of the telescope is 20×20 mm and it is equipped with an off-axis parabolic mirror (22×33 mm) and has a focal length of 100 mm. All occultations were observed by the far-ultraviolet (112–191 nm) channel of UVIS using the low-resolution slit width of 0.15 mm, which has a field of view (FOV) of 1.5×60 mrad.

Spectroscopic data reveal that Titan's atmosphere is the site of complex photochemistry, forming hydrocarbon and nitrile species that play a crucial role in the formation of organic hazes observed in Titan's stratosphere (see Fig. 1). The density profiles for methane and other carbon-hydrogen compounds revealed by the spectroscopic data yield not only important information about the atmosphere of Titan as a whole but also provide broader atmospheric insight into how aerosols grow from small seed particles into large fractal aggregates.

Raman astrospectroscopy

Beyond UV spectroscopy, Stanley Michael Angel, professor and Fred M. Weissman Palmetto Chair in Chemical Ecology in the Department of Chemistry and Biochemistry at the University of South Carolina (Columbia, SC), and colleagues at the University of Hawaii (Honolulu, HI) and NASA Ames Research Center (Moffett Field, CA) are applying Raman spectroscopy to remote planetary applications.[2]

Just as in terrestrial handheld spectrometer measurements for explosives detection or any type of chemical/substance analysis, Raman spectroscopy can offer improved specificity for analysis of minerals and chemical compounds based on the vibrational frequencies, relative intensities, and number of bands in the spectrum of the sample. While visible,

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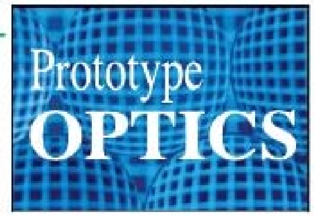

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near-infrared, thermal, reflection, and emission spectroscopy suffer from broad overlapping spectra, especially in the presence of mixtures, Raman spectroscopy reduces ambiguity and lends itself to standoff measurement at distances up to hundreds of meters.

In early 2012, Angel and his team received the William F. Meggers Award from the Society for Applied Spectroscopy (Frederick, MD) for their proof-of-concept development of a spatial heterodyne interferometer-based Raman spectrometer (SHS) for planetary Raman spectroscopy.[3]

Unlike dispersive (grating) approaches that require large spectrographs and very narrow slits to achieve high spectral resolution, the UV SHS has only a weak coupling of resolution and throughput, so it can be small and use a wide slit to maximize throughput. The SHS—with no moving parts for robust extraterrestrial performance—measures all optical path differences in its interferogram simultaneously with an ICCD detector array, making the technique compatible with gated detection using pulsed lasers, which reject ambient background and mitigate fluorescence that could be encountered on a planetary surface with uncontrolled samples.

The European Space Agency's ExoMars mission will include an orbiter (launching in 2016) with a lander (launching in 2018) that will be the first to feature a Raman spectrometer, coupled with a laser-induced breakdown spectroscopy (LIBS) system for mineral analysis. The system will operate in either a micro-mode to look at samples crushed into fine grains (20–100 µm in size) or in macro-mode, in which a probe attached to the lander's robotic arm is extended to measure larger areas using a larger source beam diameter (a few hundred microns).

In addition to mineral identification, Raman spectroscopy is also being considered for remote detection of biological analytes such as cyanobacteria, chlorophyll, or amino acids that could indicate the presence of life beyond Earth. While studies show that a Raman system would need a demanding 16 cm^{-1} resolution in the spectral range from 500 to 1700 cm^{-1} for unambiguous identification of these biomarkers, Angel and his colleagues have demonstrated that Raman spectroscopy can detect amino acids near femtomole levels using UV excitation (see Fig. 2).

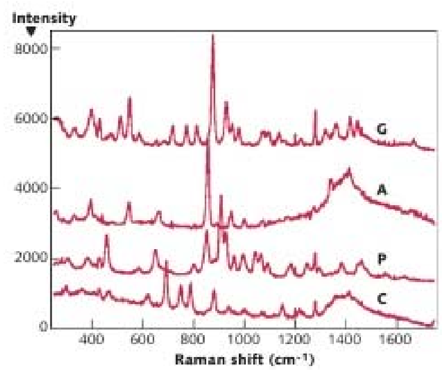


FIGURE 2. Raman spectra are shown for the amino acids glutamine (G), alanine (A), proline (P), and cysteine (C)—important biomarkers that could indicate the presence of life beyond Earth. (*Courtesy of University of South Carolina*)

Raman astrospectroscopy is also being considered for missions to Venus. Remote Raman measurements conducted at the University of Hawaii were able to identify minerals under high temperatures up to 1003 K at 9 m and under supercritical carbon-dioxide (CO_2) conditions—approximately 95 atmospheres and 423 K—such as those that exist on the surface of Venus. Minerals important to Venus such as anhydrous sulfates, carbonates, and silicates were detected under both dark and ambient light conditions, demonstrating the ability of the remote Raman system to analyze surface mineralogy and identify atmospheric constituents without landing on the harsh Venusian surface.

Withstanding harsh environments

In the hot environment of the planet Mercury, continuing flybys of the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission show that volcanoes were involved in the formation of vast plains and that surface chemistry and mineralogy is varied, based on reflectance and high-resolution imaging data. The mechanisms of planetary formation on Mercury will be better understood through detailed mid-IR spectral and temperature analysis data from the Mercury Radiometer and Thermal-infrared Imaging Spectrometer or MERTIS, part of the European Space Agency (ESA) Mercury Planetary Orbiter mission BepiColombo scheduled for launch in 2015 with planned arrival at Mercury by 2022.[4]

Housing a push-broom IR grating spectrometer (TIS; 7–14 μm) and microradiometer (TIR; 7–40 μm), MERTIS consists of a series of modules for the sensor head, electronic units, and power/calibration systems with a combined 3.4 kg mass and <13 W power consumption (see Fig. 3). All modules are thermally

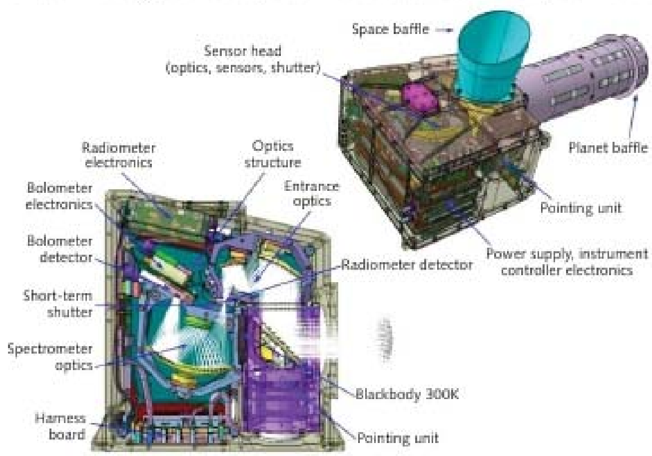


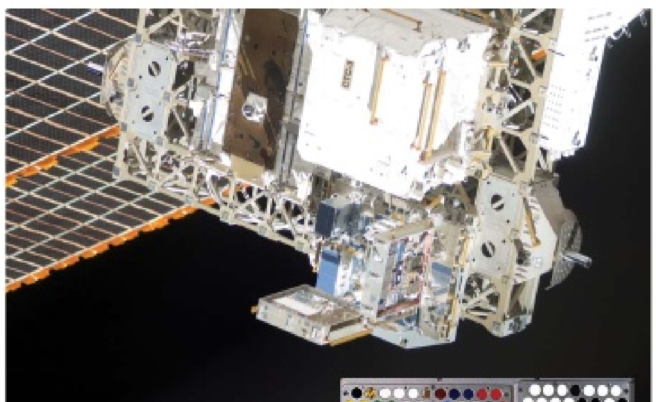
FIGURE 3. A structural and thermal model is shown for the Mercury Radiometer and Thermal-infrared Imaging Spectrometer (MERTIS). (*Courtesy of University of Münster and German Aerospace Center*)

separated for optimal performance, and the in-flight calibration routine uses sequential observation of four targets: a planet, deep space, and two onboard blackbody sources. A 45° tilted mirror between baffles and optics allows frequent views of the calibration targets (at 300 and 700 K) and both cold space and the planet Mercury, viewed through two separate baffles oriented perpendicular to each other, with a cylinder to shield the optics and electronics against incoming radiation.

Its 50 mm focal-length telescope (*f*/2) produces a 4° field of view, enabling the TIS spectrometer to map the entire planet with a spatial resolution of 500 m. The TIS imaging spectrometer uses an uncooled microbolometer array for detection and combines a three-mirror anastigmate (TMA) with a modified Offner grating spectrometer.

"Mid-IR spectroscopy provides many different modalities for studying and mapping the composition and texture of planetary surfaces; by gathering this information on planet Mercury it is hoped to learn more about its formation and sequence of development," says Gabriele E. Arnold, staff member at the German Aerospace Center (DLR; Berlin, Germany) and the University of Münster (Münster, Germany) with more than 30 years of experience in planetary science and space flight instrumentation. "MERTIS is a state-of-the-art instrument using a modular approach. The unique challenges of MERTIS' development required new optical, optomechanical, and front-to-end electronic solutions with minimum power consumption and mass, which had to be integrated into a novel technical-engineering concept," she adds.

In addition to facing extreme weather conditions on Mercury and Venus or the everyday in-flight or orbiting hazards of deep-space debris and particle bombardment, spectrometers are also



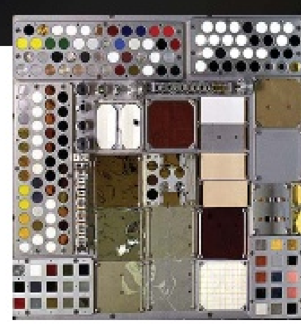
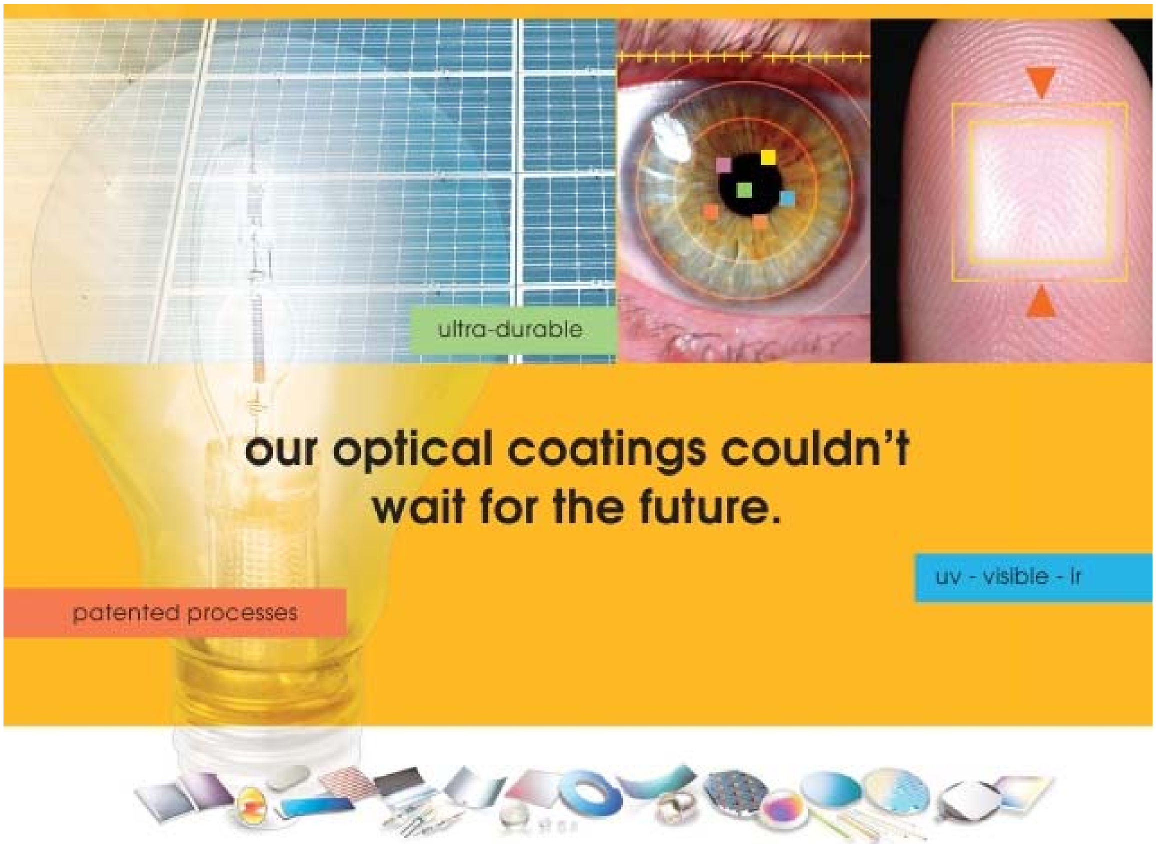


FIGURE 4. The MISSE 7 experiment on the International Space Station was photographed by a space-walking STS-129 astronaut. The experiments expose materials and composite optical and electronic samples (inset) to the external environment; the materials—including solar cells, optics with coatings, sensors, electronics, and structural and protective materials—are evaluated both *in situ* and after exposure using a variety of instruments such as BLUE-Wave spectrometers. (*Courtesy of NASA*)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playing a role in understanding what types of optical and electronic components and materials best endure the rigors of the space environment. As part of NASA's Materials International Space Station Experiment (MISSE), two miniature BLUE-Wave spectrometers from StellarNet (Tampa, FL) were launched in 2009 on the STS-129 shuttle mission as part of the MISSE 7 instrumentation that was mounted externally to the International Space Station (ISS) to evaluate more than 700 new optical and electronic materials. The rugged spectrometers tested the optical properties of the materials as a function of exposure to atomic oxygen, UV radiation, direct sunlight, space vacuum, debris impact, and temperature extremes (see Fig. 4).

Until MISSE 5, only passive material experiments limited analysis to the period before and/or after deployment; but

> The BLUE-Wave spectral reflectivity data for the MISSE 7 revealed a better understanding of the durability of next-generation materials when exposed to space with the mission of designing future spacecraft to travel far beyond Earth's orbit.

for the first time, MISSE 7 transmitted digital data from the experiments through the ISS down to several ground stations for real-time processing.

The *in situ* BLUE-Wave spectral reflectivity data for the MISSE 7 revealed a better understanding of the durability of next-generation materials when exposed to space with the mission of designing future spacecraft to travel far beyond Earth's orbit. "As spectrometers are becoming more miniaturized, rugged, and lower in cost, we are seeing new and exciting applications way beyond the scope of standard lab and field research," says Jason Pierce, director of business development at StellarNet. "Who would have imagined 20 years ago when StellarNet first designed a little rugged spectrometer that one day humans would be mounting them on the Space Station to test specialized materials for exploration into the new frontier!"

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2

Optical system design improves fluorescence light capture

CHRISTOPHER COTTON

Maximizing fluorescence light collection in single- and multiphoton microscopy reduces noise from excitation sources and improves lens performance.

Fluorescence microscopy is used in a wide range of medical and biological applications, and recent improvements in image quality are extending the number of applications. However, life science companies using this technique to investigate complex molecular and cellular structures still encounter significant obstacles to acquiring information from the sample.

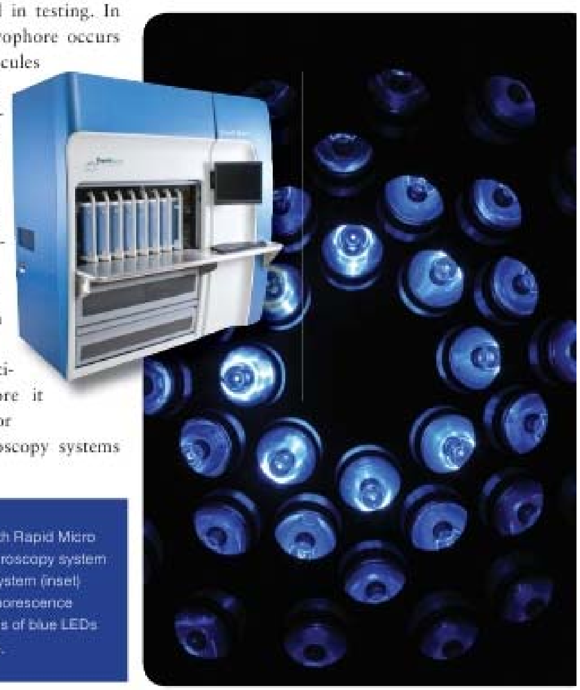
Their optical designs must provide effective illumination, sufficient filtering to isolate the fluorescent light from the illumination without signal loss, and efficient collection of light from the sample. Improving system performance can mean reduced sample size, as well as earlier and more accurate testing.

ASE Optics works with life science companies to improve optical system design and identify novel techniques to speed research and reduce risk for systems such as the Growth Direct System by Rapid Micro Biosystems (Bedford, MA). While the microbiology method of testing has not changed since the times of Louis Pasteur, new test systems like the Growth Direct System automate and speed testing, shortening grow time and shrinking needed sample size (see frontis, this page).

Optical fluorescence is a phenomenon that occurs when a molecule absorbs excitation light at a wavelength within its absorption band and then, nearly instantaneously, emits light at a longer wavelength within its emission band. A fluorophore is often applied to the sample to bind to the specific molecules or cellular structures that need to be identified in testing. In many cases the fluorophore occurs naturally in the molecules or cellular structures that are being investigated. An optical fluorescence system design needs to:

- illuminate the sample with excitation light
- efficiently collect light emitted from the sample
- reject scattered excitation light before it reaches the detector

Fluorescence microscopy systems detect fluoresced light that results from the interaction of a single photon with a fluorophore. The wavelength emitted in these systems is usually longer than the excitation wavelength. However, the difference between the two wavelengths is often quite small. A typical fluorescence microscopy system addresses this with an excitation source and filter that provide light at the proper wavelength, a dichroic beamsplitter for directing the excita-



ASE Optics worked with Rapid Micro Biosystems on the microscopy system for its Growth Direct System (inset) to efficiently capture fluorescence light resulting from rings of blue LEDs illuminating the sample.

tion light to the sample and directing the emitted light, through an appropriate emission filter, to a detector (see Fig. 1).

The filter problem

The arrangement of filters is intended to isolate the bright excitation light from the path of the weak emitted light. Fluorescence lines for the emitted light can be very narrow, requiring highly accurate filter specification and design. Advances in thin-film optical filters have significantly advanced fluorescence microscopy, but their use presents challenges: cost and angular sensitivity.

The wavelength transmission characteristics of thin-film filters will vary with incident angle. The collection efficiency of systems with a large field-of-view, a high numerical aperture (NA), and a narrow distance between the excitation and emission wavelengths will be limited by the size and angular acceptance of the filter.

A common layout for a fluorescence imaging system is to have the excitation light injected into the system in an area where the light can be collimated. In this arrangement, the beamsplitter selectively reflects the excitation light from the light source to the sample and transmits the emission light from the sample toward the sensing system. The beamsplitter will place a lower limit for how close together the excitation and emission wavelengths can be.

By locating the beamsplitter in an area where the image light can be collimated, we avoid introducing aberrations into the illumination and imaging paths, which will appear when a tilted plate is introduced in either a converging or diverging ray fan.

Alternate illumination approach

In designing the optical system for the Growth Direct System, the ASE Optics engineering team helped to optimize an alternate

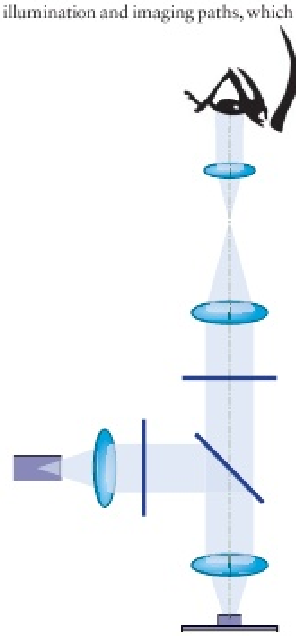


FIGURE 1. Standard fluorescence microscopy design uses multiple filters to isolate light in both illumination and signal channels. Getting the right filter performance can be challenging and costly.

approach (see Fig. 2). The illumination approach was key to achieving the required performance: The blue light that causes the cells to fluoresce allows the sensor to identify fluorescence from just 100 cells vs. the nearly 5 million cells needed for the human eye to see colonies.

To improve the overall efficiency of collected fluorescence, the optical system design eliminated the need for the beamsplitter. This scheme still presented performance challenges. The illumination source is provided by an array of several dozen blue LEDs arranged in a pattern that provides uniform light and optimizes the aspect ratio of the excitation energy to help simplify the imaging problem. Each LED has a corresponding microlens and filter for directing its narrowband energy toward the sample.

A single long-wavelength pass filter then transmits the fluoresced light and rejects the excitation wavelengths from the imaging path. The sample light still has high etendue that must be handled by the fil-

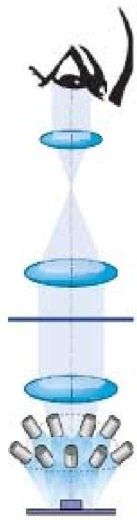


FIGURE 2. The microscopy system designed for Rapid Micro Biosystems eliminates the need for the beamsplitter and provides a highly uniform illumination to the sample. The system, which tests pharmaceutical drug lots for contamination, allows earlier detection of fluorescence from a smaller sample, speeding testing and product shipping.

ter. However, this light is incident at angles about normal—not angles centered about 45° as in a standard system. This helps to reduce the cost and performance requirements on the filter without compromising the quality of the data obtained from the sample.

Proper materials selection

There are also considerations for providing suitable materials for optical components in the fluoroscopy environment. When illuminated with ultraviolet light, some types of optical glass exhibit fluorescence at particular wavelengths, primarily caused by impurities within the glass or incorrect choices for optical adhesives.

Using materials that fluoresce complicates the task of filtering and adds unwanted noise to the sensed light signal. In many cases in which the ASE Optics engineering team was engaged to specify optical components with best-fit materials, crystals, high-purity optical materials, and nonfluorescing cements have enabled our customers to reduce the overall system noise due to optical sources.

Once the correct illumination sources and filter configuration had been chosen, we could ensure performance of the imaging lens with the proper optical design and packaging. Often the imaging lens performance is overlooked in fluorescence imaging systems until the first one is built. The availability of high-pixel-count cameras enables the collection of significant amounts of data from a single image; however, as the amount of information increases, so does lens complexity.

Fluorescence microscopy in practice

The availability of high-purity optical materials like fused silica, Cleartran, and other crystalline materials; the expanding use of LEDs; availability of off-the-shelf thin-film filters; and advanced assembly techniques has broadened the applications for fluorescence microscopy, bringing it from the research lab to the manufacturing floor.

Rapid Micro Biosystems' Growth Direct System is used by filterable pharmaceutical companies to conduct microbiology testing that would have previously been done via Petri dish with growth observed by microbiologists. Through the use of the optical system, Rapid Micro Biosystems has been able to deliver results in half the time of traditional microbial test methods. The end result? Faster moving product and reduced risk for the pharmaceutical companies, as well as safer products for consumers.

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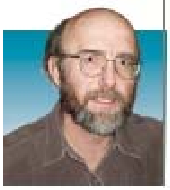


Digital techniques render real-time response in holography

JEFF HECHT contributing editor

Digital imaging and display technology opens new possibilities for holography. Digital holographic microscopes can display 3D images of living cells in real time on computers, and digital holographic telepresence is emerging on the technological horizon.

Holography was born as an analog technology, and the development of laser holography by Emmett Leith and Juris Upatnieks drew heavily from Leith's earlier work on optical signal processing, a form of analog computing. Holograms were long recorded on special photographic emulsions applied as coatings to glass plates or film.

The idea of computer generation of holograms dates back to 1966, but that technology long was limited by practical issues of computing capacity, and early computer-generated holograms often were recorded on photographic media. Now a new generation of digital technology has replaced photographic media for recording holograms, and has created new options for processing and displaying holographic images. As in photography, the digital approach offers important advantages, including real-time response, and convenient processing and storage. Applications include 3D microscopy, displays, and video or "telepresence."

Basic computing concepts

Holography is based on recording both the amplitude and phase of the wavefront of light from an object. This is done by combining the wavefront of light from the object with a coherent reference beam from the same source to produce an interference pattern, which is called a *hologram*. Illuminating the recorded hologram with an identical reference beam reconstructs the original wavefront, which the eyes perceive as showing the original object as if it were present.

In Dennis Gabor's original concept, the object and reference beams followed the same path, and the object itself was two-dimensional. This approach, called *on-axis holography*, is easy to implement and is still used for some applications, but it is inherently limited to small objects and produces troublesome twin images that overlap. Leith's invention of off-axis holography, in which the object and reference beam follow separate paths, allowed holography of larger objects and removed the twin image from the reconstructed scene.

Computer-generated holography used computers to calculate the interference pattern that a virtual object would produce. That computer-generated hologram was then printed, often on photographic media, and illuminated with a reference beam that produced a 3D image of the virtual object.

The new digital holography replaces the analog photographic film or plate

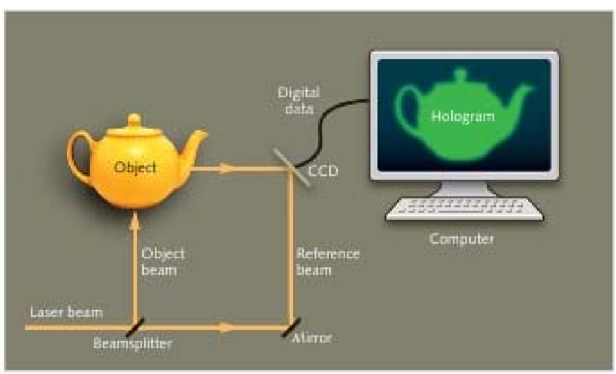


FIGURE 1. Digital off-axis holography uses a CCD array to record a digital hologram where the reference beam interferes with the object beam. The data are transmitted to a computer and analyzed.

used to record early holograms with a digital detector array that records the hologram, as shown for off-axis holography in Fig. 1. The resulting digital version of the hologram then goes to a computer for further processing.

One possibility is using the computer to extract phase and intensity data from the digitized hologram and further process that data to create a 3D digital model of the original object viewable on a computer display. Alternatively, the digitized hologram can be reproduced on a digital display or a photorefractive material, which is illuminated by a reference beam to optically reconstruct a 3D image. Images can be recorded and displayed singly, as fixed images, or in sequence to produce holographic videos, movies, or telepresence.

How is digital holography used in microscopy?

Microscopy has been a particularly successful application for digital holography, a reminder that Gabor had an impressively sharp view of the future when he invented holography as a way to improve the electron microscope. Digital holography works well for living cells, which can be difficult subjects for conventional microscopy because they are soft and have little natural color contrast. Holography, like phase-contrast microscopy, can record refractive-index differences, which can distinguish cellular components.

For microscopy, the digital hologram is recorded electronically then the resulting digital data usually are processed in real time to create a 3D model for display on a computer screen, as shown in Fig. 2. This method avoids time-consuming photographic processing and allows recording of a time series of images to study dynamic effects. Moreover, writes Myung Kim of the University of South Florida (Tampa, FL), "the complete and accurate representation of the optical field as an array of complex numbers allows many imaging and processing capabilities that are difficult or infeasible in real-space holography."[1] Image-processing options include focusing on the object at various distances, quantitative phase-shift measurements, and digital manipulations such as aberration corrections. Digital processing also can suppress the troublesome twin images produced by in-line Gabor holography.

A key advantage of digital holography, first demonstrated in 2003, is that it can study living cells without staining, labeling, or otherwise affecting them. This "makes it possible to easily measure cell properties that previously have been very difficult to study in living cells, such as cell thickness, volume, and cell refractive index," write Kersti Alm of Phase Holographic Imaging (Lund, Sweden) and colleagues in a review paper.[2] Real-time digital processing permits a series of observations to monitor changes, and the recorded holographic data can be reprocessed to better compare different views.

Digital holographic microscopy does have its limits. A major one is the relatively low spatial frequency response of digital cameras, which limits resolution of reconstructed holograms, write

Damien Kelly of the National University of Ireland (Maynooth, Ireland) and colleagues.[3] That arises from the spacing of detector elements and their larger size than the grains in photographic media. But Kelly says that new processing techniques promise improvements.

Digital hologram displays

A digitally recorded hologram also can be reconstructed by displaying it on a spatial light modulator (SLM) or photorefractive medium and illuminating it with a reference beam. Diffraction of the input light by the displayed hologram produces a 3-D image, as shown in Fig. 3.

Producing a good-quality holographic image requires digital processing of the recorded hologram that takes into account both the illuminating wavelength and the physical characteristics of the display device. That could best be done by transmitting holograms in a standard interchange format and doing the final processing at the device, to account for its particular features, writes V. Michael Bove of the MIT Media Laboratory (Cambridge, MA) in recent review of digital display holography.[4] "An ideal SLM would be able to control both the intensity and the phase of light, but given that most practical SLMs can affect only one or the other, a phase-only modulator is more desirable as it is theoretically over five times more diffraction-efficient ... than an amplitude-only modulator." Both types have been demonstrated.

Another advantage of SLMs is that the displayed hologram can be changed dynamically, changing the way it diffracts light. This allows their use as dynamic holographic optical elements for applications requiring adjustable optics, such as generating a conjugate wavefront for adaptive optics, or beam directors for (holographic) optical tweezers. Although the space-bandwidth product of the digital devices is smaller than those of analog holographic materials, with suitable processing liquid-crystal displays and digital micromirrors developed for mass-produced consumer products can be used for many applications, writes Tobias Faist of the University of Stuttgart (Stuttgart, Germany).[5]

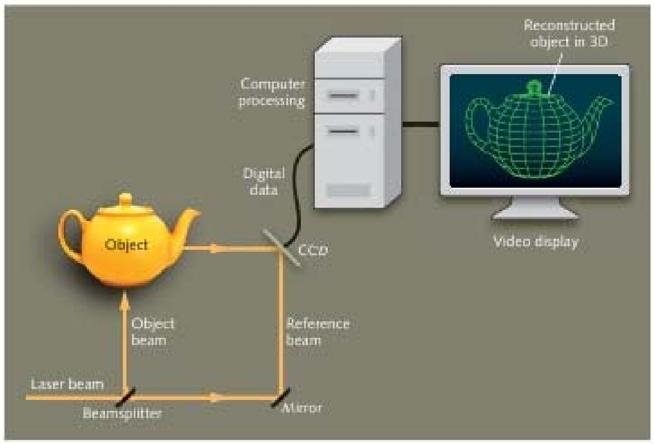
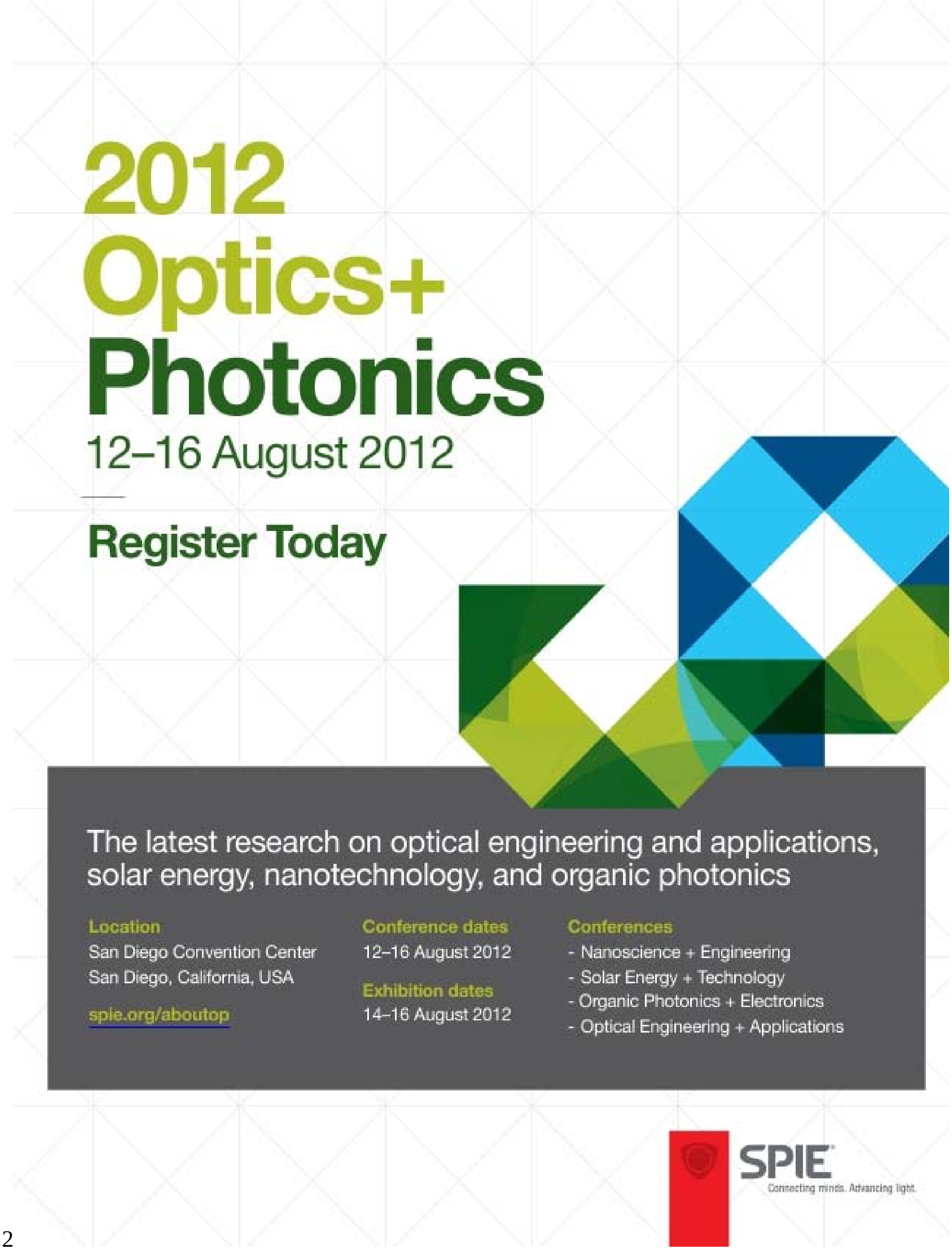


FIGURE 2. A digital hologram is recorded on a CCD array, and the data are processed on a computer to create a digital 3D model in the computer. That model is then displayed on the screen, shown as if in three dimensions.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Holographic television or telepresence

The next step beyond dynamic digital holography is holographic television or telepresence. The idea is to record digital holograms at a video-like frame rate, transmit them, then display them in their full three-dimensional glory at the same frame rate.

So far, the most impressive "holographic" demonstrations have not involved any real holograms. The famed "hologram" of Princess Leia pleading for help in *Star Wars: Episode I* in 1977 was a nonholographic special effect. A series of recent demonstrations of "holographic telepresence" including futurist Ray Kurzweil and long-dead rapper Tupac Shakur were also fakes, based on the "Pepper's Ghost" illusion, which projects a 2D image onto a clear screen on stage.

Holographic motion pictures or television has been a dream since the 1960s, but years of development with analog technology faded away in the mid-1990s. In the past few several years, digital real-time holography has made major progress. "Capture and computation are proving not to be the barriers that people have been assuming they would be," says V. Michael Bove of the MIT Media Laboratory. "The display itself is the limiting factor." Developers are using inexpensive cameras to capture images in incoherent light, then using computers to generate the holograms, with much of the computation done at the display.

The results have included some eye-catching demonstrations. Nasser Peyghambarian of the University of Arizona (Tucson, AZ) and colleagues in 2010 demonstrated telepresence at one frame per second using a new photorefractive material.[6] In 2011, Bove's group at MIT hacked the gesture-

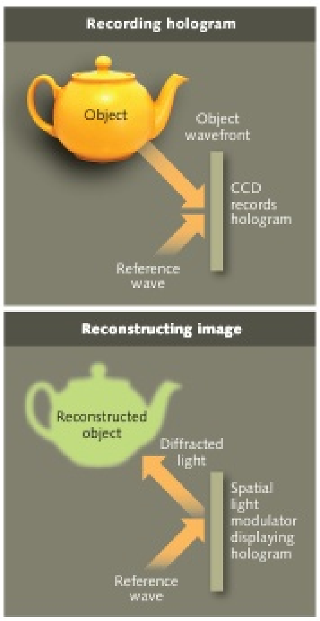

FIGURE 3. A digital hologram is recorded on a CCD, then stored in a computer and processed. For digital reconstruction of the hologram, the processed digital hologram is displayed on a spatial light modulator, which is illuminated by the reference wave to reconstruct an image of the object.

recognition camera from a Microsoft Kinect to generate input images, which they processed with imaging chips and displayed using a custom-built acousto-optic projector, showing

FIGURE 4. Shown is a holographic telepresence of a student dressed as "Princess Leia," demonstrated by MIT and the University of Arizona. (*Courtesy of MIT Media Lab and University of Arizona College of Optical Sciences*)

graduate student Edwina Portocarrero dressed up as Princess Leia (see Fig. 4).

Outlook

Digital technology has brought big improvements to holographic imaging. Digital imaging and processing continue their relentless advance, and Kim is optimistic that thanks to such new technology and improving pixel resolution, "new holographic imaging capabilities yet to be conceptually imagined will emerge."

The progress of real-time holographic video also has been impressive, but tough problems remain. The resolution remains more like that of early electronic television demonstrations than those of Apollo-era color television broadcasts. Don't expect to keep that old analog CRT television set hooked up to a digital converter and a VCR working long enough to replace it with holovision. ◂

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Lens-free on-chip microscope is field-portable

ALON GREENBAUM, UZAIR SIKORA, and AYDOGAN OZCAN

A field-portable on-chip holographic microscope images dense and blended biological samples using multiheight lens-free imaging.

Brightfield microscopy is widely used in various fields, including biomedicine. Nevertheless, a fundamental limitation of optical microscopes is that they have a limited field of view (FOV), which makes it labor intensive, tedious, and relatively expensive to detect rare microscopic features of interest (for example, abnormal cells or signatures of parasites). Another limitation is their relatively bulky structure, which makes the technique less suitable for field use.

Digital in-line holography

To address these limitations, lens-free holographic on-chip imaging techniques can provide high-resolution images over large sample areas using compact, lightweight, and cost-effective designs.[1-4] In one example of a lens-free holographic microscope, the underlying operation principle is based on partially coherent digital in-line holography, where light-emitting diodes (LEDs) are used for illumination (see Fig. 1). Butt-coupled to multimode optical fibers, each LED illuminates the specimen with an effective aperture size of about 0.1 mm. This illumination configuration ensures that the light impinging on the specimen, which is positioned very close to the image sensor, is sufficiently coherent that the scattered object field can interfere with the background (that is, unscattered) light.

The resulting interference pattern encodes the phase information of the object in the form of an in-line hologram sampled using, for example, a CMOS sensor array. The same hologram-recording geometry, under unit fringe magnification, can also handle the relatively large bandwidth of the source without sacrificing spatial resolution. On the other hand, the pixel size

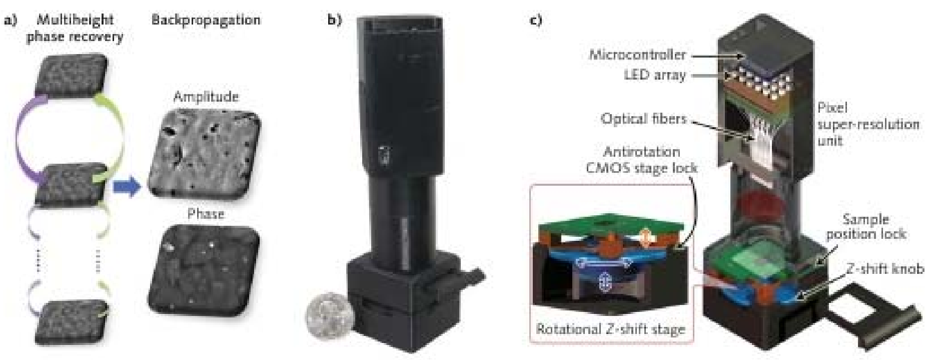
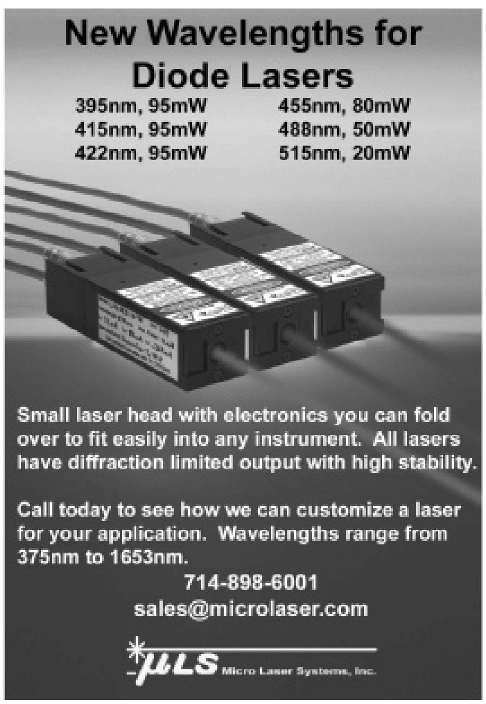


FIGURE 1. a) A multiheight phase-recovery process enables imaging of dense and confluent samples by propagating back and forth between super-resolved holograms acquired at different heights. The resulting complex field is then backpropagated to the object plane, yielding amplitude and phase information of the specimen. b) Weighing only ~122 grams, the lens-free multiheight holographic microscope achieves submicron resolution across a field of view of about 30 mm^2. c) A schematic of the same device is shown.



at the sensor array presents a challenge for improving spatial resolution to submicron range.

To mitigate this sampling limitation, we use an array of LEDs, which are individually turned on and off to shift the lens-free in-line holograms of the objects at the sensor plane. Based on pixel super-resolution techniques, we can synthesize an in-line hologram that has effectively much smaller pixel size, yielding sub-micron spatial resolution across an FOV of, for example, 30 mm^2, which is more than 100 times larger than the FOV of a typical brightfield microscope with a comparable resolution.[1, 2, 5] As a proof of concept, such lens-free holographic on-chip microscopes based on partially coherent in-line holography were used, for example, for imaging of malaria parasites, performing cytometry on a chip, and high-throughput detection of waterborne parasites.[1, 6, 7]

Multiheight phase recovery algorithm

Relatively recently, the same platform has been modified to better handle dense and confluent samples, which present challenges for lens-free on-chip imaging in general due to its transmission geometry. To address the image distortion that occurs for dense samples, a multiheight phase recovery algorithm was implemented in partially coherent in-line holography.[8-10]

This algorithm requires a few intensity measurements acquired at different sample-to-sensor distances. Each measured in-line hologram is pixel-super-resolved independently, after which phase recovery is iteratively achieved by propagating (using the angular-spectrum approach) back and forth among these different super-resolved planes (see Fig. 1a). This iterative process neither assumes prior information about the sample dimensions nor imposes a spatial mask for affecting the convergence of the algorithm. Instead, it reinforces the super-resolved field amplitude of each hologram plane while converging on the unknown object phase.

In our field-portable design, a Z-shift stage was implemented to obtain different intensity measurements at different heights (see Figs. 1b and 1c). This stage is based on a nut-and-screw principle, where the CMOS image sensor is positioned over the moving nut while the screw is stationary. As the Z-shift knob is manually turned, the distance of the image sensor to the sample is decreased or increased. This design is cost effective and has a precision on the order of 10–15 µm. On the other hand, the exact Z shifts do not need to be known *a priori* since they can be digitally estimated by applying an autofocus algorithm.[7]

Pap smears imaged

To validate the performance of this field-portable microscope, liquid-based Papanicolaou tests (Pap smears) were imaged. The Pap smear/test is considered to be one of the gold-standard tests for cervical cancer screening, which is the second most common cancer among women worldwide. Cervical cancer leads to about 0.3 million deaths each year around the world,

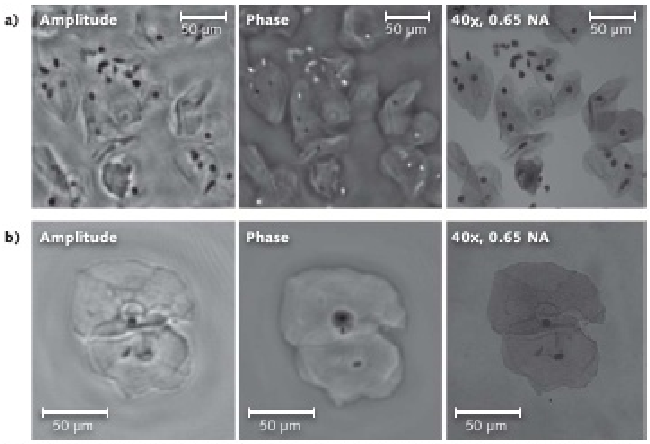


FIGURE 2. Imaging results of the lens-free multiheight holographic microscope are shown. a) Amplitude and phase images are shown of a confluent Papanicolaou test (SurePath preparation). A 40X-objective-lens microscope image is also provided for comparison. b) The amplitude, phase, and conventional microscope images of a Papanicolaou test (ThinPrep preparation) are shown. The reconstruction process does not require additional information such as spatial mask or object dimensions.

especially affecting developing countries where prescreening programs are not enacted.

Figure 2a shows the backpropagated lens-free images that were obtained with our field-portable microscope, using five intensity measurements acquired at different heights. The sample is a 2D confluent Pap smear (the SurePath preparation, produced by BD of Franklin Lakes, NJ), and only a small portion (30 mm^2) of the reconstructed FOV is shown. For comparison, a 40X (0.65 numerical aperture) objective lens image of the same FOV is also provided. Note that the inner morphology of the cells shows an enhanced contrast in the amplitude image, while the boundaries of the cells are better resolved in the phase image. This might facilitate the calculation of the nuclear-to-cytoplasm ratio (NC ratio) of these cells, where a high NC ratio might indicate that a specific cell is abnormal or precancerous.

To further validate the performance of the field-portable microscope, a different type of Pap test (the ThinPrep liquid preparation, by Hologic of Bedford, MA) was also imaged. The backpropagated amplitude and phase images and the corresponding 40X microscope objective image of this test are shown in Figure 2b. These results demonstrate that multiheight phase recovery is able to reconstruct samples with complex structure, without the need for spatial masking or filtering, which reveals the promising potential of this microscopy platform for pathology needs in resource-limited settings. ◀

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Broadband OPO spans the mid-IR, no tuning needed

NICK LEINDECKER and KONSTANTIN VODOPYANOV

A doubly resonant, mid-infrared degenerate optical parametric oscillator (OPO) produces an extremely broad instantaneous output bandwidth, eliminating the need for the finicky tuning required in nondegenerate OPOs.

Optical parametric oscillators (OPOs) have long been recognized as a versatile means of producing optical output in important spectral regions unreachable by laser sources. The mid-IR is one such region, rich in spectroscopic information but underpopulated by convenient laser lines. Over the last few years, our group has investigated a special class of doubly resonant OPOs for broadband mid-IR generation.

In a typical OPO, a strong laser pumps the second-order nonlinear susceptibility of a suitable optical material. When combined with an appropriate resonator for optical feedback, oscillation is established at one or more longer wavelengths. The oscillation wavelength is often tuned by adjusting the parameters of the resonator or nonlinear material.

With their broad tunability and substantial output power, OPOs are used extensively for mid-IR spectroscopy. Quantum-cascade lasers (QCLs) now offer a tantalizing alternative, but the restricted tunability of individual devices is still a limit for very broadband measurements. On the other hand, while an OPO may be tuned over a wide spectral range, it is challenging to do so in a precise and continuous fashion.

Doubly resonant, degenerate OPOs

In contrast, we have developed an instantaneously broadband OPO system. It is especially suitable for parallel, high-resolution spectroscopy based on the principle of Fourier transform IR spectrometry.[1] The OPO is designed to operate doubly resonant for low pump threshold (less than 10 mW) and is locked near degeneracy where the center wavelength of the output is twice that of the pump, and the acceptance bandwidth of the nonlinear process is very broad. When coupled with a low-dispersion resonator, we achieve extremely broad output bandwidth, with no need (or knob) for wavelength tuning.

Key to enabling these designs has been the commercialization of stable modelocked ultrafast fiber lasers in the near-IR (NIR). When used to synchronously pump our systems, the "comb" of modes of the NIR pump laser is rigorously translated into the

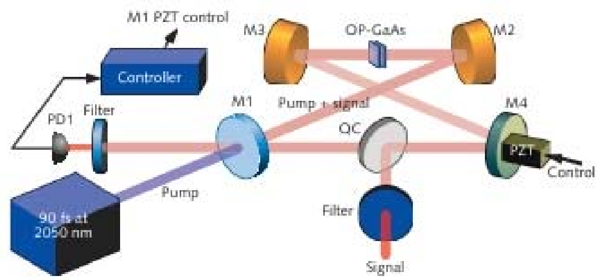

FIGURE 1. A schematic of a synchronously pumped broadband subharmonic OPO system illustrates its simple form. The pump laser is a 800 mW Tm-fiber oscillator-amplifier system operating at a 75 MHz repetition rate with 93-fs-long pulses. The pump beam enters the OPO through a dielectric mirror M1. The remaining resonator optics are metallic gold mirrors. In the short leg of the cavity, mirrors with a 50 mm radius of curvature define a tightly focused eigenmode inside a 0.5-mm-long OP-GaAs crystal. Cavity length is precisely stabilized by a piezoelectric actuator (PZT). Plates of CaF_2 or YAG (designated as OC) are used to compensate the dispersion of GaAs and provide outcoupling by virtue of Fresnel reflection.

mid-IR by phase- and frequency-locked downconversion, with extensive spectral broadening, a characteristic of doubly resonant degenerate OPOs.[2]

So far, we have demonstrated broadband mid-IR generation in a number of systems using both periodically poled lithium niobate (PPLN) and orientation-patterned gallium arsenide (OP-GaAs) as the nonlinear optical material, with pump sources including erbium-fiber (1.5 μm) thulium-fiber (2.05 μm) and Cr:ZnSe (2.45 μm) modelocked lasers.[3-5] In our most recent system (see Fig. 1), the pump laser is a Tm-fiber oscillator-amplifier system provided by IMRA America (Ann Arbor, MI) with 600 mW average power at a center wavelength of 2.05 μm. It produces pulses with duration of 93 fs at a repetition rate of 75 MHz. The OPO resonator is a 4-m-long ring cavity that is matched in length to the pump repetition rate. The intracavity optics comprise a flat dielectric mirror M1 with high transmission for the pump and high reflectivity in the 3–6 μm range, and several gold-coated mirrors with high mid-IR reflectance.

OP-GaAs crystal provides gain

Broadband gain centered at 4.1 μm is provided by a 0.5-mm-long quasi-phase-matched (QPM) OP-GaAs crystal, grown at BAE Systems (Nashua, NH) by a combination of molecular-beam epitaxy and hydride vapor-phase epitaxy, resulting in a QPM "film" thickness of greater than 1 mm. The samples have a usable aperture of 1 × 4 mm. The QPM period was 60.5 μm, which amounts to only eight domain reversal periods over the full length of the 0.5 mm crystal. The crystal was cut and polished for operation at Brewster's angle (73°) and polarizations of all interacting waves were parallel to the <111> direction in GaAs. Yttrium aluminum garnet (YAG) or calcium fluoride (CaF_2) with negative group velocity dispersion (GVD, $d^2k/d\omega^2$) at 4.1 μm is inserted

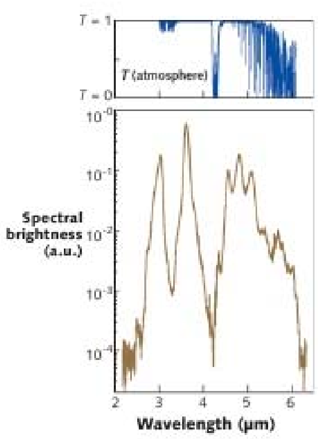

FIGURE 2. When locked, the OPO produces a stable and extremely broad (2.6–6.1 μm) bandwidth output in the middle of the spectroscopically important "fingerprint" region. The dip near 4.25 μm is due to CO_2 absorption in the unpurged path to the spectrum analyzer. Transmission of the atmosphere is shown in the top graph.

inside the cavity at near Brewster's angle, partly compensating the positive GVD of GaAs. Output is taken as Fresnel reflection from this plate.

Double resonance imposes strict phase constraints on the resonator lengths at which the OPO will oscillate. Typically, as we scan the round-trip cavity length, we observe several peaks in the output separated by the pump wavelength. Near threshold (20 mW pump power), oscillation occurs at a single length. As the pump power is increased, we observe oscillation at adjacent length detunings, with about 20 peaks at 600 mW of pump power. The output spectrum is found to vary with cavity length due to the interplay of additional resonator phase and uncompensated dispersion. However, when locked at the optimal resonant length, the spectrum is stable and exhibits extremely broad bandwidth of 2.6–6.1 µm (see Fig. 2). We have outcoupled up to 40 mW from this system using the Fresnel reflections from the dispersion compensating plate.

Absorption spectroscopy

The resonator is enclosed in a plastic box to permit purging with dry nitrogen. Otherwise, strong effects from intracavity absorption and dispersion due to atmospheric CO_2 and H_2O appear in the output spectrum. By introducing trace gases into the OPO resonator, we were able to make sensitive measurements of their absorption spectra through their effect on the OPO spectrum. Fig. 3 shows the absorption spectrum of methane gas near 3.3 µm.

These results demonstrate that degenerate synchronously pumped OPOs show great promise for achieving ultra-

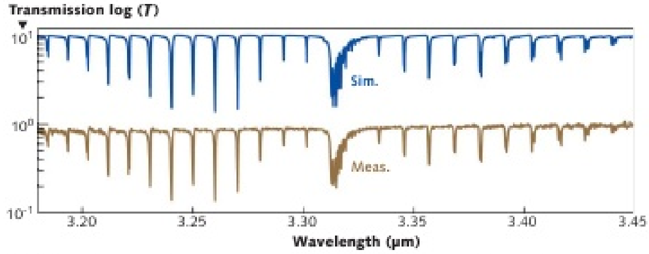

FIGURE 3. An absorption spectrum of methane gas (at a concentration on the order of 10 ppm) near 3.3 µm was obtained by intracavity spectroscopy. Shown for comparison is the methane spectrum obtained from the HITRAN (high-resolution transmission molecular absorption) database currently maintained by the Smithsonian Astrophysical Observatory (Cambridge, MA).

2

broadband outputs in the mid-IR. Our degenerate GaAs-based OPO pumped by a Tm-fiber laser offers a more-than-octave-wide output from 2.6 to 6.1 μm—a range where OH, CH, CO, and NH chemical bonds show their strongest vibrational signatures. Proper intracavity dispersion management is essential for achieving such wide bandwidths. In addition to the broad frequency coverage, the low pump power required to reach OPO threshold and the phaselocking of the signal/idler to the pump render this system a potentially ideal source for precision frequency-comb spectroscopy in the mid-IR. ◀

The GaAs-based OPO pumped by a Tm-fiber laser offers a more-than-octave-wide output from 2.6 to 6.1 μm, where OH, CH, CO, and NH bonds show their strongest vibrational signatures.

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Gain peaking doubles the bandwidth of Ge photodetectors in CMOS

JOHN WALLACE

Techniques now exist for greatly increasing the bandwidth of germanium photodetectors fabricated in silicon integrated photonics, taking advantage of newer, more complex structures created via CMOS processes.

Integrated photonic systems based on silicon (Si) can dramatically boost data transmission rates over those for all-electrical transmission. Network and rack-to-rack optical interconnects based on Si photonics are already in use; in development are chip-to-chip and, further out, intrachip Si-based optical interconnects. A powerful motivating force behind Si photonics technology is the ability to fabricate integrated photonic systems using standard CMOS processes commonly used in the electronics industry.

However, neither light emitters nor photodetectors fabricated from Si on Si substrates tend to perform well, so germanium (Ge)—which can also be part of a CMOS-compatible process—is often used as the active component material, integrated into the silicon platform via epitaxy.

For photodetectors, the low absorption coefficient of 0.2 dB/μm for Ge at 1550 nm (the wavelength usually used for Si photonics) results in physically large detectors. Although larger sizes increase responsivity, they also lead to larger parasitic electrical capacitance, which reduces the detector bandwidth. In addition, if bump-bonding is used to bond the Ge component to the Si substrate, the parasitic capacitance is even further increased.

Three types of gain peaking

A team of researchers from the University of Washington (Seattle, WA) and the University of Delaware (Newark, DE) has developed an approach to Ge-on-Si detector fabrication that allows for larger detector sizes while reducing the parasitic capacitance.[1] The approach, which so far exists only as a simulation, would take advantage of recent fabrication techniques that allow the fabrication of multi-metal-layer devices, such as metal-insulator-metal (MIM) capacitors, adjacent to waveguide-coupled integrated detectors (see Fig. 1).

The researchers' approach is called gain peaking—a technique that is most commonly used by electrical engineers for optimizing the design of amplifiers. There are a number of different types of gain peaking, and the researchers tried out three of them.

The first is called series gain peaking, which produces an increase in detector bandwidth of about 40%. The second involves incorporating an additional capacitor to produce a bandwidth increase of up to 100%. The third,

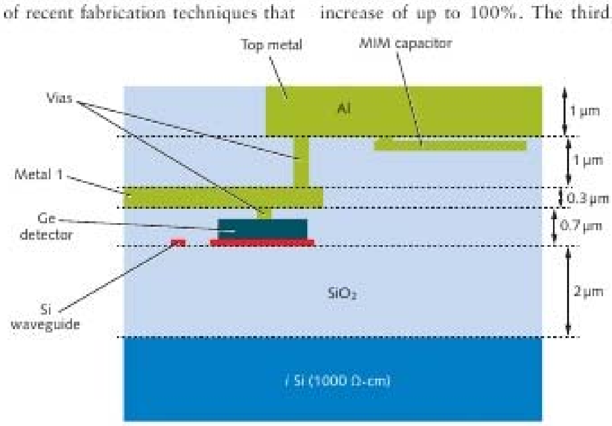

FIGURE 1. Silicon waveguides are combined with two layers from a CMOS metal stack that allows the fabrication of a metal-insulator-metal (MIM) capacitor layer. Such devices are fabricated on a high-resistivity Si wafer. Use of these additional layers can enable bandwidth-boosting enhancements to Ge photodetectors.

called shunt gain peaking, results in a tradeoff of narrowband operation for a large increase in operating frequency.

Series gain peaking requires the addition of an inductor in series with the load of the photodetector. In one example, a detector with a parasitic capacitance of 35.2 fF and a resistance of 130 Ω has a bandwidth of 25 GHz. Adding an inductor of 0.57 nH (a reasonable value for an integrated inductor) raises the bandwidth to 35.5 GHz.

One thing to watch out for in series gain peaking is the possible introduction of dispersion (differing time delays for differing frequencies). In the example detector, the maximum dispersion is only 0.3 ps at a 30 GHz frequency, which is very small in comparison to the 28.2 ps period of the full 35.5 GHz bandwidth.

In enhanced series gain peaking, an extra parasitic capacitance becomes part of the circuit, either intrinsically (through bump-bonding), or intentionally added by including a MIM capacitor. Though this capacitance would normally detract from the detector's performance, optimizing the added inductor can actually increase bandwidth.

The researchers determined optimal capacitance and inductance values via a two-dimensional gradient that maximizes the 3 dB bandwidth. They calculated such values for detectors with a variety of bandwidths and other characteristics. For example, the 29 GHz bandwidth of one detector was boosted to 57 GHz using this technique—an improvement of 97%. The maximum dispersion for this detector was only 0.6 ps at 46 GHz—again, small in comparison to the period of the full bandwidth.

Shunt peaking

In shunt gain peaking, a detector circuit for a detector operating in only a narrow band can be made to operate at a very high frequency (far above that of a broadband detector) by adding another capacitor to prevent a short circuit at low speeds. In one example, a detector with an unmodified bandwidth of 30.6 GHz can, with proper values for capacitance, resistance, and inductance, be altered to have a bandwidth from 59.1 to 93.4 GHz, peaking at 73.4 GHz with a responsivity of 82% of that at 0 Hz (see Fig. 2).

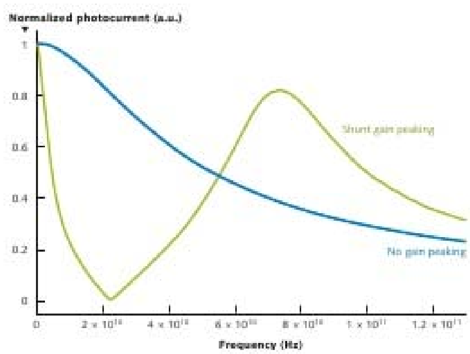

FIGURE 2. Normalized photocurrent as a function of frequency is shown for an unmodified Ge photodetector (gold) and a similar detector modified via shunt-peaking to create a narrowband operating region (blue) at far higher frequencies than those for the unmodified broadband detector.

While inductors are not always easy to add to CMOS integrated circuitry, the inductors required for gain peaking for Ge photodetectors can take a relatively simple geometry, that of a double square spiral taking up a total area 75 × 75 μm square, with a 10 μm width for the spiral trace itself. Most of the spiral is made from the top metal layer, with the single crossover fabricated from the lower metal layer.

The researchers did a noise analysis of the photodetector circuits, especially the combination of parasitic resistance and the inductor, which together produce thermal noise. For the shunt-peaked detector, the ratio of excess noise from shunt-peaking to the load noise was about 0.4 at 80 GHz.

The researchers note these capabilities stem entirely from the complex structures now available in CMOS-compatible Si photonics; taking advantage of them could realistically double Ge photodetector bandwidths with no harmful side effects. ◀

REFERENCE

1. M. Gould et al., *Opt. Expr.*, 20, 7, 7101 (Mar. 26, 2012).

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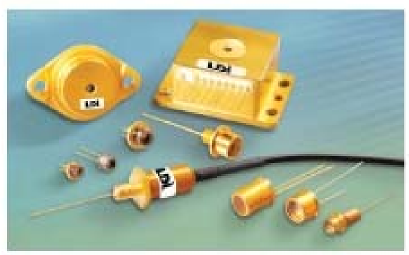

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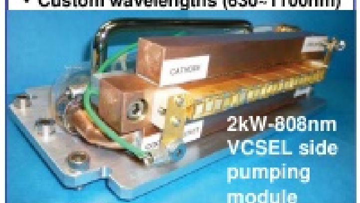

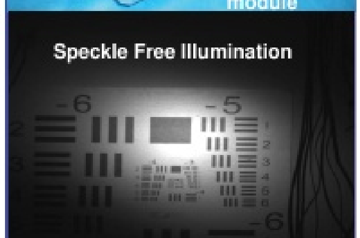

long continuous lengths. The standard fiber has an optical diameter of 245 µm and a reduced version has an 80 µm cladding and 160 µm optical diameter.

OFS Specialty Photonics Division
Brøndby, Denmark
www.specialtyphotonics.com

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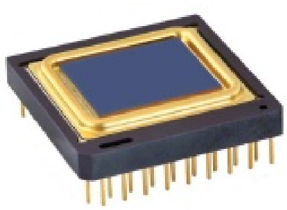

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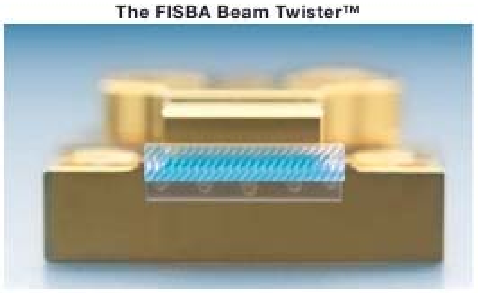

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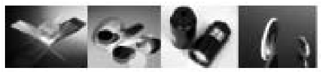

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IN MY VIEW

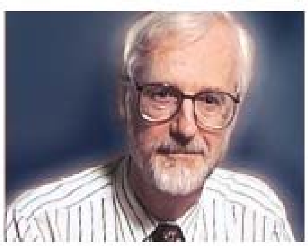
BY JEFFREY BAIRSTOW

This is not your grandpa's planetarium

So it's July and the kids are getting restless and the tree-house chatter turns to the so-called "theme parks" that are scattered across the country. I refer, of course, to such lofty temples of sanitized enjoyment (and equally sanitized teenage deployment) as Disneyland and Hogwarts College, etc. etc.

These theme parks are, in my view, often costly and misguided attempts to provide an entertainment that vaguely reminds the participants of the origin of the concepts but in a highly scrubbed and aseptic arena. Yes, water slides and the like are fun, but what do you have to offer for an encore?

Let me suggest you take a trip to your local planetarium. I say "local" since there are at least 20 large commercial planetariums in the United States, and there may be at least as many in the rest of the world. Some of the early planetariums (planetaria?) are mechanical marvels that are limited in display; others use the traditional dome and the familiar barbell-shaped projector made by the German optics experts at Carl Zeiss–Jena, in the former East Germany.



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However, as you might expect, the contemporary displays are largely digital and offer graphic opportunities for displaying the cosmos that are expanding the form and function of the planetarium. The latest installations combine advanced electromechanical technology, complex video and slide projectors, impressive laser displays, computer graphics, and stereo and full-surround audio systems.

I'm not going to mention *all* the new planetarium systems, but I'll give you my comments on a few that really impressed me. If you would like to do further research yourself, you can always do a Google on the planetarium of your choice. You will get more details than you asked for, but most of the web sites have a pretty good consumer orientation that makes them easy to navigate.

My comments are in no particular order. Boston's outstanding Museum of Science houses the somewhat recently renovated Charles Hayden Planetarium, which has a couple of contrasting shows: the rather noisy "Cosmic Collisions" and "Undiscovered Worlds." The latter show can be a visual assault if you have sensitive eyes.

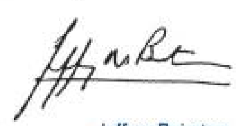
The Hayden Planetarium also has a live Friday night show, "The Sky Tonight," which has a long tradition among Boston's budding cosmonauts. Warning: Although the museum and planetarium have a fine position on the Charles River, exhibits are often crowded during school vacations.

Of course, no list of planetariums could possibly omit the grandfather of them all, the "Adler Planetarium and Astronomy Museum" in Chicago. The Adler actually houses several planetariums, among which is the first commercial planetarium built in 1913 for the Chicago Academy of Sciences. Called the Atwood Sphere and so named after its designer, the Atwood Sphere seems quite primitive when compared with the museum's recently installed twin planetariums: one a traditional Zeiss projector and the other a fully digital IMAX theater that has yet to be fully explored and exploited.

My third choice would be the UK's National Maritime Museum and Royal Observatory, Greenwich. This is the home of the Greenwich Meridian (GMT). It is also the home of London's only planetarium. The Royal Observatory is hosting several events during the 2012 London Olympics and ParaOlympics that could result in limited access to the observatory and planetarium from July through September. Check the museum's web site before you go. Google "Peter Harrison Planetarium" for details.

You don't necessarily have to go to a planetarium to experience the effects of a ride through the galaxies. Indeed, all the major planetaria have put a kind of slide or movie show on YouTube. Just open up your iBook to see some startlingly good displays. I particularly enjoyed the section recorded at Chicago's Adler Planetarium entitled "Deep Space Adventure." Just search for "Deep Space" on your YouTube extension.

Happy galactic explorations!



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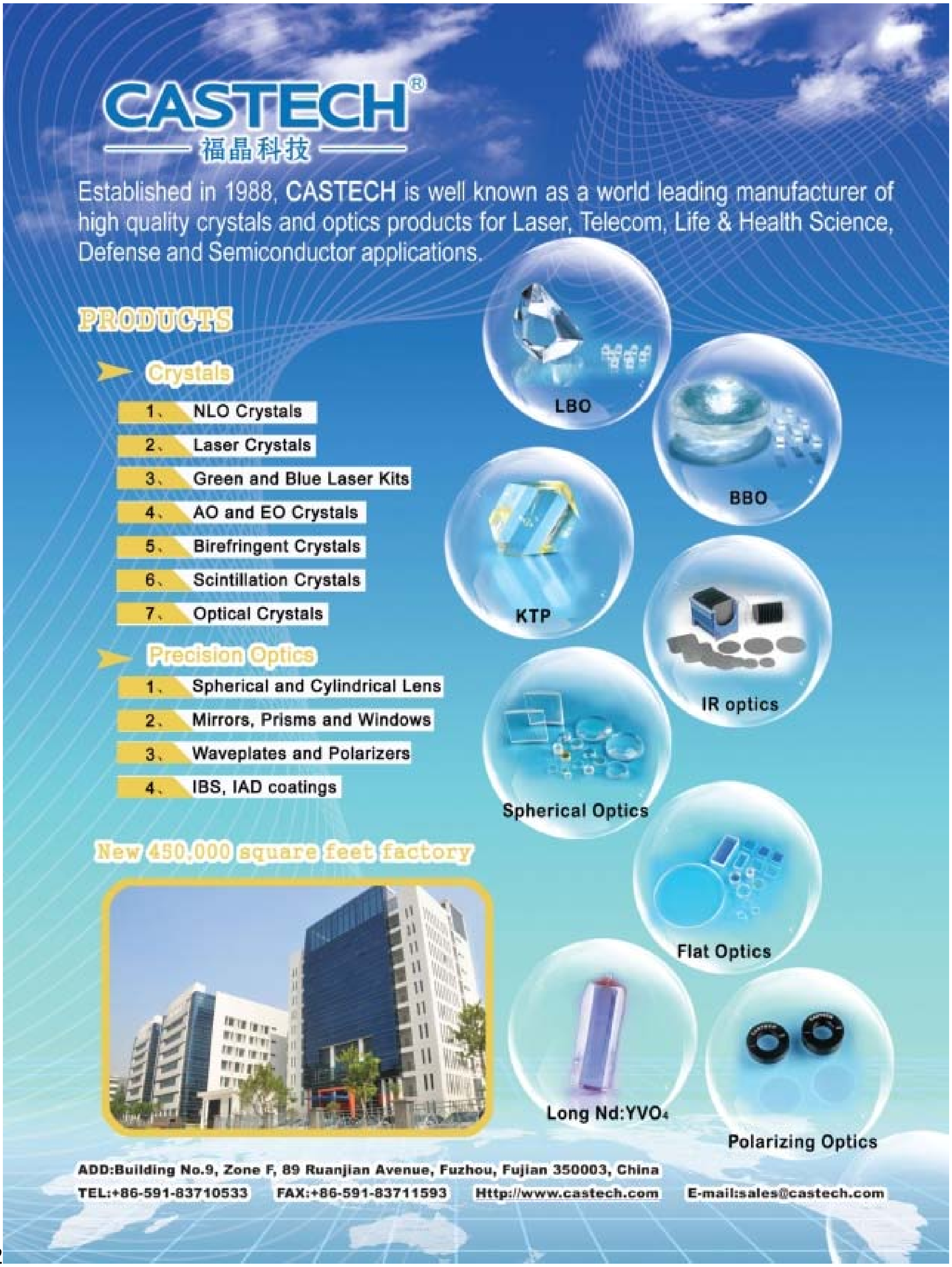
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