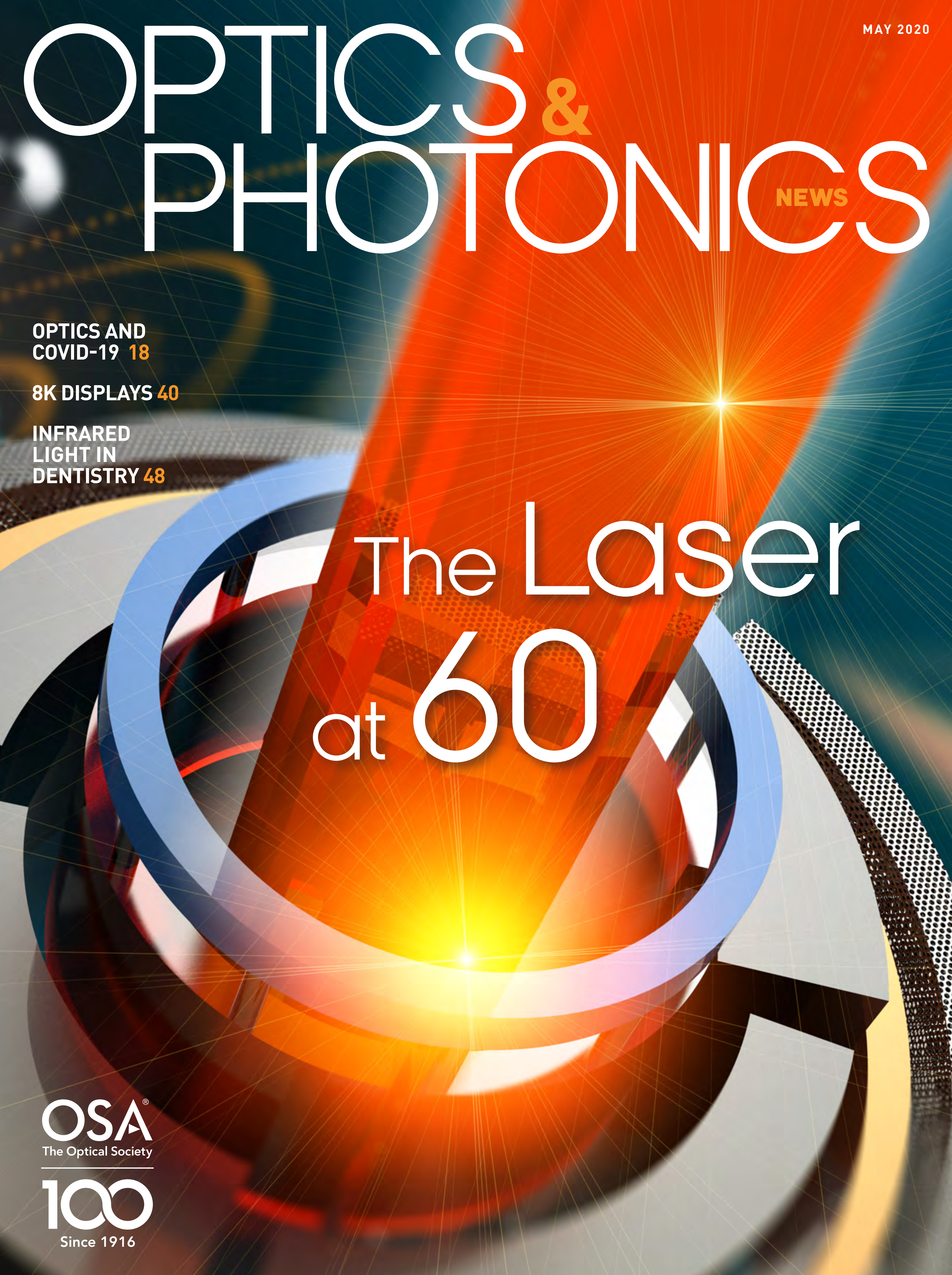
MAY 2020

OPTICS & PHOTONICS NEWS



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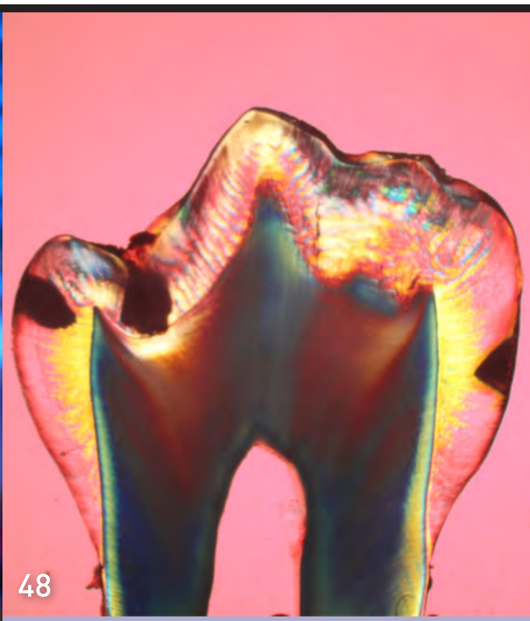
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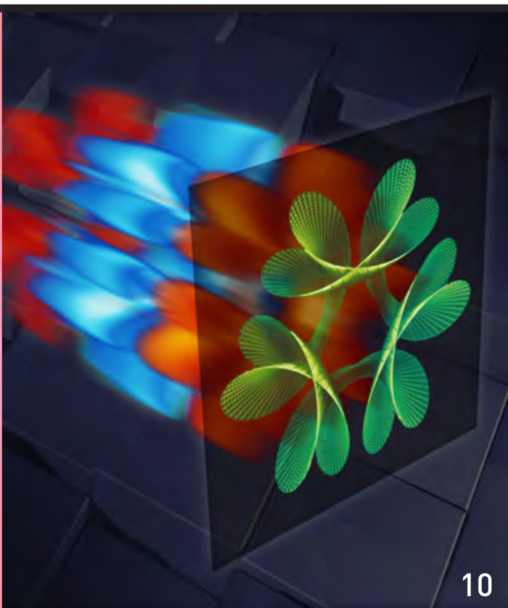
OPN talked with eight OSA Fellows, including Ursula Keller of ETH Zurich, about the laser's 60-year journey.

OPTICS & PHOTONICS NEWS

DEPARTMENTS



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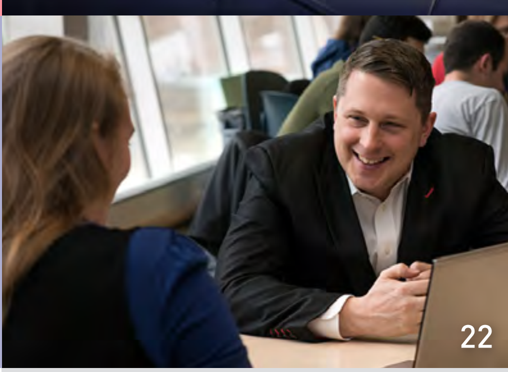

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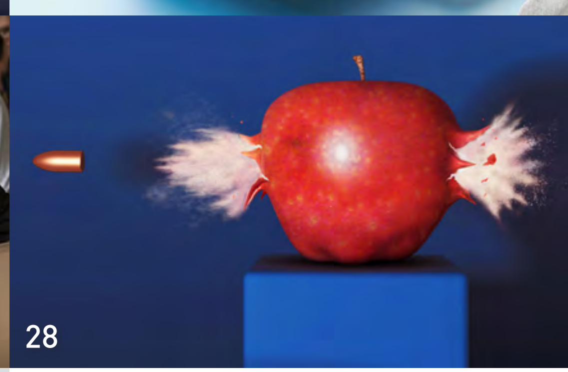

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COVER: On 16 May 1960, the first demonstration of the laser launched an incredible journey for science and technology. To mark the laser's birthday, our cover feature (p. 30) tells a few stories of how lasers are being used six decades later. [Illustration: Getty Images]

President's Message

In the early weeks of the COVID-19 crisis, I drafted my President's Message for the April issue of OPN. There was much uncertainty as to the course the virus would take—and whether my message would be relevant when published. And now, a month further along, I can't predict what life will be like for us in May any more than I could have foreseen in April.

With much of the world under stay-at-home orders, people everywhere are making a valiant effort to cope with our new normal: embracing videoconferencing, communicating from six feet away, hand-and surface-washing as never before—fundamentally changing how we interact with each other. As we adjust, OSA is focused on adapting alongside its community and leveraging our technology for timely solutions. As 2009 OSA President Thomas Baer of Stanford University and Christina Baer of the University of Massachusetts Medical School, USA, write on p. 18, many technologies used in fighting the virus—ranging from gene sequencing, diagnostics and UV sterilization to telemedicine and videoconferencing—have been enabled or improved through advances in optics and photonics.

OSA is focused on adapting alongside its community and leveraging our technology for timely solutions.

In March, the OSA team delivered a large-scale, virtual OFC conference that included 11 tracks, three show-floor theaters, live-streaming plenary talks and more. In early April, OSA was scheduled to hold its annual Leadership Conference in Washington, D.C., USA, a key event that brings together volunteer leadership and staff to plan for the organization's future. A virtual meeting, quickly and capably pulled together by our technical team, allowed us to seamlessly carry on with this important work. The outcomes include a coordinated effort across all divisions of OSA to provide free, virtual programming available at osa.org/WeAreOn for the next few months, and virtual conferences, including CLEO. Please join us in the celebration of the 60th anniversary of the laser this month.

In all of these efforts, we benefited from the findings of the Digital Rapid Action Committee spearheaded by 2019 OSA President Ursula Gibson.

As we look ahead to the now-annual International Day of Light on 16 May, we find ourselves similarly adapting to a new reality in celebrating this milestone. This celebration usually consists of a worldwide network of grassroots, in-person events. This year, however, we will celebrate by using online channels to share our stories of the importance of light science and technology in improving lives.

While I know better than to make any predictions for May, I can and do hope that the resilience of our professional community, friends, and families—and so many who offer their essential services selflessly—will have helped us turn a corner in resolving this pandemic. Although we're together in spirit more than ever before, I look forward to the time we can all connect again in-person and (unmasked!) face-to-face. Until then, please stay safe and healthy.

—Stephen D. Fantone,
OSA President

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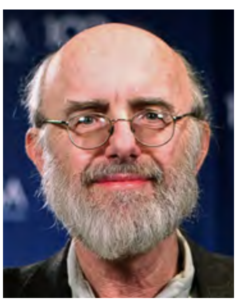
OPTICS & PHOTONICS NEWS®

OPN® MAGAZINE

Contributors

The Laser at 60

In May 1960, Theodore Maiman [pictured] successfully fired the world's first laser. To celebrate the 60th anniversary of that event, OPN's senior editor **Stewart Wills** talked with eight OSA Fellows active in laser research and industry today about about the device's enduring imipact. "Over and over in my conversations with these researchers, they stressed the amazing leaps that laser technology has made in the six decades since Maiman's original ruby laser demonstration," Wills says. "Clearly, the laser is no longer 'a solution looking for a problem'; it's become a linchpin of science and industry."



Television Goes 8K

OSA Fellow **Jeff Hecht** explores some of the latest developments in television displays. "I was surprised how fast LCD displays advanced once their cost and performance made them practical for television, and the digital HDTV standard was adopted. It's a remarkable contrast to the old analog standards for color television broadcasting that were used for over half a century!" Hecht expects "HDR and 8K to be widely adopted as their prices come down. Higher resolution screens and cameras won't offer a big advance for the human eye, but they are likely to be used in niche applications."

Detecting Dental Decay with Infrared Light

Daniel Fried, University of California, San Francisco, USA, sheds some light on "new optical tools that can differentiate between active and arrested lesions," or dental cavities. When asked about an area to watch for growth in the near future, Fried noted that he is "disappointed that there are [not yet] approved OCT systems available to dentists after more than 20 years of research," but said that "as more and more dentists are exposed to this technology and are excited by its capabilities, we are finally getting very close to the introduction of clinical dental OCT systems."

The Expanding Laser

In the 10 years since its special issue celebrating the laser's 50th anniversary (**www.osa-opn.org/issues/May_2010**), laser science has continued to rapidly grow and branch into new areas; while some of these developments were predicted, others were not. To see how far the field has come in just a decade, check out some of the content in that 50th-anniversary issue, including a historical feature on the laser's development, an interview in which 2018 Nobel Laureate and OSA Fellow Gérard Mourou shared his vision for the evolution of the laser over the next 50 years, and a short history of laser light shows.

W.E. Engler (left) and M. Garfinkel with the first diode laser. Courtesy of General Electric

tweeted

@NASALaserComm (NASA Laser Communications)

Big news on #science and #Artemis! NASA just selected the first science instruments for Gateway, our planned lunar-orbiting outpost. Optical communications might just carry their data to Earth from Gateway over infrared lasers.

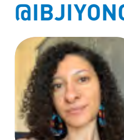
@tomwarren (Tom Warren)

50,000 Microsoft employees are currently replying all to a company-wide email. It's not just your own workplace that grapples with the reply all feature

@ElinorHortle (Dr Elinor Hortle)

In an excellent turn of the events, my chef brother-in-law has moved in with us during #StayHomeAustralia. I have since learned that "did we just make a non-Newtonian fluid?" is the wrong question to ask someone who's trying to teach you to make mac&cheese.

@IBJIYONGI (Chanda #COLA4ALL Prescod-Weinstein)



I have often felt like I didn't belong in science because I wasn't competitive enough. But the idea that competition has any kind of relationship to knowing how the universe works is a human projection. It has nothing to do with the correct Lagrangian for dark matter.

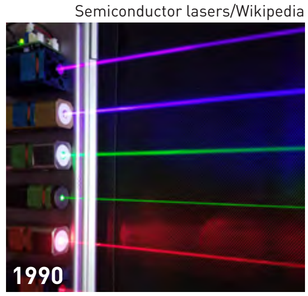

Think Precise

30, 20, and 10 Years Ago in OPN

"A blue semiconductor diode laser has been sought for many years, but the fabrication of *p-n* junctions in semiconductor materials capable of emitting blue light has proven to be a very difficult technical challenge ... Developing compact blue lasers has depended on finding combinations of lasers and nonlinear materials compatible for upconversion and on finding configurations that permit an efficient interaction. So far, the lasers available have been limited to GaAlAs laser diodes at wavelengths in the 700 to 900 nm range and to solid-state lasers that could be pumped by these laser diodes."

"Compact blue laser devices," *Optics & Photonics News*, May 1990, p. 10

Semiconductor lasers/Wikipedia



"A survey of the early literature on tunable lasers incorporating a single prism or isosceles multiple-prism arrays does not yield citations to *Opticks*. In retrospect, however, it was Newton who first hinted at the use of a single prism as a beam expander, introduced multiple-prism sequences, and applied these arrays to control dispersion, as they would later be applied in early tunable lasers. In other words, as far as these initial developments are concerned, Newton's *Opticks* constitutes at least the cultural precursor to these aspects of laser research."

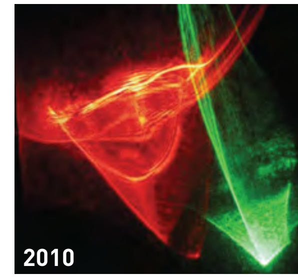
"Newton, prisms, and the 'Opticks' of tunable lasers," *Optics & Photonics News*, May 2000, p. 24

Newton using prism/Getty Images

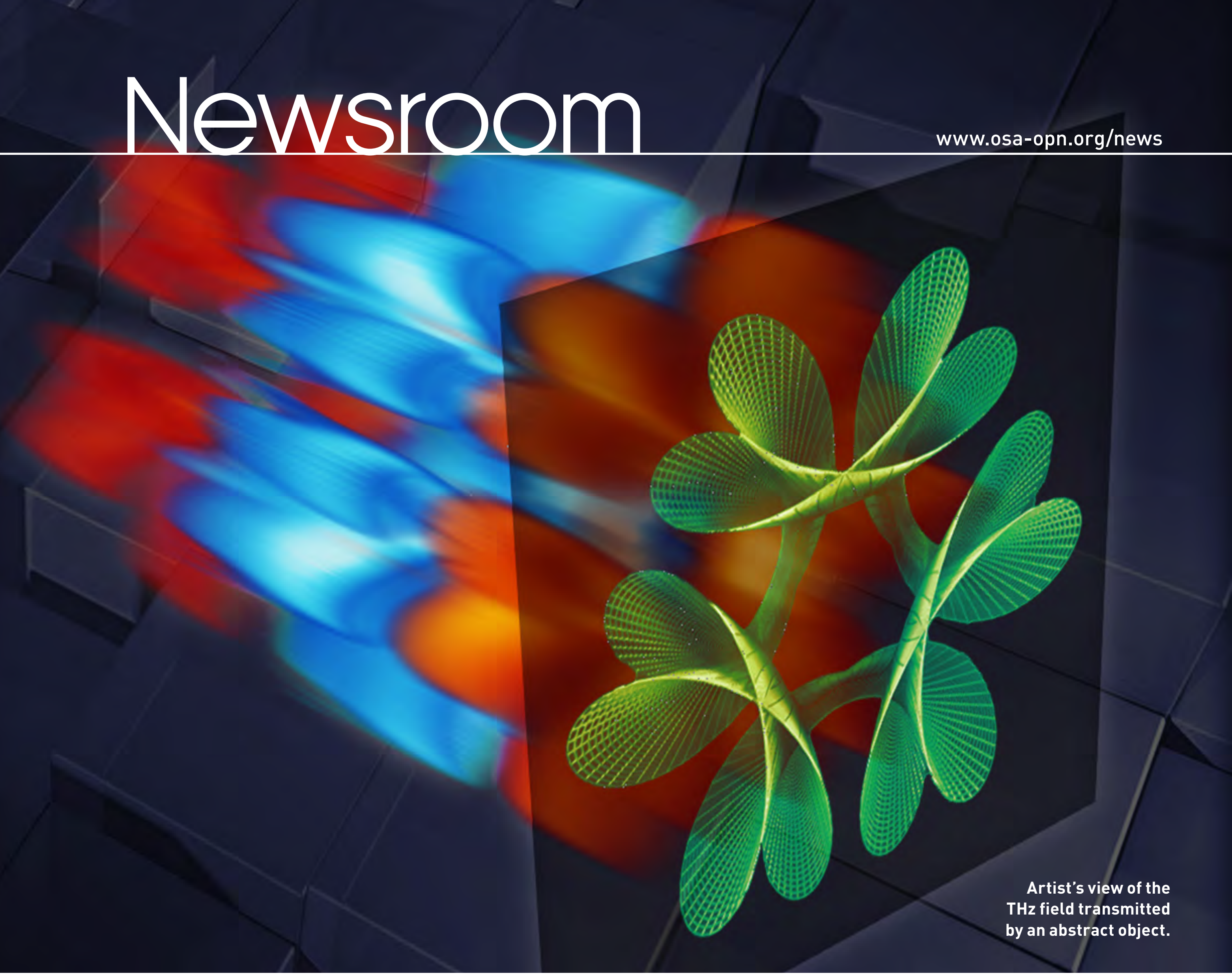
"As part of Caltech's celebration of the first moon landing in 1969, [Elsa] Garmire designed a laser light 'wall' that people could walk through. In another experiment, she and her friends hauled an argon laser all the way to the top of the campus library and staged a light show ... [I]n January 1973 [Ivan] Dryer formed a company called Laser Images Inc., with Garmire as president. The company provided some laser effects for a rock-music documentary called Medicine Ball Caravan, as well as some live concerts by Alice Cooper and a building's grand opening."

"A short history of laser light shows," *Optics & Photonics News*, May 2010, p. 42

"Lumia" effects for Laserium/Elsa Garmire



Please direct all correspondence to the Editor, *Optics & Photonics News*, opn@osa.org.



Artist's view of the THz field transmitted by an abstract object.

University of Sussex

NONLINEAR OPTICS

Hyperspectral Terahertz Microscopy

Nonlinear ghost-imaging setup could enable terahertz cameras for security and biomedicine

U.K. researchers have unveiled a prototype camera that performs hyperspectral imaging in the terahertz (THz) band, using nonlinear "ghost" imaging (Optica, doi: 10.1364/OPTICA.381035). The device can reportedly capture THz field details at subwavelength scales.

As non-ionizing radiation, THz waves can penetrate many materials without harming them, and can return information on structure and composition even from fragile living materials. THz time-domain spectroscopy (TDS) has emerged as a powerful tool for getting at the precise internal chemical and physical characteristics of samples.

For commercial applications, though, THz imaging has posed challenges. One possible solution is ghost imaging, in which an object is illuminated by different structured light patterns, and the transmitted or reflected light is captured by a single-pixel bucket photodetector, allowing an image to be computationally reconstructed.

Combining ghost imaging with terahertz TDS should allow full-field analysis (intensity and phase) with a simple detector setup. But the necessary structured light patterns are difficult to create in the THz realm. In the new work, instead of trying to create structured THz light directly, the team created it using a spatial light modulator in the optical domain, and then converted into THz structured light using a nonlinear crystal. —*Stewart Wills*

www.osa-opn.org/news/hyperspectral-thz-microscopy

"Filming" a Quantum Measurement

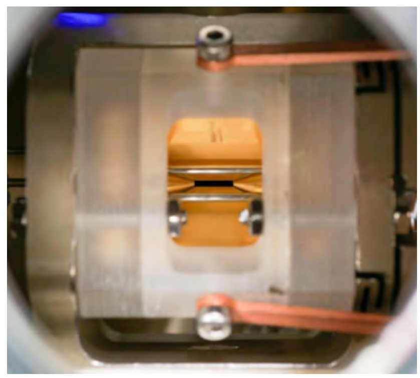
Experiment sheds light on how coherence between quantum states evolves during measurement

Measuring a quantum system will change it, but how does such a measurement proceed in time? A team has now provided some insight, by "filming" a quantum measurement in progress (Phys. Rev. Lett., doi: 10.1103/PhysRevLett.124.080401).

A key idea of quantum mechanics is that a quantum state constitutes a superposition of multiple wave functions describing possible solutions. A measurement causes the wave function to "collapse" into a single solution. Yet, Gerhard Lüders' theory from 1950 holds that superpositions involving degenerate eigenstates (characteristic states) not involved with the quantum measurement could survive it. Thus some quantum coherence could be preserved across a sequence of ideal measurements.

To find such ideal processes in nature, the researchers designed an experiment to track the evolution of a natural "Lüders process": measurements of fluorescence of an $^{88}Sr^{+}$ ion, confined in an RF trap. Specifically, they looked at the coupling of the trapped ion to the environment of the emitted fluorescent photon.

After trapping the ion, the researchers used a combination of magnetic fields and a 674-nm laser to tickle the ion into a so-called qutrit—a superposition of three electronic states, $|0\rangle$, $|1\rangle$ and $|2\rangle$. Next, they used a 422-nm laser to drive the transition of one of those states, $|0\rangle$, to a



F. Pokorny et al.

short-lived excited level, $|e\rangle$, which would emit a photon into the environment upon relaxation. Using quantum process tomography, they took "snapshots" of the nine possible superposed states involving $|0\rangle$, $|1\rangle$ and $|2\rangle$, to see how they evolved during the fluorescence detection.

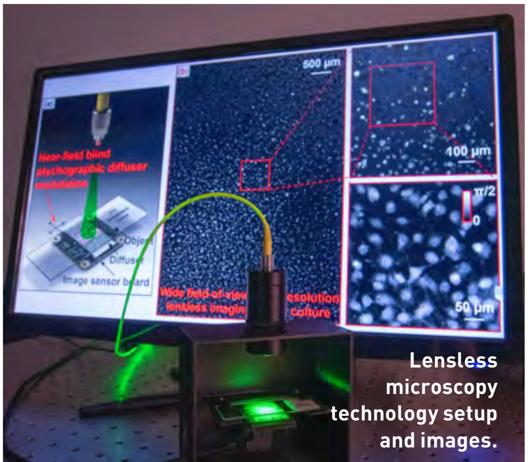
In principle, because only $|0\rangle$ participates in the fluorescence process, the coherences between $|1\rangle$ and $|2\rangle$ should be unaffected by the measurement, while coherences involving $|0\rangle$ and $|1\rangle$ or $|0\rangle$ and $|2\rangle$ should decay across a non-instantaneous but still very brief (microsecond-scale) time. The experiments showed precisely that pattern.

The work both sheds light on the nature of quantum measurement, and could offer insights useful in further development of trapped-ion-based quantum computers.

—Stewart Wills

www.osa-opn.org/news/measurement

The team's experiment showed agreement with the model of an ideal quantum measurement with an average fidelity of **94%**.



Lensless microscopy technology setup and images.

Sean Flynn, UConn Photo

MICROSCOPY

Lensless Imaging

A team has developed a lensless on-chip microscope that delivers both a broad and detailed glimpse of tissue samples and other biological specimens (Lab Chip, doi: 10.1039/C9LC01027K).

Instead of a lens, the ptychographic microscope uses a randomly moving diffuser positioned 1 mm above the sample. The ultra-high Fresnel number of 50,000 allows the system to record the position of the diffuser directly from the raw images.

The system employs ptychography, a computational method for deriving images from interference patterns generated from a function moving across the field of view. It has been used to boost the resolution limit of electron microscopes, but the technique also works with visible and shorter wavelengths of light.

The researchers created a diffuser by sticking 1-µm-wide polystyrene beads onto a microscope slide cover slip, placing it 1 mm away from the target. They illuminated the target with a 532-nm laser diode. Microcontrollers moved the diffuser randomly in the *x-y* plane. The computational phase-retrieval process that generated the images from the raw data converged within two to three iterations of the algorithm. *—Pat Daukantas*

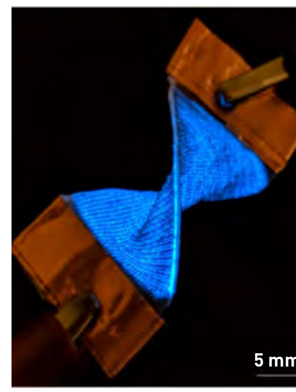
www.osa-opn.org/news/lensless-on-chip

WEARABLES

Stretchy Light-Emitting Textiles

A Canadian research team reports a fabrication technique for light-emitting textiles that deposits metal directly on individual fibers of an ultrasheer fabric (Matter, doi: 10.1016/j.matt.2020.01.017). The method produces a wearable, conductive and highly stretchable electronic textile.

More often than not, today's smart clothing is made by simply stitching electronic components into the fabric. But having stiff optical fibers running through a garment is less than ideal.



Y. Wu et al., Matter 2, 1 (2020)

To try a different approach, the team started with an ultrasheer knitted fabric made of nylon and spandex—pantyhose. They used electroless nickel-immersion gold metallization, a solution-based technique used in printed-circuit-board fabrication, to deposit a gold metal film on the surface of the fibers.

Scanning electron microscopy confirmed that both the nylon and spandex fibers had an approximately 100-nm-thick uniform gold coating. The material retained its softness, stretchiness and transparency.

The gold-coated ultrasheer fabric exhibited an average sheet resistance of 3.6 ohms per square, which is slightly higher than the sheet resistance of a flat gold film of similar thickness. The textile's conductivity remained stable throughout durability testing, including 10 simulated laundry cycles.

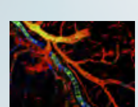
Lastly, the team made patterned e-textile electrodes in different shapes. *—Meeri Kim*

www.osa-opn.org/news/e-textile

In the Spotlight ...

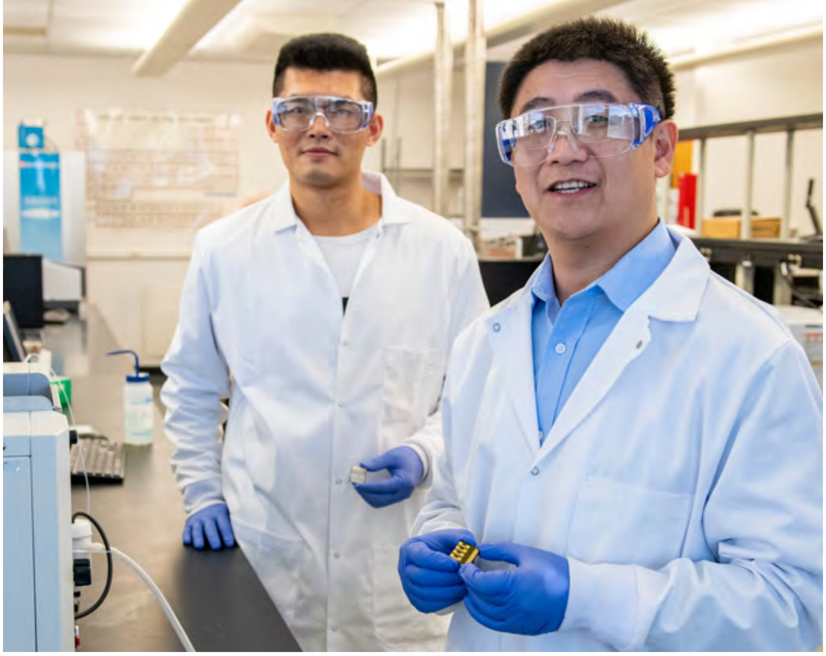
Here is some interesting research recently highlighted in OSA Publishing's *Spotlight on Optics*:

Igor Aharonovich looks at an *Optical Materials Express* paper that reports that **defects in cubic boron nitride (cBN), a cubic polymorph of boron nitride, can act as quantum light sources**.



Robert Zawadzki describes a *Biomedical Optics Express* study that explores the effects of **photobiomodulation on lymphatic drainage and clearance** as an avenue for treating Alzheimer's.

For more on this and other research in the spotlight, check out **www.osapublishing.org/spotlight**.



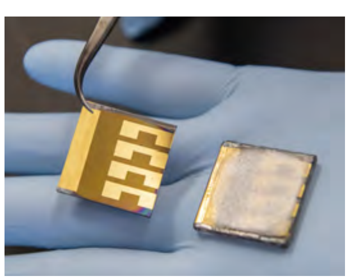
Northern Illinois researchers Xun Li (left) and Tao Xu. Northern Illinois University

PHOTOVOLTAICS

Toward Safer Solar Cells

Researchers believe that they may have found a way to reduce the risk of lead leaching from perovskite solar cells (PSCs) into groundwater or soil—a concern that has stymied commercialization of this otherwise promising and efficient solar technology.

The U.S. team has developed protective lead-absorbing films for the cells that are easy to apply and do not lower efficiency (Nature, doi: 10.1038/s41586-020-2001-x).



Northern Illinois University

A standard PSC stack consists of several layers—a glass substrate with a conductive coating, followed by a semiconductor layer, a perovskite layer, a hole transport material and a metal electrode layer. If the cell becomes submerged, water can seep into the perovskite layer, carrying lead with it as water flows back out.

To protect against this possibility, the team deposited a transparent lead-absorbing film, containing lead-binding phosphonic acid groups, onto the glass side of a standard PSC stack. The metal side, which doesn't need to be transparent, was coated with a less costly polymer film blended with lead-chelating agents. The metal side was also coated with a standard photovoltaic packing film.

During lab tests, the scientists scratched the back of the solar cells with razor blades and hammered the front-side glass until it shattered. Then, they submerged the damaged cells, coated with the protective layers, underwater and measured the coatings' efficacy, finding that the films absorbed more than 96% of lead leakage.

Further experiments confirmed that the protective coatings do not affect cell performance or long-term stability. The team has applied to patent the films. —*Molly Moser*

www.osa-opn.org/news/toward-safer-PSCs

Explore Science VIRTUALLY

The effort to contain COVID-19 has many millions around the globe working and learning from home. Here we look at a few popular sites for virtually exploring our world through science.

NEXT-GEN SCIENTIST

STEM CONNECTION

Weekly online sessions and tutorials led by female role models in STEM fields

stemettes.org

SCIENCE FUN

Learn biology, physics and chemistry through quick and easy experiments

funology.com

EXPERIENCE OPTICS

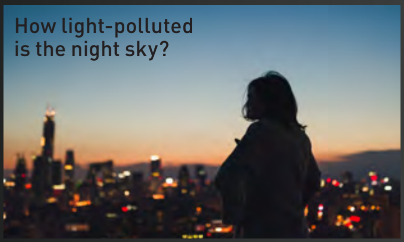
Optics demos and activities to help kids understand the physics of light

optics4kids.org

CITIZEN SCIENTIST

LOCAL & GLOBAL ISSUES

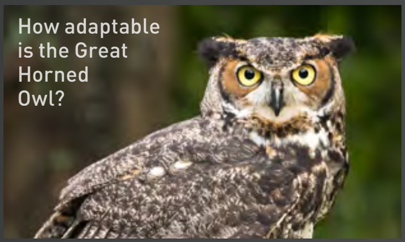
Use science to raise awareness and address local and global issues



scistarter.org

WILDLIFE RESEARCH

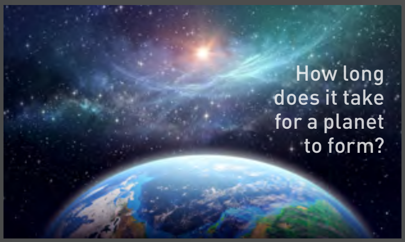
Learn about wildlife research needs through 78 live cam videos



explore.org

EARTH & SPACE STUDIES

Comb through data to assist NASA with scientific discoveries



science.nasa.gov/CitizenScience

SEE THE LIGHT

International
Day of Light
16 May

Celebrate virtually on 16 May!

Join the conversation and share on social media #idl2020 #seethelight

Enjoy webinars, videos and activities celebrating light and photonics osa.org/WeAreOn

Learn the importance of light and light-based technologies lightday.org/SeetheLight

Images: Getty Images / Infographic: Alessia Kirkland

Getty Images

COMMUNITY

Europe, Photonics and COVID-19

In late March, OPN talked with several European scientists for a reading on how the COVID-19 crisis was affecting the photonics community. While the crisis changes daily, the conversations suggested a number of touchpoints for evaluating its possible longer-term impact.

One area to watch is the fate of small- and medium-sized enterprises (SMEs), which form a large share of photonics-related business in both the EU and the U.K. Roberta Ramponi of INF-CNR, Italy, pointed out that such firms may lack the "critical mass" to survive a long crisis, and hoped that governments would provide support to help such firms through.

Yet some photonics areas, she added, will play a key role in fighting the coronavirus (see the Viewpoint article in this issue by Thomas Baer and Christina Baer, p. 18). And still other advances in photonics have underpinned society's ability to adapt through social-distancing and stay-at-home restrictions. The very fact "that we can now talk easily in such distant and remote locations—from our homes—is enabled by photonics," 2018 OSA President Ian Walmsely told OPN on a videoconference call.

Those capabilities, coupled with the crash course in distance-learning techniques that European educational institutions were forced to take early in the crisis, could have long-term implications for higher ed, in the view of Walmsley and others.

For these and other insights, check out the story online. —*Stewart Wills*

www.osa-opn.org/news/euro-covid

Spain's Evolving Photonic Network

Secpho—a Spanish photonics cluster that brings together companies, technology centers and research groups to collaborate and advance light science—recently celebrated its 10th anniversary.

In the past decade, Secpho's scope has expanded "beyond networking," explains cluster manager Sergio Sáez. "All of our actions are aimed at connecting the technologies of our members with all kinds of sectors in the Spanish economy."

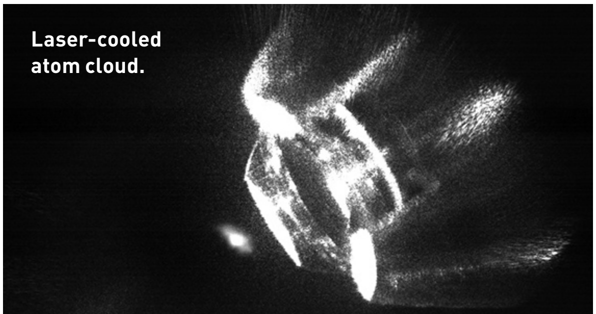
The cluster accomplishes this in many ways. It hosts workshops where members connect with companies of a specific sector—such as agriculture, automotive or steel—to try and define the technological challenges facing the field. Then, it creates working groups to design collaborative projects and develop innovative solutions to meet those challenges.

Secpho also offers digital resources, the convenience of which allow the cluster to rally its membership and respond quickly to major global challenges. One example was a March webinar on applying "deep tech" and photonic solutions to the global COVID-19 pandemic.

Secpho has connected with more than 25 different industrial sectors and participated in 11 Europe-wide initiatives. "We have a lot of talent in Spain," says Sáez, "and I believe our photonics ecosystem will continue to grow." —*Molly Moser*

www.osa-opn.org/news/secpho-10th

University of Otago



Laser-cooled atom cloud.

OPTICAL TWEEZERS

Atoms Go Colliding Three by Three

Physicists in New Zealand have for the first time assembled groups of three atoms one by one. Using optical tweezers to bring individual cold atoms together and then set them colliding, they were able to tell how many atoms were lost when the trio subsequently broke up (Phys. Rev. Lett., doi: 10.1103/PhysRevLett.124.073401).

Optical tweezers have allowed researchers to isolate and manipulate single atoms to better understand atomic systems from the bottom up. However, three-body recombination—which happens when three atoms get close enough to one another that two of them form a molecule and the binding energy released is enough to eject all three from the system—is difficult to model in detail.

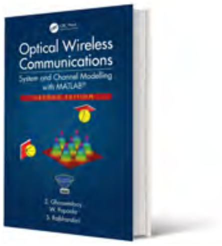
To plug this gap, the researchers isolated three atoms using three separate optical tweezers, spaced about 4 μm apart. Using an acoustic-optic modulator, they then brought the centers of the three tweezers to within less than a micrometer of each other. Held in a merged, single beam, the atoms' temperature was just above 0 K. They ramped up the beam power adiabatically, to squeeze the atoms closer together and speed up collision while barely raising the temperature. Using fluorescence, they established how many particles were left in the trap after collision.

They found that the loss of all three atoms happened less than theory predicts. *—Edwin Cartlidge*

www.osa-opn.org/news/three-atoms-collide

BOOK REVIEWS

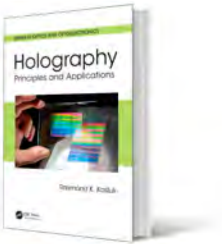
Optical Wireless Communications



Z. Ghassemlooy, W. Popoola and S. Rajbhandari, CRC Press, 2019

The book starts with the very basics of device and channel issues, and moves on to modulation technologies for both indoor and outdoor applications. In terms of updates, a new final chapter on relay-assisted free-space optics has been added in this edition. As in the earlier edition, the book includes mathematical formulas, charts (some in color), and extensive, clearly updated references at the end of each chapter. *—Bogdan Hoanca*

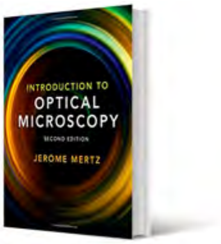
Holography: Principles and Applications



R.K. Kostuk, CRC Press, 2019

The author has written a practical and accessible reference on design-oriented and theoretical aspects of holography. This useful text should be of interest to graduate students in physics, optics and engineering as well as researchers involved with applications of holography. Beyond the physical and geometrical optics for holography, the author includes practical image analysis and Huygens-Fresnel as well as Fraunhofer diffraction analysis. *—Axel Mainzer Koenig*

Introduction to Optical Microscopy



J. Mertz, Cambridge University Press, 2019

This excellent, perspicuous textbook, based on Fourier and statistical optics, details the derivations of the equations used to mathematize the physics of optical microscopy. Mertz begins with the electric field and clearly, step by step, develops the interactions with the microscope and the specimen in its propagation to the detector. He then relaxes the constraints to yield approximations that can be analytically solved for specific cases, and carefully states the assumptions and their limitations. *—Barry R. Masters*

Optical Inspection of Microsystems

W. Osten (Ed.), CRC Press, 2019

This book is the second edition of a seminal reference work on the topic of optical inspection methods for microsystems that was first published in 2007. In 17 chapters, the authors detail the working principles of various optical methods for examining the surface quality of microsystems, as well as the advantages, drawbacks and applications of each method. The target audience is any producer of microsystems, hence primarily industrial users and applied research labs. *—Marko Spasenović*

Bogdan Hoanca, University of Alaska Anchorage, USA. Axel Mainzer Koenig, CEO, Mainzer Koenig Research Associates, USA. Barry R. Masters, Fellow of AAAS, OSA and SPIE. Marko Spasenović, Institute of Chemistry, Technology and Metallurgy, Serbia.

Patricia Daukantas, Edwin Cartlidge and Meeri Kim are freelance science writers. Molly Moser is OPN's associate editor. Stewart Wills is OPN's senior editor. Alessia Kirkland is OPN's creative director.

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VIEWPOINT

Optics and the COVID-19 Pandemic

Optics and photonics technologies are helping to combat coronavirus on multiple fronts: from prevention and detection to disease monitoring and disinfection.

Thomas M. Baer and Christina E. Baer

As the COVID-19 pandemic spreads across the world, patients, technicians and scientists depend on state-of-the-art molecular-analysis instruments as they fight against SARS-CoV-2, the virus causing this disease. Optics and photonics technologies embedded in these instruments—such as high-quantum-efficiency multi-spectral cameras, visible-light laser diodes and LEDs, infrared bolometer arrays, narrowband optical filters and wideband multispectral optical spectrometers—play an essential part in the story.

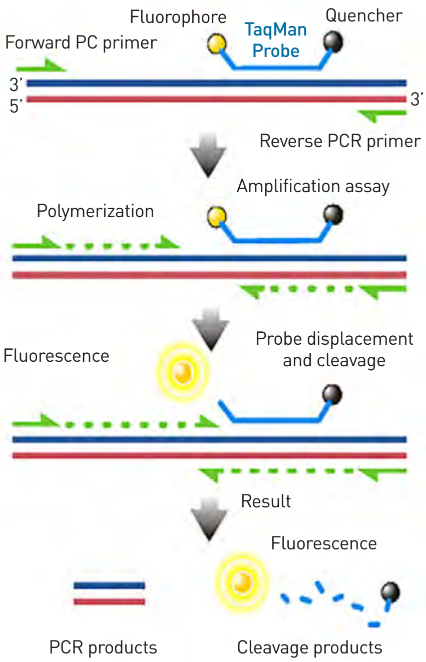
Whether in the hospital or in the lab, optics technologies make possible rapid preliminary screening of potentially infected individuals, more accurate molecular diagnosis, reliable monitoring of disease progression and even, potentially, disinfection of contaminated surfaces. Our community developed these enabling technologies over the past several decades for applications ranging from telecommunications to machine and night vision. Now, they're playing a life-saving role in the battle against SARS-CoV-2.

Safer screening

Early detection of infected patients—one of the primary challenges of the COVID-19 pandemic—is complicated

As the COVID-19 pandemic spreads, patients, technicians and scientists depend on state-of-the-art molecular-analysis instruments as they fight against SARS-CoV-2.

by the wide variability in the disease's symptoms. Monitoring for an increase in body temperature is the most commonly used preliminary screen. Under normal circumstances, direct body-cavity temperature measurements are the most accurate way to monitor a fever; however, given the pathogenicity of SARS-CoV-2, remote, non-contact options that employ infrared imaging cameras to simultaneously image and measure groups of individuals provide a significant safety advantage.



In "TaqMan" real-time polymerase chain reaction, a nucleic-acid probe molecule, tagged with a fluorescent molecule and an accompanying quencher, attaches to the stretch of DNA or RNA being copied. With each round of amplification, the fluorescent molecule is released into the buffer solution and separated from the quencher, allowing the amplification of the targeted genetic sequence—such as one from SARS-CoV-2—to be detected via fluorescence in real time.
Wikimedia Commons

Many clinicians now rely on infrared-based thermometers for measuring forehead temperature. These imaging and spot-measurement thermometric devices provide medical personnel with a safer and useful non-contact patient screen. These thermometers are based on single detectors or arrays of MEMS-based microbolometers or semiconductor diode detectors—thermal sensors that are sensitive in the far-infrared spectral region (8 to 14 µm) and detect changes in the blackbody radiation intensities in persons with above-normal body temperatures.

Molecular diagnosis

If a patient presents with a fever or other symptoms typical of viral infection (sore throat, dry cough, muscle aches and fatigue), the next step is a molecular diagnostic test. This screen, based on a technique called real-time reverse transcription polymerase chain reaction (RT-PCR), uses sensitive spectroscopic methods to detect extremely small quantities of viral genetic material from a patient's nasal or throat swab. And once again, optical technology is an essential component for disease detection.

The diagnostic procedure requires significant sample processing, beginning with a specimen collected from a patient. Real-time RT-PCR works

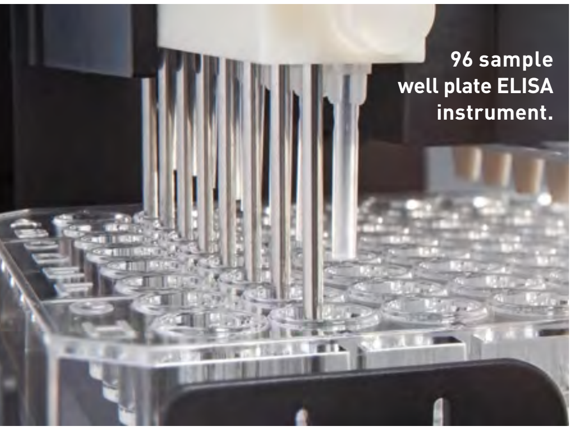
Cepheid doctor's office RT-PCR instrument.
Cepheid

by copying specific nucleic acid sequences within that sample, using probes—nucleic-acid primers—that selectively bind very specifically to the RNA sequences present in the SARS-CoV-2 virus. The probes are tagged with molecules of fluorescent dye.

Enzymes are then used to copy the nucleic-acid sequences bound to the probes. The sample is thermally cycled roughly 40 times between 37 °C and 95 °C. If the target nucleic-acid sequences are present, they are amplified twofold with each cycle.

It is optical technology that puts the "real time" in RT-PCR. As the amplification enzymes create the duplicate copies, the fluorescent molecules are released into the buffer solution. The overall fluorescence is measured in real time after each cycle, increasing as the number of amplicons increases for positive samples. By measuring the intensity buildup during the thermal cycling, the virus is detected and the amount of virus present (the viral load) can be estimated.

Real-time RT-PCR instruments employ narrowband visible laser



96 sample well plate ELISA instrument.

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Optical instruments are also used to test if a person has been exposed to SARS-CoV-2 virus and has developed an immune response.

diodes or LEDs as excitation sources and semiconductor diodes or photomultipliers with narrow band-pass optical filters for detection. These instruments are fully automated and can typically process 96 or 384 samples in parallel in less than an hour.

Real-time RT-PCR is one of the most sensitive and specific molecular-analysis techniques available today. This assay is crucial for tracking and controlling the spread of COVID-19. However, the overall sensitivity of the method may be limited by the efficiency of the sample collection and preparation process. The amount of virus present in the sampled tissue, which varies between individuals and as the disease progresses in each patient, may also be a limiting factor.

The false-negative rate of this approach is currently estimated at roughly 30%. Repeated testing can reduce this admittedly significant percentage, which is why many hospitals require two or three sequential negative real-time RT-PCR tests after a patient has recovered before that patient is classified as non-infectious.

Tracking disease progression

In addition to molecular diagnostics, imaging of the lungs of COVID-19 patients has also proved very sensitive for detecting SARS-CoV-2 infection using high-resolution computed tomography (CT) scans. Clinicians look for signs of lung damage as evidenced by "ground-glass" patterns in the lung tissue or fluid accumulation as signatures of pneumonia. Clinics in China have reported that this approach can detect a significant number of infected individuals that have negative RT-PCR readings—only, however, later in disease progression, once lung damage manifests.

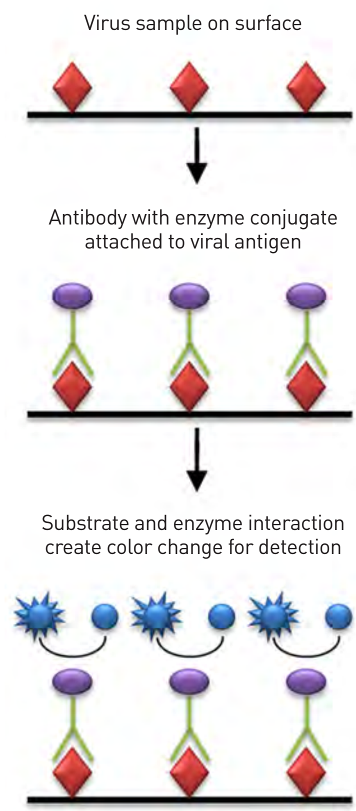
If a patient is diagnosed with COVID-19, disease progression and respiratory function are determined using an oxygen-saturation meter, which measures the percentage of oxygenated hemoglobin in blood. As the disease progresses, breathing can become difficult, causing a reduction in oxygenated hemoglobin—if levels dip below certain thresholds, then supplementary oxygen or a ventilator may be warranted.

Oxygen-saturation devices use LEDs emitting at two different wavelengths, typically around 665 nm and 894 nm. The oxygen-saturation percentage is measured from the ratio of the absorption at these two wavelengths. These battery-powered devices fit comfortably on a finger or toe, providing real-time measurement of oxygen-saturation levels.

Measuring immunity: ELISA

Optical instruments are also used to test whether a person has been exposed to SARS-CoV-2 virus and has developed an immune response. These instruments—which can be automated to analyze hundreds to thousands of samples per day—use a technique called an Enzyme-Linked Immunosorbent Assay (ELISA) to measure the presence of antibodies specific to the SARS-CoV-2 virus in a patient's blood-serum sample.

In a typical assay, an antigen found on the virus surface is immobilized on the bottom of a sample well, which is optically transparent. Antibodies in the serum sample are attached to an enzyme (typically horseradish peroxidase) and allowed to incubate on the surface containing the immobilized antigen. Any antibodies specific for the SARS-CoV-2 antigen bind to the target



Schematic of ELISA, which measures the presence of specific antibodies in a COVID-19 patient's sample. The technique relies on a colorimetric change in the sample generated by an enzyme attached to antibodies specific to SARS-CoV-2 virus.

Cavitri/Wikimedia Commons, CC-BY 3.0

and become immobilized on the surface of the optical window. The unbound, nonspecific antibodies are washed off.

A solution containing the enzyme's substrate with a colorimetric indicator is then added to the sample well, and the enzyme linked to the antibody reacts with the substrate, producing a color change in the sample. The enzyme reacts with multiple substrate molecules, thereby amplifying the signal. SARS-CoV-2 antibodies in the blood serum can then be detected and quantified, via multispectral imaging of the sample substrate's fluorescence or absorption indicator.

This approach is used to measure the extent of the virus' spread within a community, even after the pandemic has passed; to measure the duration of an individual's immune response; and to investigate the efficacy of antiviral drug candidates and potential vaccines. Currently, medical workers who have recovered from COVID-19 and have a protective immune response to the virus are being identified using an ELISA. Once immunity is confirmed, these personnel safely resume working with infected patients—a common approach in pandemic medicine.

Toward vaccines and sterilization

Optical devices also form the core technology for the most common high-throughput gene-sequencing instruments. These typically use high-quantum-efficiency, very-high-resolution multispectral cameras to map the sequences of hundreds of millions of target DNA molecules simultaneously and can sequence the complete genome of the SARS-CoV-2 virus in just a few hours. Virus genetic sequences can vary with location, since the SARS-CoV-2 virus occasionally mutates during

Prototype of an LED sterilization system being tested by Bolb, Inc.

Bolb Inc.

its replication phase. Infections in separate geographic regions can be compared, and the origins of infections traced, by comparing the specific mutations in samples taken from patients in different locations.

High-throughput sequencing of the virus genome also can determine the proteins in the virus and identify suitable targets for synthetic vaccines that will safely stimulate immune response. This technology has greatly improved over the past 20 years, largely due to the human genome project, and will be an essential tool for developing effective vaccines and antiviral drugs to combat the COVID-19 pandemic.

Beyond the molecular-biology lab, optics is emerging as a weapon on another vital front: the sterilization of surfaces. Most viruses and bacteria are very sensitive to ultraviolet light, particularly in the UV-C spectral region (200–280 nm), which causes mutations in the RNA that is essential for viral replication. Recently, great progress has been made in the development of UV LEDs that emit in this region. LED arrays emitting hundreds of milliwatts have been developed with lifetimes of over 1000 hours and electrical efficiencies around 10%.

Arrays of these diodes can generate significant UV power levels to potentially decontaminate certain surfaces more efficiently than chemical reagents. Recent lab results indicate that exposure times of about 1 minute were sufficient to kill bacteria and viruses with a 1-W-average-power device located about 1 meter above a contaminated surface. Further testing on the efficacy of UV LEDs for decontaminating surfaces infected with SARS-CoV-2 virus is in progress.

Future needs

As global health faces this novel and deadly threat, laboratories around the world are using technologies developed by the optics and photonics community to help stem the spread and save lives. In the near future, as social distancing begins to slow the spread of COVID-19 disease, medical focus will shift to the early detection and isolation of COVID-19 recurrence in hot spots, which will present new challenges for diagnostic and decontamination technologies. These challenges represent new opportunities for optics and photonics technologies—with their advantages of low cost, high speed, sensitivity and specificity—to make major contributions to global health. OPN

2009 OSA President Thomas M. Baer (tmbaer@stanford.edu) is with Stanford University, USA. Christina E. Baer is with the University of Massachusetts Medical School, USA.

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CONVERSATIONS

Optics and the Electrification Transformation

An optical-sensing entrepreneur shines a light on the role optics will play in the utilities industry as the grid gets smarter.

Entrepreneur **Michael Oshetski**, co-founder and CEO of Micatu Inc., USA, was set to deliver a keynote talk at the OSA Applied Industrial Optics Topical Meeting, originally scheduled from 20 to 22 July 2020. While the in-person meeting has been cancelled, three webinars presented on the same dates will encompass some of its content—including Oshetski's talk, entitled "The Optics of the Electrification Transformation." OPN caught up with him to get his insights on the subject and the opportunities for optics professionals in this changing field.

Q. Micatu specializes in optical sensing for the utilities industry. How did you get into that field?

I was working for a telecom company in 2010, which is when I started seeing a growing trend for the need for better sensing to help integrate renewable energies into the power grid. Micatu's co-founder and I knew that optical sensing technology was going to be the key player to do this for three reasons: the extensibility of optical solutions, the accuracy and precision needed for next-generation sensing, and the need for more insight into the operations state of the power grid.

So, like all good entrepreneurs, we quit our jobs and started working on expanding a full-platform solution company based on our experiences in the optics trade, eventually forming a joint venture with Gridview Optical Solutions. Now, we supply voltage and current optical solutions. What Micatu sensing technology really enables is the understanding of what you're producing when you tie a renewable resource into the grid, and also what problems you're creating.

Q. Is this integration of renewable energy the "electrification transformation" you're referring to?

It's about moving toward distributed energy. In a traditional centralized grid system, you have a power provider, then the power goes to transmission lines, and then it goes to a substation that steps that voltage down. And after that station, maybe it goes to other substations or is distributed to your house.

The way that grids work now is that your house is one of the power plants, because you have solar power on top of it—not to exclude wind and tidal power; these are all factors. So now it's a big circular loop, and the utility companies have to predict when to make power and when to consume power. This requires a lot more intelligence on the grid. That's really where this revolution is taking place—bridging that gap between situational awareness and the new circular topology of the power grid.

We're near full saturation rate where we can't take on more renewable energies without having infrastructure supported—we're racing toward that right now. To be CO_2 neutral or carbon free by a certain time frame will require a quantum leap in technology in all parts of the power grid, from the consumer level up to the big nuclear plant.

Michael Oshetski

> "It's an exciting time to be in the field as we are going toward a decentralized, data-heavy society."
>
> —*Michael Oshetski*

Q. What are the opportunities for optics?

These are exciting times, and I think optics, in particular, solves problems that people don't even know they have and where there appear to be no viable solutions. We should be thinking about how optics plays into this new world of distributed energy because we need robust solutions.

Obviously optical sensing is going to be a large component of this, but it's not just sensing. It's everything—from the consumer level to the actual major power generation on the industrial side—that requires solutions. From software to hardware, to infrastructure to contracting, to planning to design, it's everything. And there's optical solutions for each one of those.

For example, optical-based fiber communications are becoming intertwined with the utilities industry. I'm seeing fiber being embedded into power lines because now utilities are becoming service providers for your internet. It's all interconnected, and it makes sense that we're heading down these paths. This is the next generation, and I think that there are a lot of opportunities for optics companies to be a part of the supply chain or part of these solutions.

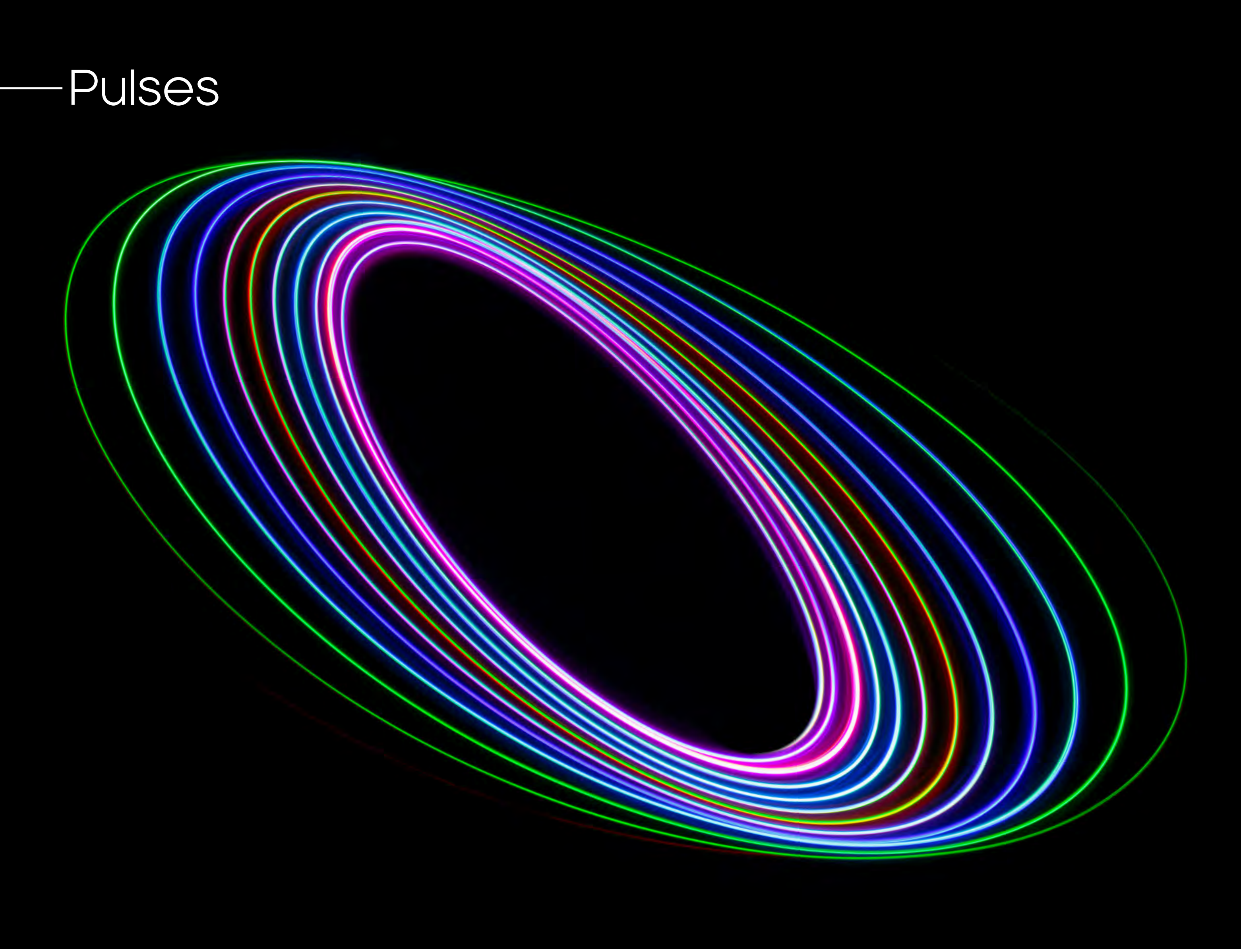
It's all good business and this is how change happens—there has to be a capital driver behind it.

Q. More intelligence behind the grid must mean more data. Are there optical solutions there?

Data will be another big part of the business and building out all the separate parts of how to control all this. We need solutions from data collection, to data processing, moving data and also control. There will be growth in all of these areas.

Another opportunity in optics is not only the fidelity and quality of the data, but the edge processing—because now that you have all this data, what are you going to do with it? And that's where AI plays into this and machine learning. When you consider all of the intelligence behind the data, there's a lot of opportunity for companies now to define what this next-generation grid will look like. That's the next phase of this revolution.

When optics steps in, it changes the way that people live—look at 5G. It's an exciting time to be in the field as we are going toward a decentralized, data-heavy society. OPN



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LIGHT TOUCH

Laser Beam Orbits

Stephen R. Wilk looks at the interesting mathematical truths that explain the elliptical plot of paraxial ray tracing between the mirrors of a laser resonator.

"Nothing can ever replace the effect of just fooling around," as one of my professors once remarked. And it's true. Undirected exploration in the laboratory, or in theory, lets you stumble across ideas and results that you would never otherwise find.

Certainly in my own experience I have stumbled upon odd and interesting results while playing with pen and paper or compass and straightedge. (Doodling with the latter pair, for example, I "discovered" the mathematical relationship, Poncelet's porism. And I was curious about the connection between the legs of a triangle and its hypotenuse before learning about the Pythagorean theorem.)

The mystery of the ellipse

Several years ago, I set up a spreadsheet to perform paraxial ray tracing between the two mirrors of a simple laser resonator, keeping my rays in the axial plane. Such rays could be described by two variables—the ray height at the n^{th} bounce, h_n, and the ray angle after the n^{th} bounce, θ_n. After calculating the successive heights and angles, I could plot them on a coordinate system, with height along the x axis and angle along the y axis.

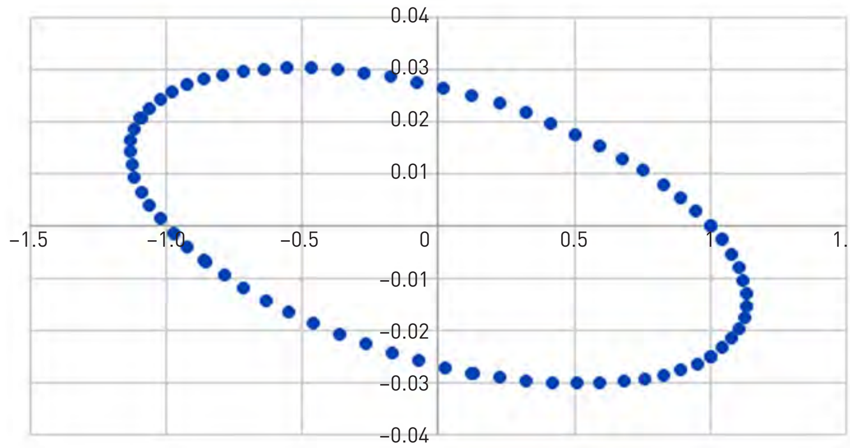
I'm not sure what I expected—some sort of chaotic result, probably. But what I obtained was unexpectedly orderly. No matter what ray height or angle I started with (as long as it was "reasonable" and still paraxial, and as long as the resonator fell into the range of stability), the plot of ray height versus ray angle described an ellipse.

Furthermore, it was a very stable ellipse. If I kept the initial ray angle and height unchanged, but slowly varied the separation of the laser mirrors, *d*, the ellipse remained very nearly constant, having the same major and minor axes and the same tilt of the major axis relative to the horizontal.

Some special cases took a simpler form. If the end mirrors were of identical curvature (*R*) separated by a distance equal to the radius ($d = R$), the result is a confocal resonator. In this case, the ray returned to its original height and angle after four bounces. Plotting the heights and angles described a parallelogram by its corners.

If the mirrors were separated by a distance, $d = R/2$, then the beam returned to its original height and angle after six bounces, and so the plot was a distorted hexagon. This configuration has the focal point of each mirror at the surface of the opposite mirror, and is identical to that of a "mirage" toy. (See OPN, October 2012, p. 23). On a laser stability diagram plot, it lies exactly midway between a confocal and a plane parallel configuration.

This was far more regular than I expected—why should the points always fall in an ellipse? The points, after all, represented a ray height and an angle. It wasn't like the situation with a Herriott cell, which is essentially a laser resonator without gain medium. For a Herriott cell, a beam injected as a skew ray will execute an elliptical pattern with successive bounces on either end mirror. But in my case, I was plotting a location against an angle.



Paraxial ray angle (vertical) plotted against paraxial ray height (horizontal) for $d = 35$, $R = 80$.

No matter what ray height or angle I started with, the plot of ray height versus ray angle described an ellipse.

Algebra to the rescue

Eventually, I realized that the answer was right in front of me. The same mathematics that defined the laser stability diagram also dictated the form of my ellipse.

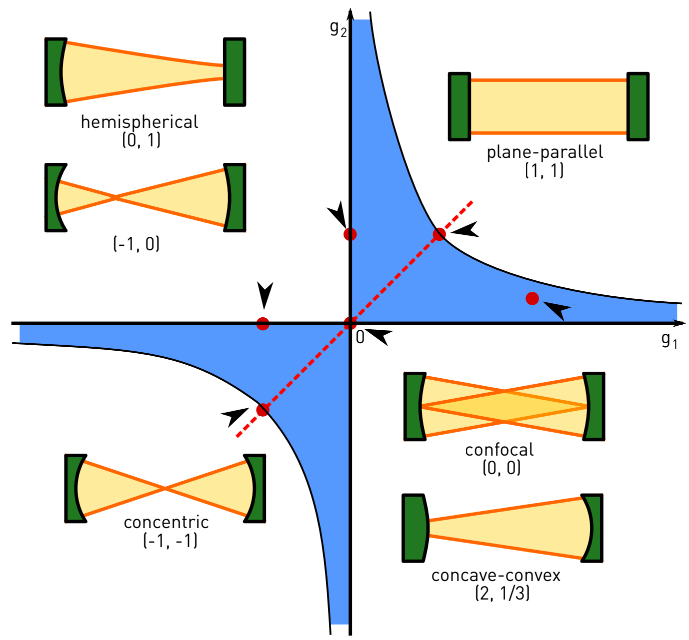
The formalism was originally laid out in a classic 1966 *Applied Optics* paper by Herwig Kogelnik and Tingye Li, which is freely available at the OSA Publishing website (https://doi.org/10.1364/AO.5.001550), and I encourage readers to have a look at the clean, elegant mathematics they lay out. Kogelnik and Li show that a paraxial ray in a simple optical system can be characterized by a vector with two elements—"its distance from the optic axis" (my ray height h_n), and "its angle or slope … with respect to that axis" (my ray angle θ_n).

The ray's propagation and interaction in a given system is described by a 2×2 matrix, which Kogelnik and Li call the ray transfer matrix. Propagation through empty space is associated with one matrix, reflection from a surface with optical power has another. These matrices can be multiplied together to give the effective matrix for an entire system, including a single round trip through the resonator.

It turns out that, within a resonator, *n* round trips through the resonator are described by raising the 2×2 ray transfer matrix to the n^{th} power. That operation, in turn, can be evaluated, through a linear-algebra relationship called Sylvester's theorem, by multiplying the elements of the transfer matrix by a series of trigonometric relationships, as shown in Kogelnik and Li's paper. This, ultimately, is the source of the ellipses I had stumbled upon in my spreadsheet exercise. You can show, through some tedious algebra, that the transfer matrix, with its sines and cosines, can be rearranged to give the characteristic formula for an ellipse, regardless of the initial slope and height of the ray.

Kogelnik and Li also use these relationships to derive the stability condition for the laser resonator:

$$0 < (1 - d/R_1)(1 - d/R_2) < 1$$



Resonator stability diagram. Stable resonator systems lie in the shaded regions.

In this formula, we allow the curvature radius, *R*, of the two end mirror radii to differ, which is the familiar stability relationship for a resonator. As long as the product of the terms in parentheses lies between the values of zero and one, the cavity is stable, and the ray will not walk off the axis. It will continually return to it.

Visualizing laser designs

All of this is clear in the mathematics that Kogelnik and Li lay out. But plotting angle versus ray height, as I had done via my spreadsheet, provides a new dimension to the relationship—now we can see *why* the resonator is stable. The plot of ray height versus angle must only produce points that lie on that ellipse. This provides a more intuitive feel for the rays within the resonator, just as making sigma circles and pi circles allows us to visualize laser parameters—giving us an intuitive feel for the way the beam waist varies with mirror radii and separation.

What if we leave the region of paraxial optics by tracing the ray using real heights, sags and angles? My expectation was that the plot would depart from the simple elliptical trajectory and start following different paths, entering the realm of chaos with a pattern that varied from "orbit" to "orbit," and would look more like an interlocking tracing of spiraling designs. But I was surprised to find that the deviations from the paraxial results were extremely small, so that the paraxial trace was, to the eye, identical with a meridional ray trace.

I don't see any significant use for this interesting ray trace artifact. Certainly, it is easy enough to calculate beam parameters directly from the relevant formulae, or to simply rely upon the calculations made on our behalf by any of a number of ray-tracing or laser-beam software packages. But the mental picture this scheme provides might prove useful as a first step in visualizing laser designs. OPN

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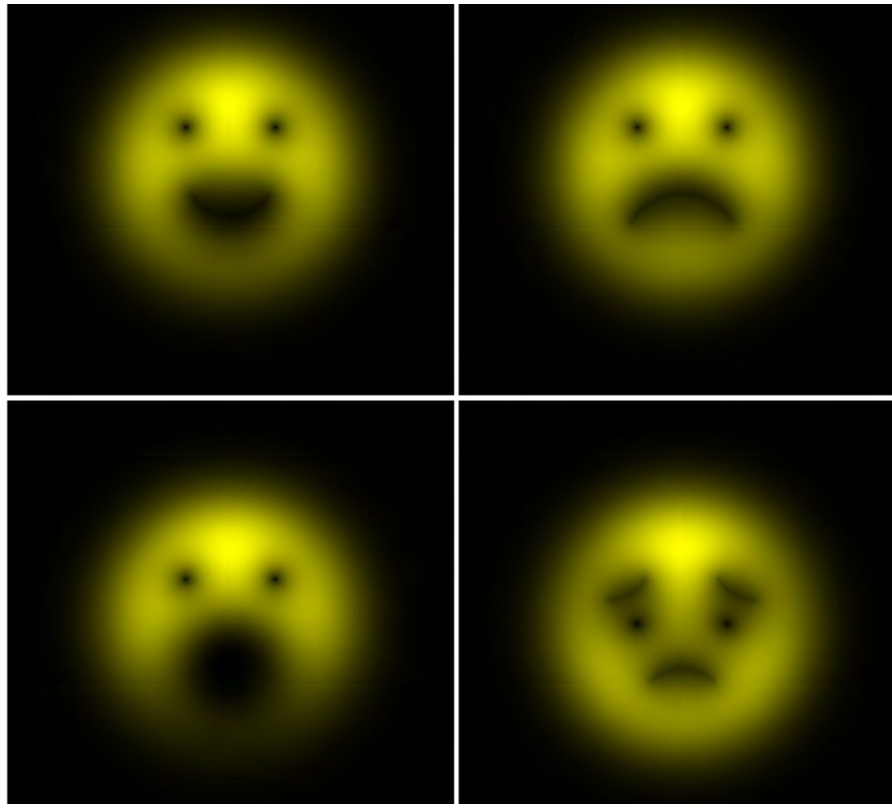


Different emojis formed by embedding fractional optical vortices in laser or Gaussian beams theoretically. Optical vortices are phase singularities in the light field, which create the dark holes.

— Pravin Vaity, IMTEK, Germany

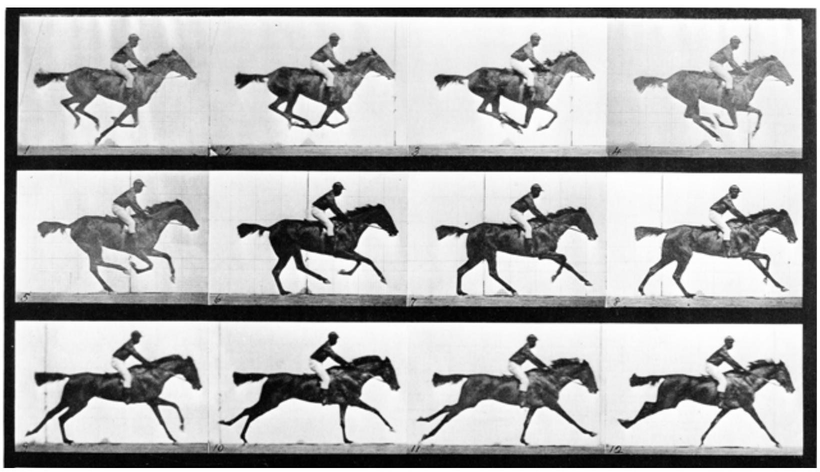
UV-driven high-harmonic generation occurs in Kr gas within a vertical, end-sealed glass capillary. Bright emission (center) results from the ionized atoms, while colors from the laser fundamental, second-harmonic, and green pump lasers in the lab reflect within the vacuum chamber.

—Robert A. Kaindl, Lawrence Berkeley National Lab

then

Early Ultrafast Photography

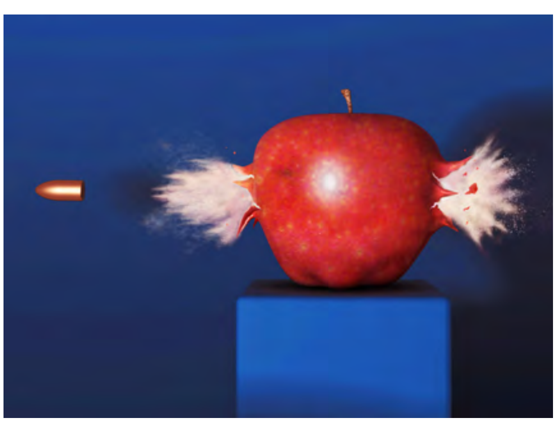
Since the dawn of the medium, photographers have been fascinated by the possibilities of capturing rapid motion in one frozen frame.



Eadweard Muybridge/Library of Congress

1878: Off to the races

Photography was a relatively new phenomenon in the 1870s, and multisecond shutter speeds were the norm—until Eadweard Muybridge developed an innovative stop-action photography technique. By arranging 12 cameras along a race track with trip wires, Muybridge took 12 photos in rapid succession—one twenty-fifth of a second apart, with the shutter speeds less than 1/2000 s. The shots revealed that a horse is completely airborne for a brief moment while galloping.



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1931: Stroboscopic photography

MIT electrical engineering professor Harold Edgerton took the stroboscope—which produces short repetitive flashes of light—from the lab and combined the technology with the camera, laying the groundwork for the modern electric flash. The high-speed bursts of light from electrically controlled neon tubes allowed him to capture fast-event photography, such as a bullet piercing an apple, and to overcome the mechanical restrictions of the camera shutter.

Maiman's first laser, disassembled.

Corning Inc., courtesy of AIP Emilio Segrè Visual Archives, Hecht Collection

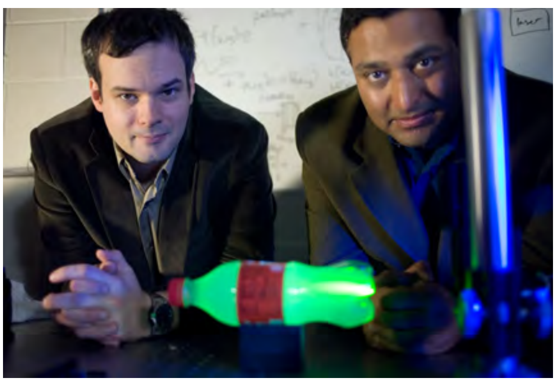
1962: Faster with the streak camera

Streak photography is another form of older high-speed photography, one that employs slits instead of a camera shutter. Early mechanical versions used rotating mirror systems to take high-speed images of ultrafast processes, such as for ballistics. Photoelectric streak cameras can act as time-resolved detectors for measuring ultrafast light phenomena, such as the streak camera used to study the coherent radiation from a ruby laser in 1962—the same type of laser that Theodore Maiman demonstrated for the first time just two years earlier.

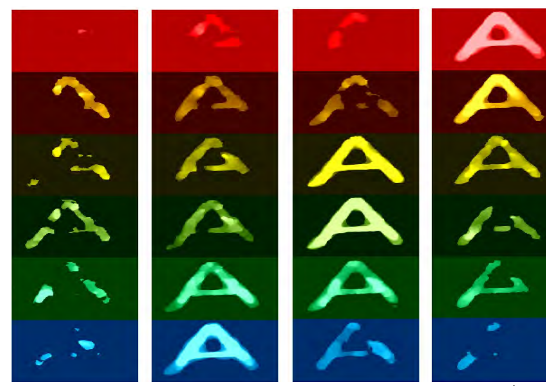
now

Capturing Light in Slow Motion

As lasers and electron sources explore shorter and shorter timescales, optical imaging continues to develop to characterize ultrafast events, often in a single shot.



A. Velten and R. Raskar, MIT/Photo by M. Scott Brauer



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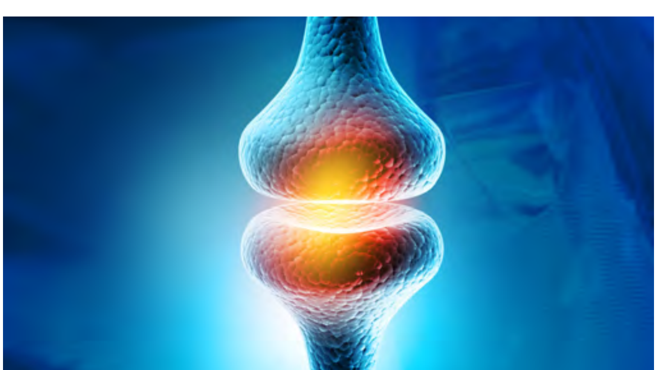
2018: Folding time

Researchers in the U.S. have exploited time as an extra dimension in the optical design of ultrafast cameras. Using a technique it calls "time-folded optics," the team folded large spaces in time using mirrors inside the lens system to reflect light signals, allowing for new time- or depth-sensitive camera capabilities that aren't possible with conventional camera optics. The team believes the method could have a broad impact in time-resolved imaging and depth-sensing optics.

2019: CUST photography

Despite recent advances, it's been tough to image non-repeatable ultrafast processes, such as laser surgery or laser–tissue interaction. Researchers in China have developed a relatively low-cost imaging technique, compressed ultrafast spectral–temporal (CUST) photography, that they say can record transient, highly complex and non-repetitive events with ultrahigh spectral or temporal resolution, a large frame number and femtosecond-scale speed.



Getty Images

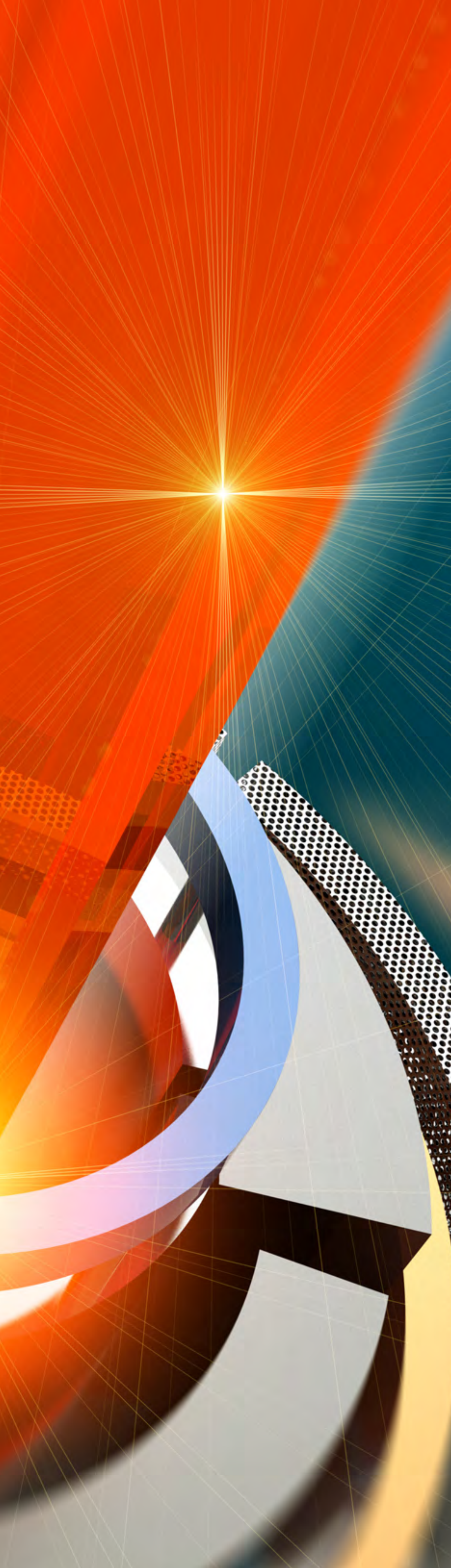
2020: Trillions and transparency

In 2018, a U.S.–Canadian team created the world's fastest camera—able to take 10 trillion pictures per second in a single shot, thanks to the combination of streak imaging and compressed sensing. This year, Caltech, USA, researchers updated the device for a new application. By combining the previous system with phase-contrast microscopy, the technique was adapted to image ultrafast phenomena in transparent materials—including shockwaves and possibly even signals traveling through neurons—at a rate of up to a trillion pictures per second.

Ultrafast forward

Ultrafast photography is widely used both for scientific and industrial applications to visualize events on the shortest of time scales. As technology continues to improve and get more precise, there must be corresponding progress in the techniques for recording images in real time at a very high temporal resolution and spatial resolution. These data can offer insights into the mysterious interactions between light and matter, with applications across many fields.

Getty Images



Six decades after the first working laser was demonstrated, OPN offers a few samples of the incredibly rich field the device has created.

The Laser at 60

Stewart Wills

Theodore Maiman, in a May 1960 photograph from Hughes Research Laboratories.
Courtesy of HRL Laboratories, LLC

Over the years, the photo has become an icon of engineering and scientific discovery. A youthful Theodore Maiman, slightly out of focus and clad in safety goggles, stares intently at the laser apparatus standing out sharply in the foreground—a slender ruby rod, surrounded by the coiled photographic flashlamp that served as the laser's optical pump.

The publicity photo from Hughes Research Laboratories, USA, was taken to herald Maiman's demonstration of the first working laser on 16 May 1960. The ruby rod and flashlamp shown in the picture—as author Jeff Hecht notes in *Beam*, his classic account of the race to create the laser—weren't the ones that Maiman had actually used, and were selected by the photographer for artistic effect rather than scientific accuracy. But that scarcely mattered. The laser was born, and the world never looked back.

The subsequent six decades have been a riot of discovery, driving Maiman's initial invention in undreamed-of directions. For a present-day reading on a few of those, OPN talked with eight OSA Fellows about work they're doing now to take lasers to new wavelengths, shorter pulse durations, smaller dimensions and new applications. Here we can offer only a few snapshots from the vast frontiers of laser technology. But we hope that the resulting collage gives a hint of how far the laser has come since that first demonstration—with no sign of slowing down.

Terahertz lasers: Minding the gap

The red pulses that shot out of Maiman's laser 60 years ago had a wavelength of 694.3 nm—the value for the R_1 electronic transition of the pink ruby he used as the device's active medium. Announcements rapidly followed of lasers using other gain media (and, hence, sporting other wavelengths): solid-state lasers, gas lasers, dye lasers, semiconductor lasers and more. Diode-pumped solid-state lasers and optoelectronic and nonlinear wavelength-conversion techniques further filled in spaces in the spectrum.

Even so, a few interesting wavelength bands have stubbornly resisted the development of cost-effective lasers. One of those is the terahertz (THz) band—sometimes called the far-infrared, and loosely defined as covering wavelengths from 30 to 1000 μm. THz radiation, being non-ionizing, is harmless to biological tissues, yet can potentially penetrate a variety of otherwise opaque substances. Thus, in addition to uses in radio astronomy, THz shows up in airport security and laboratory spectroscopy. But researchers have also envisioned a plethora of new applications in high-bandwidth wireless communications and high-resolution bioimaging—given the right light sources.

And there's the rub. Because, while THz lasers exist, they have often been large, operated only in pulsed mode, sported limited tunability, or needed frigid cryogenic temperatures. The lack of a convenient, compact, continuous-wave laser source between the microwave and infrared bands has even been referred to as the "terahertz gap." And, in recent years, scientists have put a great deal of ingenuity into filling it.

At center stage in that effort has been the quantum cascade laser (QCL), first demonstrated in 1994 by a team at Bell Laboratories led by Jérôme Faist and Federico Capasso. These semiconductor lasers have proved an invaluable light source in the mid-infrared "molecular fingerprint" region, and tunable mid-IR QCLs are now workhorses in compact devices for atmospheric sensing, standoff detection of explosives and other applications. Terahertz QCLs are likewise compact—but still require operation at well below room temperature, and so far have been tunable across only a limited frequency range.

QCL co-inventor Capasso, now at Harvard University, USA, has been working with colleagues at Harvard, MIT and the U.S. Army on a different approach: using the QCL not as a primary THz laser, but as a pump for a molecular gas laser. These lasers, Capasso explains, use a collection of gas molecules with a permanent dipole moment as the gain medium; the right pump laser can

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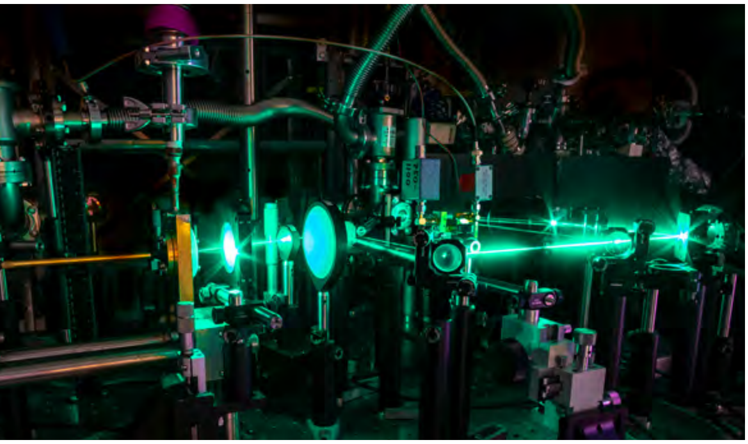
OSA Fellow Federico Capasso co-led a team that used a mid-IR quantum cascade laser as a pump to create a tunable, room-temperature terahertz laser. Arman Amirzhan, Harvard SEAS; Federico Capasso



kick those molecules to a higher-energy rotational state, and as they relax into a lower-energy state they release photons at the difference frequency between the states.

Terahertz molecular gas lasers had been created in the 1970s, but they were far from compact, with meters-long cavities. In 1986, a theoretical model by Henry Everitt, then at Duke University, USA, suggested that a much more compact version might be built. But, says Capasso, the CO_2 lasers used as pumps at the time were bulky, had limited tunability and could access only a few rotational states. The idea of using mid-infrared QCLs as pumps didn't come until much later; such a laser was reported in 2016 by researchers in France.

In 2017, Capasso and Everitt decided to team up to develop a broadly tunable THz gas laser. Two years later, in November 2019, the research group unveiled just such a device, which uses a commercial, widely tunable mid-infrared QCL to pump a 15-cm-long, 5-mm-diameter copper tube of nitrous oxide, or "laughing gas." The device lased at room-temperature—with the lasing frequency tunable from 250 GHz to around 1 THz by tuning the mid-IR QCL pump. And, Capasso adds, the tunability should be extendable to 2 THz by using different molecular gases with different rotational states.

What will these tunable THz lasers be good for? One application, Capasso says, could be use as compact local oscillators for heterodyne detection of THz signals from space, which at present requires complex chains of frequency multipliers. There are also prospects for kilometer-range free-space communication, and, of course, much-discussed applications in security, given THz radiation's well-known ability to pass through fabric, plastic wrapping and paper. "It really opens up a new area," Capasso says. "I hope that we can do in the far-infrared now, what we did in the mid-infrared with quantum cascade lasers."

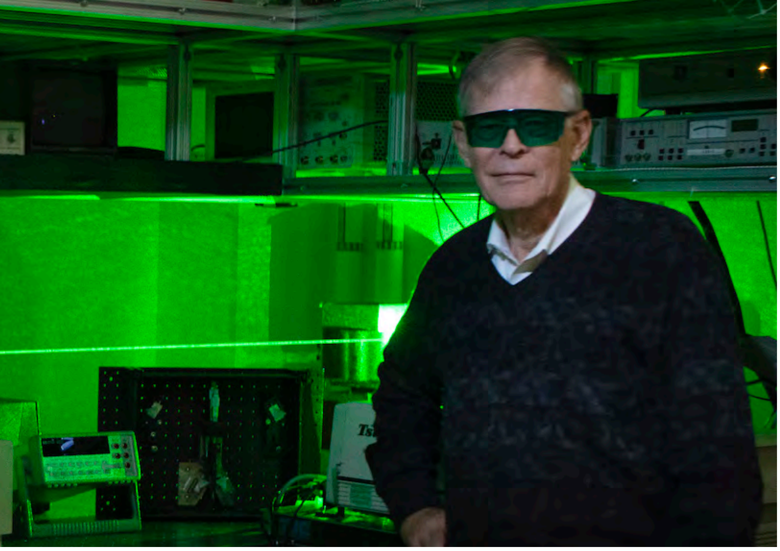
> "I hope that we can do in the far-infrared now, what we did in the mid-infrared with quantum cascade lasers."
>
> —OSA Fellow Federico Capasso

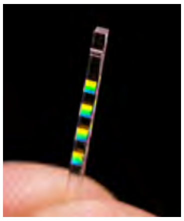
Toward tabletop XFELs

Elsewhere on the frequency spectrum, Robert L. Byer of Stanford University, USA—who published his first paper on lasers only a few years after Maiman's successful demo, and who has been associated with many laser breakthroughs ever since—has his eye on coherent X-ray sources.

"It's overwhelming how many applications there are in the X-ray spectral range," says Byer, "whole new ways to explore chemistry, biology, physics." Synchrotron light sources, which churn out streams of incoherent X-rays, have already opened up many such horizons. But pushing into time-resolved studies of atomic physics and molecular chemistry requires coherent X-rays.

Several such coherent sources, X-ray free-electron lasers (XFELs), have come online in the past several decades. Byer's Stanford office lies only around a 10-minute drive from one of them, the SLAC National Accelerator Laboratory's Linac Coherent Light Source





OSA Fellow Robert Byer is co-leading ACHIP, a project that aims to leverage laser technology to reduce the size and cost of particle accelerators, such as those at the Linac Coherent Light Source, to the scale of a chip.

Misha Bruk Photography; ACHIP program; SLAC Linear Accelerator Laboratory/Christopher Smith.

> “It’s overwhelming how many applications there are in the X-ray spectral range—whole new ways to explore chemistry, biology, physics.”
>
> *—OSA Fellow Robert Byer*

(LCLS), which began hard-X-ray lasing just over 10 years ago. LCLS and other XFELs, such as the European XFEL in Germany, are massive instruments; they involve kilometers-long linear accelerators and huge magnetic “undulators” to create coherent X-rays from wavelike motions of relativistically accelerated electron bunches. And, says Byer, the half-dozen or so XFELs worldwide at such mammoth facilities are “oversubscribed by a lot.”

Byer and the roughly 75 collaborators in the Accelerator on a Chip (ACHIP) program, which he co-leads with Peter Hommelhoff of Friedrich Alexander University Erlangen, Germany, hope to ease that capacity crunch by radically shrinking XFELs—potentially to the scale of a lab tabletop. And, as the name implies, the program would accomplish that by downsizing the required particle accelerators to chip scale—using solid-state lasers, rather than huge RF klystrons, to do the heavy lifting.

Byer says that using lasers to accelerate electrons was conceived “back in 1974,” but did not get off the ground until decades later. The DARPA-funded first phase culminated, in November 2013, in landmark papers demonstrating electron acceleration by lasers within dielectric microstructures. At that point DARPA lost interest—but fortunately, the Gordon and Betty Moore Foundation later picked up the project, rechristened ACHIP. “They wanted to fund high-risk, high-payoff research,” Byer says. “We explained that accelerator research is really high risk, and they funded us.”

At the end of 2019, the international ACHIP collaboration produced four high-profile papers in a single week, including back-to-back reports in *Physical Review Letters* demonstrating laser acceleration of bunched electrons with pulse durations in the range of 250 attoseconds (1 attosecond equals 10^{-18} seconds). Such chip-based electron accelerators would constitute only the front end of a tabletop XFEL; realizing such a device will also require the design of additional acceleration stages and a compact, laser-driven undulator to replace the magnetically driven behemoths in current XFELs—projects on which the laser community is also hard at work.

As that work comes to fruition, though, Byer believes it could spawn a new generation of compact XFELs. “Since everything is small and has a high repetition rate, we can put a resonator around the X-ray source, and build a synchronously pumped X-ray laser on a tabletop that’s both spatially and spectrally coherent,” he says.

“We think this will democratize accelerators,” says Byer. “It’ll make them small enough and cheap enough that you can design them directly to meet your science need or your manufacturing need.”

The few-cycle frontier

As Byer suggests, a key aim of the ACHIP research is to produce pulses that can probe the attosecond timescales of chemical reactions. “At the speed of light, one attosecond is equivalent to light traveling across a hydrogen molecule,” Byer notes. “That’s how short the pulses are.” It’s also 15 orders of magnitude faster than the millisecond-width pulses that issued from Maiman’s original laser.

Ursula Keller has spent some three professional decades probing such mind-bendingly short intervals, first at Bell Laboratories, USA, in the late 1980s, and, since 1993, in her current role as a professor at ETH

Zurich, Switzerland. In that time she's seen, and helped realize, enormous progress in the ultrafast lasers at the heart of the work.

"In the 1970s, everything was done with dye lasers—that was the frontier," says Keller. "You had to babysit the laser for the whole day, and at the end you could do an experiment. Now, with solid-state technology, we have much more reliable ultrafast lasers at many wavelengths, much higher power levels, and much better performance." And those lasers, she adds, have enabled a vast range of commercial applications, in areas ranging from biomedicine to materials processing to telecom.

Keller notes that once solid-state lasers with the necessary bandwidth were developed in the mid-1980s, the community was quickly able to push these lasers into femtosecond-scale pulses. But the instability of the electric field beneath the pulse envelope severely restricted the use of those pulses to create even shorter, attosecond-scale pulses.

Solving that stability problem via the medium of frequency combs—in work Keller published in 1999, in collaboration with H.R. Telle and others—not only cleared the way to push into the attosecond regime, but also helped jump-start the revolution in frequency metrology. "It's one of those examples," she says, "where if you push the performance of a laser into a regime where it has never been before—well, something new always pops up."

To push things still further, Keller's team is focusing on the repetition rate for these ultrafast lasers. One way (in addition to XFELs) to create attosecond pulses is to fire few-cycle, femtosecond laser pulses through a gas target to drive high-harmonic generation, or HHG (see OPN, May 2015, p. 28). But HHG is an inefficient process, and for applications such as doing spectroscopy on attosecond timescales—experiments that can peer into electron dynamics during biochemical reactions—there's a significant need to boost average power.

"The signal to noise in those kinds of measurements goes with the average photon flux," Keller explains. And in many kinds of experiments, the best way to improve that average flux is to boost the rate of nanojoule-scale attosecond pulses.

In work published in February 2020 in *Optica*, Keller's ETH Zurich team presented a system using optical parametric chirped-pulse amplification (OPCPA) that could push out mid-IR, few-cycle laser pulses with 14 GW peak power at a rate of 100,000 pulses per second—and used those pulses to drive HHG production of coherent attosecond soft X-rays. The 100-kHz rep rate was two orders of magnitude higher than the rates of the sources typically used in such experiments. That's a potentially huge gain in signal to noise that could, according to the paper, enable "a new generation of attosecond studies."

Looking back today, Keller says she "never could have predicted how fast progress would be in attosecond science, and in the average power scaling of the lasers. It's just amazing where we are."


OSA Fellow Ursula Keller, ETH Zurich, continues to extend the attosecond frontier.

European Patent Office/Heinz Troll

> "If you push the performance of a laser into a regime where it has never been before, something new always pops up."
>
> —*OSA Fellow Ursula Keller*

Going small

The business end of Maiman's 1960 laser could be held in the palm of one's hands. That's a far cry from the enormous, football-field-scale terawatt and petawatt laser complexes of the U.S. National Ignition Facility and Europe's Extreme Light Infrastructure (see OPN, January 2020, p. 30), and the 100-PW Station of Extreme Light being built in China (see "Platforms of Power," p. 36). But some of the laser's biggest impacts, particularly in communications, have come from efforts in the opposite direction—to make lasers very small.

Noah Berger

" VCSELs are extremely scalable. Once you master the fabrication of one, you can make tons of them. "

—*OSA Fellow Constance Chang-Hasnain*

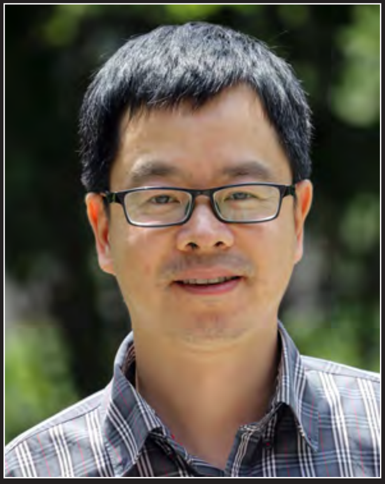
One success story has been the vertical cavity surface-emitting laser (VCSEL), originally pioneered in the late 1970s by Kenichi Iga of the Tokyo Institute of Technology, and now a fixture in everything from computer mice to short-run interconnects in data centers. Constance Chang-Hasnain of the University of California Berkeley, USA, attributes their success to two factors: a "nice, usable beam" that's easily guided and coupled to other devices, and wafer-scale manufacturing, analogous to that of LEDs. "Once you master the fabrication of one," she says, "you can make tons of them."

Chang-Hasnain became involved with VCSELs by being "in the right place at the right time," working in the late 1980s at Bellcore, the New Jersey–based research arm of the former Bell Telephone operating companies in the United States. There, she contributed to the second generation of VCSEL development, driven by advances in the fabrication and physics of semiconductor devices.

Today, the growth of 3D-sensing modules in smartphones has set VCSELs up for another explosion of growth. The firm Yole Développement recently projected that the market for these sensors could quadruple, from US$2 billion to US$8.2 billion, between 2019 and 2025. VCSELs constitute a core enabling technology for such sensors—in part, according to Chang-Hasnain, because previous demand and mass-production requirements for other applications made the technology ready to feed this emerging new market.

Chang-Hasnain's team, meanwhile, continues to push VCSEL technology further. One recent emphasis has been VCSELs featuring high-contrast gratings, which can replace the thick stack of distributed Bragg reflectors in VCSEL designs, cutting the device thickness by around 50%. That, she explains, also makes it easier to manufacture the lasers, and to integrate them into flexible MEMS devices. Such devices, she notes, are already making headway in opthalmology and have potential in real-time imaging to guide precision surgery. "It's very exciting," says Chang-Hasnain.

Another avenue for exploiting the power of small lasers lies, of course, in integrating them on silicon



Courtesy of Ruxin Li

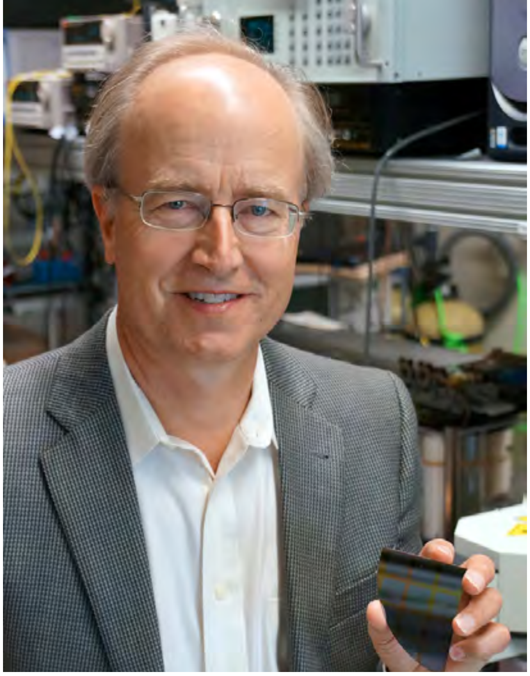
" Increases in peak power and average power significantly promote and expand applications of lasers. "

—*OSA Fellow Ruxin Li*

chips. Such laser integration, according to John Bowers of the University of California, Santa Barbara, USA, "allows a much more complex integrated circuit" that can be pressed into service in high-bandwidth data communications, lidar, and even exotic applications such as compact laser gyroscopes for rotation sensing. "Today, laser gyroscopes are $10,000 each," says Bowers. "They go on airplanes, but they don't get applied to your car or cellphone … If we can integrate the laser and the whole photonic circuit on the chip, and do it in high volume in silicon, it becomes competitive and allows new applications to enter."

Traditionally, silicon's indirect band gap, which makes it an extremely poor emitter, has been a stumbling block to getting lasers on the material. But Bowers, who will give a plenary talk on the subject at this month's CLEO Conference, says enormous progress has been made. Heterogenous integration—in which a direct-bandgap, highly efficient light-emitting "III–V" material is bonded to a silicon wafer and then processed in a conventional CMOS facility—is already well established, with more than two million transceivers per year reportedly being produced by Intel alone.

Laser integration via another process, epitaxial growth, has been tougher—but looks "very promising" for the future, Bowers says. He cites recent experiments that created epitaxially grown lasers on silicon with lifetimes of 100 million hours at room temperature. The key to these lasers, he explains, is creating the laser's active region using luminescent nanoparticles, or quantum dots, which avoid some of the materials-defect problems that have hobbled other approaches to growing lasers via epitaxy. The work is, in Bowers' estimation, "probably lagging 10 years behind" heterogeneous integration. But it's worth pursuing, as it could make lasers on silicon "incredibly cheap," priming still more applications.



UC Santa Barbara

> "If we can integrate the laser and photonic circuit on the chip, in high volume in silicon, it allows new applications."
>
> *—OSA Fellow John Bowers*

Even smaller: Nanolasers

Still smaller lasers have also captured scientific and industry attention—so-called nanolasers. These, explains

PLATFORMS OF POWER

To Ruxin Li of the Shanghai Institute of Optics and Fine Mechanics, China, some of the most interesting and productive developments in laser technology have been those that have boosted average and peak laser power, which he says "significantly promote and expand applications of lasers." A case in point: The Station of Extreme Light (SEL) that Li and his team are developing in Shanghai.

Li says that the SEL project—approved by the Chinese government in 2017, and kicked off in spring 2018—has most of its engineering design completed, and the facility front end is now being developed. The ultimate goal will be a laser capable of pulses carrying a peak power of 100 PW—around an order of magnitude greater than those of the most powerful lasers operating today—and a focused intensity of more than 10^{23} W/cm^2. The current schedule envisions completing the facility, and opening it to users, in 2025.

Once the facility is online, the "day-one experiment," according to Li, will be putting pulses from this powerful laser together with hard-X-ray pulses from an X-ray free-electron laser, for pump–probe experiments to investigate vacuum birefringence. That's a phenomenon predicted by strong-field quantum electrodynamics, in which the quantum vacuum behaves like a sort of prism owing to the presence of "virtual" particles within it. Verifying this strange non-emptiness of the vacuum would mark a significant scientific milestone for SEL. Also on the table, according to Li, is using the laser to generate high-energy particles and radiation for a variety of applications.

Northwestern University/Matthew Gildon

> “The laser has widened the space where many different disciplines can contribute to both fundamental knowledge and potential applications.”
>
> *—OSA Fellow Teri Odom*

Teri Odom of Northwestern University, USA, are lasers in which at least one of the relevant dimensions, such as cavity length or feedback mechanism, is on the nanometer scale, well below the diffraction limit of light. For example, in plasmonic nanocavities, light amplification takes place very close to the surface of the metal nanostructures. And lattices of nanoparticles can dramatically enhance the localized light field.

Odom says her involvement with nanolasers grew out of a more general interest in nanoscale light–matter interactions. “In the beginning, our goal wasn’t to say, Oh, let’s just make a nanolaser because it sounds cool,” she says. But as she and her team studied the characteristics of energy transfer between emitters, such as dye molecules and quantum dots, and plasmonic lattices, “it turned out that these systems exhibited really interesting characteristics,” such as a lasing threshold energy and directional emission, “that are reminiscent of macroscale lasers.”

In a September 2019 study in *Nature Materials*, Odom and colleagues at Northwestern, Lawrence Berkeley National Laboratory and Columbia University fashioned one such miniaturized laser. The device, hosted in a glass matrix, used a lattice of 50-nm-tall silver nanopillars to form the cavity. As the gain medium, the team coated the pillars with a 150-nm-thick film of upconversion nanoparticles (UCNPs)—inorganic nanomaterials doped with rare-earth ions that can convert lower-energy photons to higher-energy ones.

The result was a super-tiny laser that, when pumped with near-IR light, could produce continuous-wave emission in the visible. That combination, plus the fact that the platform is biocompatible, opens up opportunities in deep-tissue imaging, sensing and optogenetics. That’s because the device can be stimulated by near-IR pump light—which can be delivered externally and penetrate biological tissues—to produce, via the UCNPs, visible laser light for the deep-tissue imaging and therapeutics. And the device’s low lasing threshold also creates other possibilities, according to Odom, including use as light sources for quantum applications.

Lasers, Odom concludes, have “widened the space where many different disciplines can contribute to both new fundamental knowledge and potential applications.”

Spawning an industry

As is well known, soon after Maiman’s initial laser demonstration, someone—just who is a matter of dispute—quipped that the laser was “a solution looking for a problem.” World industry clearly got the memo. In the six decades since, the laser has spawned a global market estimated by Strategies Unlimited at more than US$16.6 billion annually. And Wilhelm Kaenders, who co-founded the laser firm Toptica Photonics AG just over 22 years ago, says that, from industry’s viewpoint, the past six decades “have pushed the technology from being just a small, first dim laser light to many extremes.”

As Kaenders observes, the laser industry’s growth reflects improvement on a huge variety of fronts, ranging from expansion of the available spectral range and improvements in stability and linewidth to the “new laser field” opened by the advent of frequency combs. One “remarkable achievement,” he says, has been the laser’s extension to an almost complete range of wavelengths, which has allowed it to penetrate a vast array of markets in manufacturing, sensing and analysis. “Most materials can today be addressed for various forms of processing … with a suitable laser source” says Kaenders, who cites some relatively new examples—cutting/ablating with UV wavelengths; welding copper with blue/green diode lasers; bioprinting with 3-μm IR laser light.

Kaenders notes that today, some venerable and well-developed lasers—such as “the ubiquitous gas lasers that were among the technologies that started the laser field"—are still "able to defend some market niches." But those niches, he believes, may fall to direct diodes, diode-pumped solid-state lasers or fiber lasers as customers increasingly focus on compactness, efficiency, integration and cost of ownership.

In the area of medical applications, for example, Kaenders believes for ultrafast techniques like multiphoton microscopy, only fiber lasers are compact, convenient and efficient enough to drive the transition of applications from research labs to the clinic—even solving the light-delivery problem as part of the design. One other example he cites is "multi-laser engines," in which one unit provides different colors to drive diverse applications such as microscopy, cytometry and DNA sequencing: A unit that once required "a cubic meter of space and kilowatts of electrical power," Kaenders says, can now "be served out of a shoebox-sized device."

In a somewhat more exotic vein, Kaenders also sees potential in the emerging market for quantum technology. "In many approaches to quantum computers," he says, "lasers are an indispensable tool to prepare, initialize and interrogate quantum states," as well as for linking quantum processors together in networks. For current experiments in quantum technology involving trapped ions or atoms, he observes, today's lasers seem equal to the task, providing the needed tunability and optical phase control. "The challenges for the future are more like how to get these lasers out out of the lab—ultra-compact and transportable, but still high performing," says Kaenders.

Whirlwind trip

With talk of quantum computers and information networks, we have come a very long way from Theodore Maiman's May 1960 lab benchtop. Even so, for an invention as fruitful as the laser, a whirlwind trip such as this story is inevitably an exercise in frustration, given how much must be skipped along the way. Unmentioned here have been the myriad applications opening up for lasers in outer space; the ultrastable lasers that enabled the first detection of gravitational waves; a vast array of active application areas in medicine, science, industry and the military; and countless other efforts to take lasers to the next level. We've put together an online library of OPN content (www.osa-opn.org/link/laser-at-60) for those seeking a deeper dive.

For now, we'll leave the last word to Robert Byer, who—having seen and contributed to laser science since its beginning—is unusually well positioned to appreciate the changes presaged by Maiman's May 1960 demonstration. Alluding to the notion of the first lasers as "a solution looking for a problem," Byer notes that the laser subsequently "found a set of problems to solve that are global in extent. All of our communication today is based on laser and optical-fiber communication. Lasers have penetrated virtually all fields of science and medicine."

"The sixty years," says Byer, "have gone by pretty quickly." OPN

OSA

> "In many approaches to quantum computers, lasers are an indispensable tool to prepare, initialize and interrogate quantum states."
>
> —*OSA Fellow Wilhelm Kaenders*

OPN thanks OSA Fellows John Bowers, Robert Byer, Federico Capasso, Constance Chang-Hasnain, Jeff Hecht, Wilhelm Kaenders, Ursula Keller, Ruxin Li and Teri Odom for their assistance with this feature.

Stewart Wills is OPN's senior editor.

There's lots more online!

Visit **www.osa-opn.org/link/laser-at-60** for:

- Longer Q&As with the OSA Fellows interviewed for this story
- References and resources
- Links to previous OPN features on laser history and science

Jeff Hecht

Television Goes 8K

Can You See the Difference?

The impressive technology promises better imaging in medicine and other fields as well as entertainment, but how much more can our eyes see?

Getty Images

Samsung

Only a decade has passed since television broadcasters stopped transmitting signals in formats developed in the 1950s for vacuum-tube technology. The digital high-definition television (HDTV) format that replaced the old analog broadcasts represented a huge advance in image quality, particularly when shown on flat-panel displays based on backlit arrays of liquid crystal devices (LCDs).

The first full HDTVs introduced in the early 2000s had resolutions of 1920×1080 pixels, and rapid advances in display technology enabled a series of improved TV sets—starting with more pixels for 3D TV, doubling resolution to 3840×2160 pixels (4K) and adding high dynamic range (HDR). Now a new generation of "8K" TVs displaying 7680×4320 pixels has reached the market. The big question for the industry is whether the improved resolution and other fresh features will generate a new wave of sales. From the optical perspective: How much of that enhanced resolution can the human eye see? And is it, perhaps, time to update how we measure optical acuity?

From cathode-ray tubes to flat panels

Television became a mass medium after World War II. Broadcasts started in black and white, followed about a dozen years later by color. The U.S. was a leader, with the Federal Communications Commission adopting the National Television System Committee (NTSC) color standard in 1953. It broadcast thirty 525-line frames every second, although cathode-ray picture tubes showed only 486 lines. Countries with 50-hertz power grids adopted PAL and SECAM standards, which transmitted 625-line frames 25 times a second.

The share of U.S. households with TV sets soared from zero in 1945 to more than half by the mid-1950s. Essentially all were black-and-white before the color standard was finalized, and most broadcast programs and televisions sold remained monochrome until the mid-1960s. The ABC network did not broadcast its first color shows—the stone-age comedy "The Flintstones" and two other cartoons—until 1962.

Color broadcast equipment and sets were expensive, and color quality was almost an oxymoron. Colors drifted so much that sets came with color tuning knobs—not that they stopped mud-covered football fields from appearing a cartoonish bright green on the screen. Critics dubbed NTSC "Never The Same Color" or "No True Skin Colors."

Color quality improved after the introduction of solid-state electronics in the 1970s, but cathode-ray tube (CRT) technology remained a bottleneck. Cost, bulk and weight of CRT TVs scaled steeply with screen size, making direct-view CRT screens larger than 35 to 40 inches impractical even into the 1990s. Larger sizes required projecting the bright image from a small screen CRT or other display onto a large translucent or reflective screen. Rear-projection sets became popular in the early 2000s, and eventually reached sizes up to 100 inches (2.5 meters), but their screen brightness remained limited.

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What finally made sales of 4K displays take off was adding HDR, which increases the range of color brightness.

The first major effort to upgrade consumer television after the introduction of color was Hi-Vision, launched in 1979 by the Japanese public broadcaster NHK. The analog system was designed to display 1125 lines on screen, so each broadcast channel was expected to require 20 to 30 megahertz of radio spectrum, a big jump from the 6 MHz of NTSC. Doubling the resolution also would require bigger and better displays, new broadcasting equipment and cable distribution systems, and conversion of existing content into the new format. Yet the electronics industry saw a profitable new market, and by the late 1980s the U.S. Electronic Industries Association projected that a quarter of U.S. households would adopt HDTV in 2000.

The digital transition

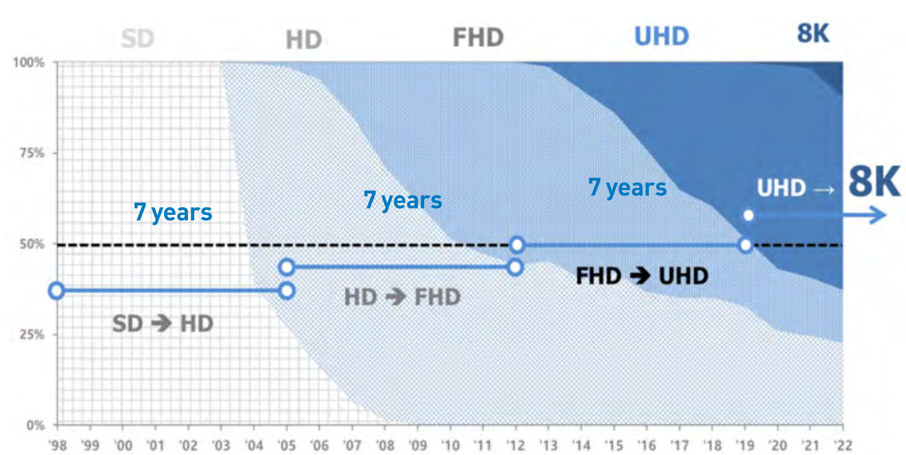
By the time developers settled down to define standards for HDTV in the early 1990s, digital technology had advanced so much that it was the clear choice for broadcasting. Digital compression could squeeze HDTV signals into the same 6-MHz band as NTSC. An industry consortium developed the Advanced Television Systems Committee (ATSC) standard, which the FCC adopted in 1996. It allowed many screen formats, but the two most important were 1280×720 pixels (HD) and 1920×1080 pixels (FHD), both using a 16:9 screen shape.

Digital television got off to a slow start. Sets went on sale in August 1998 in the U.S., and by the end of the year only 13,176 had been sold. Prices ranged from US$5,000 to US$12,000 for rear-projection sets with 55- to 72-inch screens, direct-view CRTs of 31 to 38 inches, and a single 50-inch plasma model. "Never have so many paid so much for so few hours of programming," wrote Stephen Booth in *IEEE Spectrum*.

Congress originally set shutdown of NTSC transmission for the end of 2006, but it had to be delayed three times. Only in 2007 did sales of LCD televisions eclipse those of CRT sets, helped by LCD TVs reaching the 42-inch size that plasma panels had once dominated. That year, Sharp looked to the future and debuted a 108-inch LCD. By June 2009, when the U.S. shut down analog NTSC broadcasts, big old CRT televisions were being hauled to the curb. Other viewers hooked up digital-to-analog converters to stretch the lives of their old CRT sets, but it was clear that LCDs had won the technology race. The high end of the market was shifting from 1280×720 pixels to full HDTV at 1920×1080 pixels.

Meanwhile, the industry went looking for the next game changer to boost sales, and turned to 3D TV (see "3D TV and Movies: Exploring the Hangover Effect," *Optics & Photonics News*, February 2011). With the epic film *Avatar* setting box-office records, it seemed like a good idea at the time, and advances in LCD technology could handle the extra pixels needed. However, 3D TV proved to be an epic flop, and consumers gave it a miss.

The industry then offered bigger and better screens, and doubled resolution to 3840×2160 pixels, which it dubbed "4K" or ultra-high definition (UHD). The change is noticeable, especially when the doubled pixel count is spread across a larger screen. However, the difference between HDTV and 4K is not dramatic in the showroom. What finally made sales of 4K displays take off was adding HDR, says Chris Chinnock, president of Insight Media and executive director of the 8K Association.



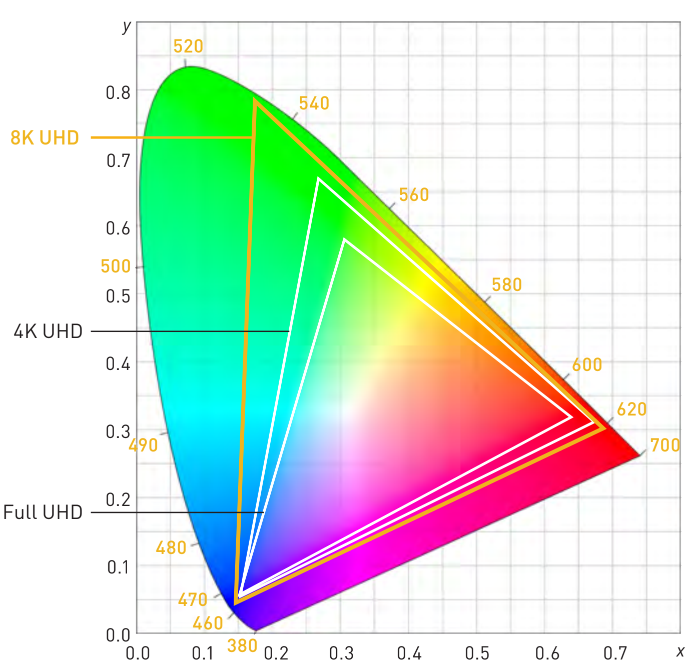
The seven-year cycle of TV resolution upgrades: from 525-line standard definition (SD) to high (HD), full high (FHD), ultra-high definition (UHD) and 8K.

IHS Markit and Samsung Display

8K displays combine HDR and an expanded color gamut with screens displaying 7680×4320 pixels, four times the number on a 4K screen and 16 times the number on a full HDTV set.

HDR increases the range of color brightness, from blacker blacks to higher-intensity colors, so images seem much more vivid, especially those chosen to highlight the effect in the showroom. Cameras have come with this feature since 2008, and photo-editing software offers a similar function. Most TV content is produced with HDR, although it is not generally shown with the expanded dynamic range. Showrooms enhance the effect by playing videos that incorporate bright objects as well as color enhancement. As with 3D effects, HDR can be used to excess, and by cranking up the dynamic range it can distort reality in ways that some find disturbing. But the effect is impressive, and it sells TVs.

Another screen improvement is enhancing the range of colors the screen can generate, called the color gamut and shown on a chromaticity diagram. For LCD displays, this is done by changing the backlight that illuminates the arrays of tiny liquid-crystal light modulators that create the image. Early LCD displays were illuminated uniformly by lamps. White-light LEDs offered an improvement in backlight quality because they can be driven individually to change the distribution of light across the screen, giving darker blacks and brighter colors.



Chromaticity diagram showing the difference between full HD, 4K and 8K color gamuts, with 8K (yellow triangle) offering the broadest color range. Adapted from Wikimedia Commons

The next upgrade came from switching to arrays of red, green and blue LEDs, which produce purer colors that are closer to the edges of the chromaticity diagram, increasing the range of the color gamut. Manufacturers now describe LCDs with LED backlighting as "LED" displays, although it's the LCDs that are modulating the light. The next step in color, says Chinnock, is coating blue LEDs with films containing quantum dots, which produce very narrow slices of the red and green spectrum, making it possible to generate an even broader color gamut.

The 8K generation

8K displays are the latest generation, combining HDR and an expanded color gamut with screens displaying 7680×4320 pixels, four times the number on a 4K screen and 16 times the number on a full HDTV set. The latest and greatest screen comes at a hefty cost, however. When I visited a nearby showroom, a 55-inch Samsung 8K set was on sale for US$2,500, but a 4K Samsung set with HDR was only US$350.

Prices may be steep, but they're likely to drop as production scales—and display makers are ramping up capacity in expectation of more sales. "Each cycle of new production facilities processes larger and larger sizes of glass panels, with the sizes chosen so the glass can be sliced efficiently into standard sizes," says Chinnock. "Generation 8" plants were optimized to produce the 55-inch screens common for 4K sets. The new G-10.5 fabs are optimized for 65- and 75-inch screens, which show off the high resolution and color quality of 8K.

One problem is that 8K televisions have left content behind. 8K cameras have been available for years, and are being embraced for ambitious new projects; however, decades of favorite films and videos remain available only in older formats. To encourage buyers to move up to 8K, the TVs offer "very compelling upscaling technology," says Chinnock. Instead of blindly following preset rules for upscaling, 8K electronics use artificial intelligence to classify parts of the image as hair, sky, faces or other things, and then apply the appropriate

8K screens display a resolution of 7680×4320 pixels for a total of 33.18 million pixels, resulting in images that are 16 times more detailed than full HD.
Courtesy of Sharp

upscaling algorithm. As a result, he says, "the fidelity of upscaling is an order of magnitude better than a few years ago."

Are returns diminishing as resolution improves?

HDTV was a huge improvement over NTSC, but the improvements between HDTV and 4K were less obvious to the naked eye. HDR is much more striking than 4K without it, but I have to wonder about the cost in realism and distortion. How different is it from early NTSC changing the color of a football field from mud to green? HDR looks great with the showroom videos, and it should brighten up animation, but what does it do to a nature documentary?

I found it hard to compare 4K and 8K sets in a local Best Buy's home-theater display. Putting on my glasses and getting within inches of the screens revealed the difference in pixel sizes and counts. I was awed by the texture of the glittering green feathers of a hummingbird blown up almost to the size of a turkey on a 55-inch 8K screen. But the 4K and 8K sets were running different demo videos, so there was no way I could compare them side by side to look for subtle differences. Were the textures of the foliage and feathers on the 8K screen really richer, or was that an artifact of my aging eyes?

The conventional metric for human visual acuity would suggest no difference should be visible between 4K and 8K. In 1862, Dutch ophthalmologist Herman Snellen designed the now-standard eye chart so that, when viewed at the proper distance, the letters would subtend an angle of five arcminutes, and lines in the letters would be one arcminute wide. One arcminute remains the standard definition of optical acuity.

To compare the eye's resolution on the chart to the display of pixels on a screen, assume the viewer sits at a distance where the screen subtends a 45-degree angle in the horizontal field. For a modern 16:9 display, that's about 2.5 times the screen height, or 6.6 feet from a 65-inch screen. The 45-degree field of view equals 2700 arcminutes, so if the eye's resolution is one arcminute, it could resolve 2700 pixels on that screen, between the 1920 pixel width of full HDTV and the 3840 pixel width of 4K. So if visual acuity was that simple, our eyes could not tell the difference between 4K and 8K screens.

The problem with that reasoning is that it is based on "a line of assumptions, each a little questionable" that make it invalid, says Martin Banks, an OSA Fellow and professor of optometry at the University of California at Berkeley, USA. Eye-chart resolution "is all based on seeing letters that are black-and-white targets, with sharp edges and no gray scale." Yet television shows us continually changing color images of various brightness.

Even when we look at eye charts, the images blur when we try to resolve the letters at the bottom where we hit our visual limits, so we succeed in reading some and fail in trying to read others. When we look at moving objects, the eye does not see fine detail as well as when we stare at fixed ones. What we can see depends on what we are looking at, and a TV screen is very different from an eye chart.

The complexity of acuity

Another problem is that ocular acuity varies across the field of view. Acuity has a sharp peak in the central fovea, where photosensors are packed most closely, and drops off on all sides, says Banks. Vision in the central fovea is limited by the optics of the eye because each

One takeaway message from the optical dichotomies of 8K is that we need more research on visual acuity and better ways to measure it.

neuron carries input from one photosensor. However, each neuron on the periphery of the eye receives input from many photosensors, so peripheral vision is limited by neural processing, which throws away the spatial information needed for high-resolution vision by mixing multiple inputs.

Sometimes our eyes can see anomalies in shape that are beyond our normal visual acuity. One well-known example of such hyperacuity is the Vernier effect, in which we can spot a slight offset in straight lines that is only a fraction of their width. This is how the Vernier scale, which lets us measure distances that subtend angles smaller than the usual one arcminute. Another example is the stair-step or "jaggie" effect where we can see pixels along diagonal lines. Moiré patterns, wavelike patterns that appear when two window screens or very fine meshes appear to cross at a slight angle, are another example.

The big advantage of 8K is that the pixels are so close together that the images we see are smooth and lose the pixelated effect, writes Florian Friedrich of FF Pictures GmbH in Germany. He shows how that makes for a better visual experience than one-arcminute resolution by showing how the moon would look broken up into one-arcsecond pixels. Thus, Friedrich concludes, our eyes see at least four pixels per arcminute—as in smartphone "retina" screens—to avoid pixilation.

"We have slightly better perceptual acuity for the stair-step [effect] than you might expect from spacing of the photoreceptors in the retina," says Jennifer Groh, a professor of cognitive neuroscience at Duke University, USA. "It's not a big effect, but it's probably the brain's ability to extrapolate … to compare across a whole bunch of photoreceptors instead of just one."

Groh points out another subtle but significant difference between looking at the real world and at a display. Screens emit light, but most other objects around us reflect light from other sources. "When we perceive in the natural environment, we have to consider what is the light source," because sunlight differs from fluorescent lights or firelight. Monitors instead supply their own light. She doesn't speculate about the implications, but notes that "it's not a natural environment."

One takeaway message from the optical dichotomies of 8K is that we need more research on visual acuity and better ways to measure it. The Snellen eye chart is a simple and valuable tool for testing the whole visual system, but more refined diagnostics are necessary to help us better understand visual acuity and its relationship to the environment. For example, it's amazing how much headlight glare can degrade nighttime visual acuity in patients with cataracts who see tolerably well in daylight.

The 8K verdict and beyond

So far, technology pundits show little enthusiasm for 8K TV. CNET's Geoffrey Morrison writes: "Unless you have money to burn, don't even consider buying one right now." Its price is too high, too little content is available in 8K format, and the slight improvement in image quality he noticed "required sitting very close to a very large screen." Morrison quoted a market

(Left) Tennis court image shows examples of hyperacuity: anomalies include jagged white lines and wavelike moiré patterns in the net. (Right) a higher resolution image showing smoother lines. Edward Reuss /JMI **126**, 33 (2017) © SMPTE

LG's 88-inch 8K OLED set. Courtesy of LG

analyst as predicting 8K would not reach 1% of unit sales until 2022.

Best Buy staffers who stopped by their home-theater showroom as I studied 4K and 8K screens said 8K sales had been slow, and that customers had expressed little interest. That is likely to change as Moore's law drives prices down, and more 8K content becomes available.

New technology also is emerging to challenge current LED-backlit LCD screens. Organic LEDs (OLEDs) are most widely used as direct-emitting small displays—such as smartphone screens—but LG uses them in large 4K televisions, and in January announced an upcoming 8K OLED set with an 88-inch screen. OLEDs have attractions for supersized screens. As direct emitters—meaning each pixel emits light—the screens have high off-on contrast which improves image quality, and can be viewed across a wider range of angles than LCD sets. Avoiding backlighting allows OLED screens to be thinner and more flexible. OLEDs also respond faster than LCDs.

However, higher manufacturing costs increase OLED prices, and operation at the high brightness needed for HDR can degrade OLEDs rapidly, a problem which also makes them vulnerable to screen burn-in. So far, only LG and Sony are pushing large OLED-based screens.

Micro-LED displays are also being scaled up to large screens. By assembling microscopic indium-gallium nitride LED emitters into arrays of direct-emitting pixels, micro-LED displays offer bright emission at low drive power and high image quality—which has led to applications in smart watches and smartphones. Now they are being scaled up for giant wall displays, which Samsung, Sony and two Chinese companies, TCL and Konka, demonstrated at the technology trade show CES.

Samsung claimed its version could produce 150-inch screens bright enough for use in partial indoor sunlight. Yet Maury Wright of *LEDs* magazine reported, "it's not clear that any of these companies have sold these TVs into more than specialty applications with configurations approaching $1 [million]." Cutting prices of super-sized micro-LED displays enough for consumer television probably would require integrating the micro-LEDs with drive electronics. Sales would also face another limitation: households that lack space for a giant 100-inch screens.

Nonetheless, Chinnock expects another generation of higher-resolution screens to follow 8K, although it may not be as straightforward as a 16K upgrade. After having seen new light-field displays based on 8K screens, he thinks that developing technology may revive 3D in a new and more realistic form. "With 8K they look amazing," he says, "and with 16K they will look even more impressive." It will be interesting to see what the new technology can develop, and how we can measure what we see. OPN

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Getty Images

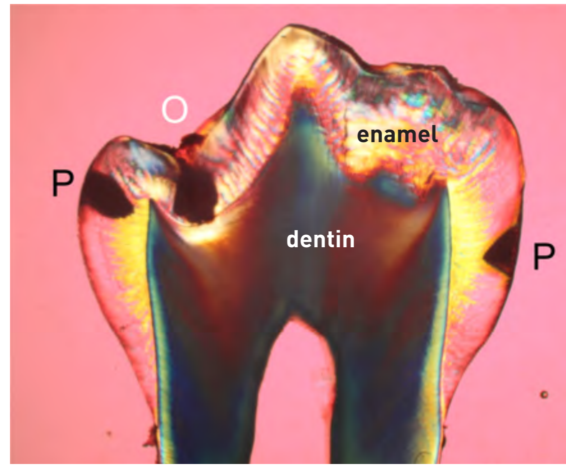
Daniel Fried

Detecting Dental Decay with *Infrared Light*

A variety of optical techniques could overcome some of the shortcomings of more traditional tools for one of the dentist's oldest tasks—finding cavities.

Despite considerable progress in treatment, dental caries—tooth decay—remains the most prevalent chronic disease in both children and adults. Dentists commonly use visual and tactile means (for example, dental probes), coupled with radiography (dental X-rays), to identify caries lesions, or cavities. The widespread use of fluoride has meant that lesions commonly crop up where fluoride doesn't easily penetrate—typically in the pits and fissures of the crowns of posterior teeth (occlusal lesions), or at the contact points in-between teeth (interproximal lesions). That makes them difficult to detect by conventional means. Lesions also congregate near dental root surfaces, and constitute an increasing problem in an aging population.

Fortunately, several new optical imaging devices that use fluorescence and near-infrared (NIR) and shortwave-infrared (SWIR) light have become available to dentists—and dental systems based on optical coherence tomography (OCT) are under development. These techniques not only lack the ionizing radiation required for radiography, but have some other significant advantages over radiographs for detecting and assessing dental caries.



A section of a premolar tooth with interproximal lesions (P) and an occlusal lesion (O), viewed under polarized light with a first-order retardation-I plate. Enamel is more transparent than dentin, and both tissues are birefringent; loss of birefringence due to strong light scattering causes demineralized caries lesion areas (cavities) to appear black.

The trouble with X-rays

When dental-caries lesions are identified early via radiography, they can be halted or arrested through partial remineralization with fluoride before surgery is needed. Unfortunately, though, radiographic methods have poor sensitivity for detecting more hidden, occlusal lesions, due to the overlapping topography of the tooth's crown. By the time the lesions become visible to radiography, they have typically progressed deep into the dentin, the inner, calcified tissue that lies

A dental-caries glossary

Dental caries: The condition commonly known as tooth decay.

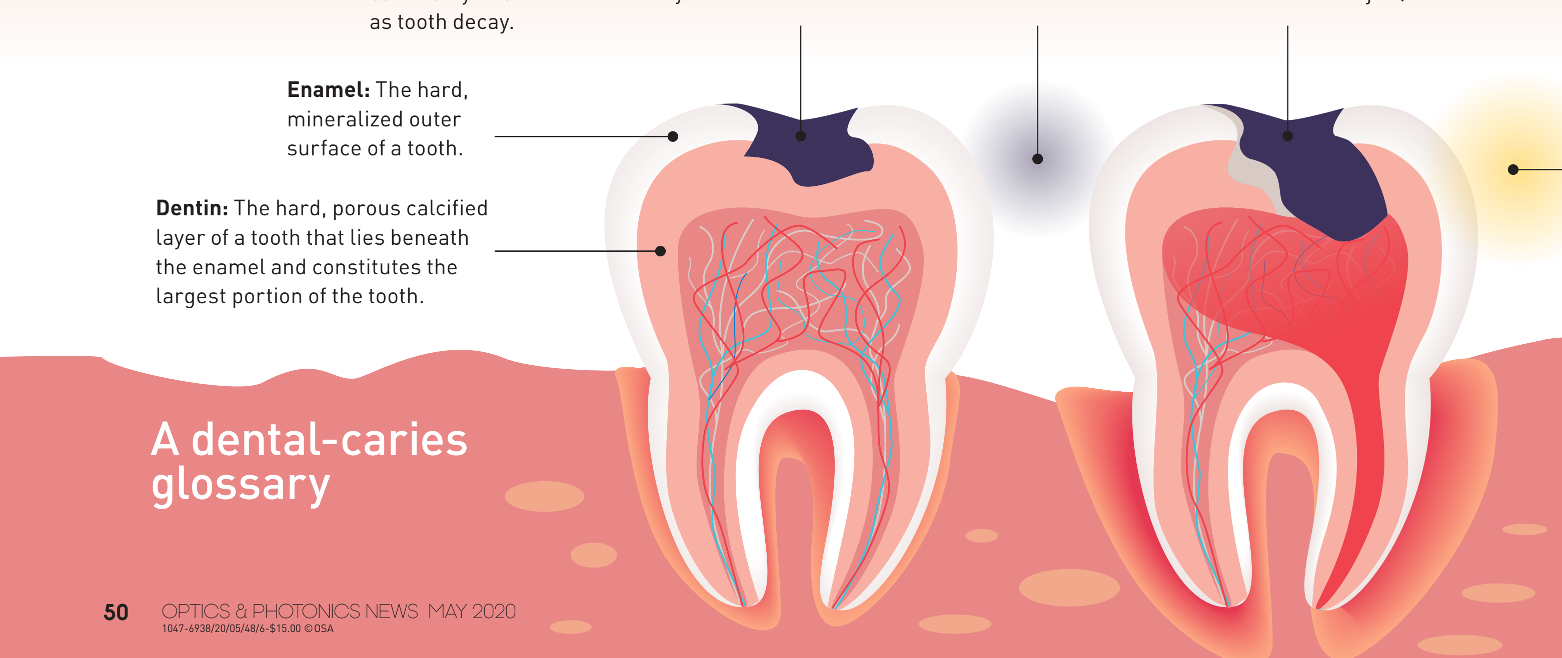
Caries lesion: An area in a tooth, commonly called a cavity, that has been demineralized by the activity of oral bacteria.

Interproximal lesion: A cavity situated in areas between adjoining teeth.

Occlusal lesion: A cavity located on the tooth crown (the area where the tooth makes contact with teeth in the other jaw).

Enamel: The hard, mineralized outer surface of a tooth.

Dentin: The hard, porous calcified layer of a tooth that lies beneath the enamel and constitutes the largest portion of the tooth.



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New optical imaging devices that use fluorescence and near- and shortwave-infrared light have become available to dentists, and OCT-based dental systems are under development.

beneath the hard outer layer of tooth enamel. At that point it's too late for nonsurgical intervention to be effective, and the dentist's drill comes out.

Radiography is more sensitive to the interproximal lesions, located between teeth. Even there, however, X-rays typically underestimate the penetration depth of the lesion. New, more sensitive methods are needed to detect these lesions, and to determine whether they are active or have been arrested.

Optical alternatives

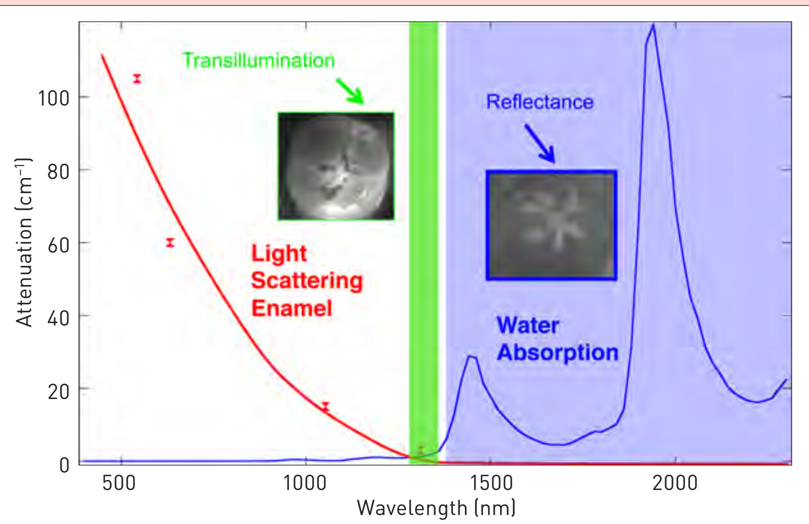
Optical methods are not new to characterizing teeth or studying dental caries; polarized-light microscopy, for example, has been used for more than a century. Understanding the potential for new forms of optical imaging in the dental suite, however, requires some background on how caries form.

Oral bacteria, fed by fermentable carbohydrates, produce organic acids that dissolve tooth structure, demineralizing the enamel and dentin. The mineral loss, in turn, leads to pores that create the subsurface lesion areas, and the demineralized tooth structure strongly scatters light. Radiography detects the changes in mineral loss, while optical methods detect changes in light scattering. The acids and bacteria can penetrate deeper into the tooth through the enamel, and spread rapidly through the underlying dentin into the tooth's interior before the decay is visible on a dental X-ray.

If fluoride is present in saliva, lesion areas can be remineralized and arrested by the deposition of fluorapatite, a mineral that fills the pores near the surface of the lesion, forming a highly mineralized, transparent cap. This surface layer, or "scar," over the lesion inhibits its diffusion, arresting further progression. Since the body of the arrested lesion typically remains visible, though, it is difficult for dentists to differentiate between those lesions that are active and progressing and those that are arrested. New optical imaging methods can help dentists to determine if a transparent surface layer has formed over the lesion, and to assess whether the lesion is active.

The first successful optical caries detection devices have employed fluorescence, with several commercial devices already available. Fluorescence-based

Transillumination: The shining of light through an object (such as a tooth) to check for subsurface abnormalities. X-rays are typically used to transilluminate teeth, and lesions are radiolucent due to the lower density of lesion areas.

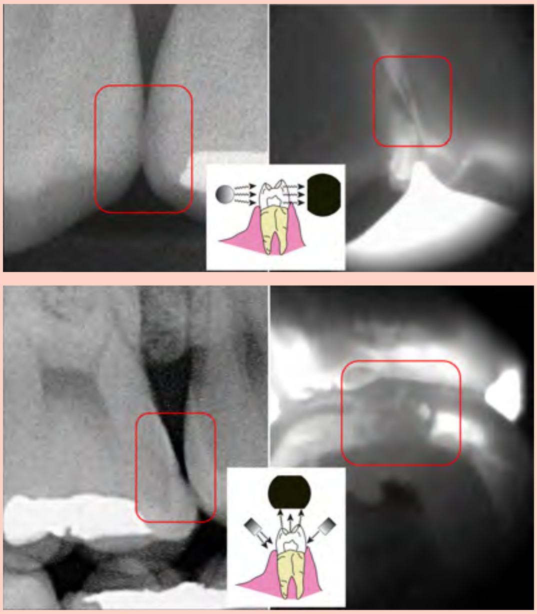


Both light scattering in enamel (red trace) and absorption by water (blue trace) are low at wavelengths near 1300 nm, making those wavelengths best for transillumination. Wavelengths above 1400 nm are best suited for study by reflectance, as scattering in enamel continues to decrease and water absorption does not decrease the contrast between healthy and demineralized tissues.

A.F. Zandona and C. Longbottom, eds., *Detection and Assessment of Dental Caries* (Springer, 2019)

The use of OCT in dentistry was first investigated more than 20 years ago, and many studies have since demonstrated its great potential for imaging dental caries.

IR light roots out decayed areas



Bitewing X-rays (left) are contrasted with NIR images (right) for proximal transillumination (top row) and occlusal transillumination (bottom row). Because of the high transparency of enamel to NIR light, lesions (red boxes) poorly visible in the radiographs show up with high contrast in the NIR images.

In a tooth that included a stained fissure (color image, left), SWIR cross-polarization reflectance imaging (1500-1750 nm, middle) and occlusal transillumination (1300 nm, right) confirmed an earlier X-ray diagnosis of an interproximal lesion (circled area), but showed that the clinicians' diagnosis of a second lesion in the fissure on the tooth crown was a false positive, attributable to the stain in the fissure.

M. Staninec et al., Lasers Surg. Med. **42**, 292 (2010)
J.C. Simon et al., Lasers Surg. Med. **49**, 215 (2017)

detection devices use one of two approaches. The first relies on the native fluorescence of collagen, present in the dentin that lies beneath the enamel. Lesions on the surface attenuate the collagen's green fluorescence (excited by UV and blue light), making the lesion areas appear darker than the surrounding, sound areas of the tooth.

The other fluorescence approach relies on porphyrins, which originate from hemoglobin and bacteria and which can also become concentrated in the pores of lesions. Porphyrins can be excited by blue to red wavelengths to fluoresce in the red and NIR. The first widely used commercial device exploiting this fluorescence was the Diagnodent from Kavo (Biberach, Germany), developed specifically to detect the "hidden" lesions below the occlusal surface that don't show up on radiographs. The Diagnodent uses longer-wavelength, 655-nm light to achieve greater optical penetration in the tooth.

The long-wavelength advantage

Light scattering in dental enamel is strong at blue wavelengths and decreases by orders of magnitude at NIR and SWIR wavelengths. Enamel is at its most transparent near 1300 nm; therefore, 1300 nm is optimal for transillumination—shining light through the tooth. At longer SWIR wavelengths, water absorption increases, and reflectance imaging for assessing demineralization improves markedly. That's because the increase in water absorption, along with the further decrease in light scattering, reduces the reflectivity from the tooth's sound areas, putting the lesion areas into much higher contrast.

Tooth surfaces are somewhat porous and rapidly accumulate stains, which absorb light strongly and often fluoresce as well. Because dentists use visual examination to identify some cavities, these stained areas can cause false positives—particularly in the pits and fissures of the occlusal surfaces, where most new decay is found and which can't be cleaned effectively. The highly conjugated organic molecules responsible for staining do not absorb light at longer wavelengths, however, and most stains are transparent beyond 1200 nm, in the SWIR. Imaging at wavelengths beyond 1200 nm is thus advantageous not only because of the higher transparency of enamel, but because the interference from exogenous stains is avoided.

In addition to proximal transillumination—in which light is directed between teeth, in a geometry similar to that of a dentist's bite-wing X-ray—NIR or SWIR light can be directed at the gums at the base of the tooth, with the light transmitted up through the occlusal surface, an approach called occlusal transillumination. Reflectance imaging of the occlusal surface is also valuable for viewing both occlusal and interproximal lesions—and can even pick up false positives in diagnosis attributable to tooth staining.

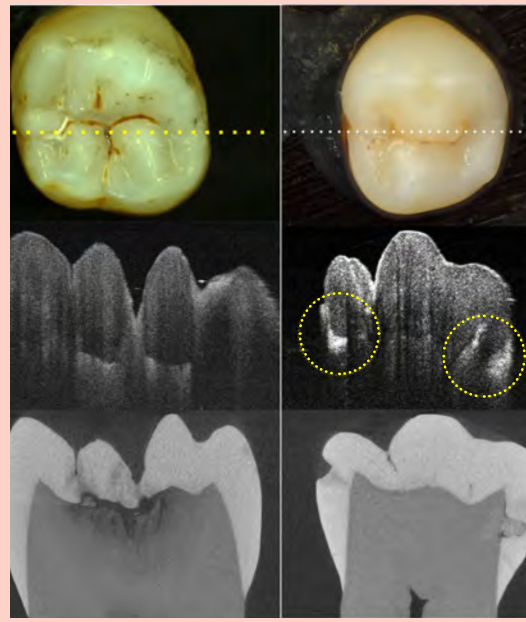
Clinical studies have shown that NIR imaging can achieve higher diagnostic performance than radiographs, and several NIR imaging systems are available commercially for caries detection. Current commercial systems, however, are only available at wavelengths less than 1000 nm, because of the high cost of sensors at longer wavelengths.

OCT goes dental

The use of OCT in dentistry was first investigated more than 20 years ago, and many studies have since demonstrated its great potential for imaging dental caries. OCT systems commonly operate near 1300 nm, which is convenient for imaging deep into the tooth; the high transparency of enamel at 1300 nm makes optical penetration exceeding 5 mm possible. Thus OCT has the potential to image occlusal and interproximal lesions from the crown of the tooth.

OCT images can show the subsurface spread and penetration of occlusal caries lesions not visible on radiographs, and can also acquire high-resolution images of lesion structure that are valuable not only for assessing the depth and severity of lesions, they can also be used for judging whether lesions are active or arrested. And OCT can be used to monitor lesions to determine if nonsurgical intervention is successful. Further, cross-polarization can be used to increase the contrast of caries lesions in OCT images. An outer, transparent (dark) zone over a bright lesion area in cross-polarized OCT, for example, can clearly show where remineralization treatment has arrested lesion growth.

At present, no clinical dental OCT systems are commercially available. As performance and speed continue to improve and cost decreases, however, systems should soon be available to dentists—opening yet another optical front in the fight against cavities. OPN



In vitro color, OCT and microCT images of two extracted teeth with occlusal and interproximal lesions. Dotted lines show line of section; lesions are in the yellow circles. OCT images were acquired using a high-speed prototype swept-source OCT system from Axsun Technologies (Billerica, MA), equipped with a MEMS-based scanner capable of acquiring 3D images of an entire tooth.

A.F. Zuluaga et al., Proc. SPIE, v. 10857, Pres. E (2019)

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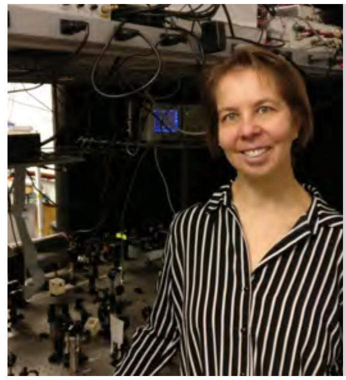
OSA Update

Thank You, Editors

We are happy to announce that the following individuals were recently appointed as new editors: *Applied Optics*: **Pengfei Wang**, Harbin Engineering University, China. *Optical Materials Express*: **Shekhar Guha**, U.S. Air Force Research Laboratory and University of Dayton, USA. *Optics Letters*: **Tatiana Alieva**, Universidad Complutense de Madrid, Spain.

We thank the following editors for agreeing to serve a second term: *Biomedical Optics Express*: **Feng Gao**, Tianjin University, China; **Ioan Notingher**, University of Nottingham, U.K. JOSA B: **Hong Wei**, Institute of Physics, Chinese Academy of Sciences, China; **Yanhong Xiao**, Fudan University, China. *Optica*: **Irene Georgakoudi**, Tufts University, USA; **Adam Wax**, Duke University, USA. *Optical Materials Express*: **Xing Sheng**, Tsinghua University, China.

We thank the following editors, who have recently finished their terms, for their years of service: *Applied Optics*: **Jung-Ping Liu**, Feng Chia University, Taiwan; **Ileana Rau**, Politehnica University of Bucharest, Romania; **Yunlong Sheng**, Université Laval, Canada; **Kimani C. Toussaint**, University of Illinois, Urbana-Champaign, USA. JOSA A: **Rosario Martinez-Herrero**, Universidad Complutense de Madrid, Spain. *Optics Express*: **Hilmi Volkan Demir**, Nanyang Technological University LUMINOUS!, Singapore, and Bilkent University UNAM, Turkey; **Tero Setala**, University of Eastern Finland, Finland.



Courtesy of Irina Novikova

OSA Fellow Stories

"You just meet people, and sometimes, even after the fact, you realize how important their influence on your life was," says OSA Fellow **Irina Novikova**, College of William and Mary, USA, about finding support and collaboration. "The most exciting things happen when we talk to other people," says Novikova. "New knowledge emerges." Read more about Novikova and other Fellows at **www.osa.org/fellowprofiles**.

Celebrate Virtually on 16 May

The organizers of the International Day of Light (IDL) 2020 anticipate that in-person IDL events planned for 16 May will not take place due to global containment measures for COVID-19. As gatherings are highly discouraged, OSA recommends that all events be either postponed or conducted virtually. Please direct funding questions to **lightday@osa.org**.

This is an opportunity to share digital content about the importance of light—and to celebrate on social media. OSA encourages everyone to share stories, history and research about light science's importance by using the hashtags #idl2020 and #SeeTheLight. Check out our infographic on p. 14 for some other ideas on celebrating light virtually!

OSA Board of Directors Meet Online: In April, OSA's leadership took advantage of digital tools to meet as planned and continue to work on addressing the challenges our community faces.

Getty Images

Advancing Gender Parity in Optical Communications

Congratulations to the 13 women who received the Women in Optical Communications Scholarships and Travel Grants. The OSA Foundation and Corning Inc. established this program to support women scholars in optical communications and to help advance gender diversity in the industry. Due to travel challenges, all participants had the option to defer their prizes to 2021.

Shaimaa Azzam, Purdue University, USA, **Ann Margareth Rosa Brusin**, Politecnico di Torino, Italy, and **Fatemeh Ghaedi Vanani**, CREOL, University of Central Florida College of Optics and Photonics, USA, each received merit-based scholarships. The following women received grants to travel to OFC: **Hannah Watson**, University of Cambridge, U.K.; **Svenja Mauthe**, Eidgenössische Technische Hochschule, Switzerland; **Monette Khadr**, SUNY Albany, USA; **Yan Fu**, Shanghai Jiao Tong University, China; **Riti Gour**, University of Texas at Dallas, USA; **Yating Wan**, University of California Santa Barbara, USA; **Erin Knutson**, Tulane University, New Orleans, Louisiana, USA; **Ligia Moreira Zorello**, Politecnico di Milano, Italy; **Uiara de Moura**, Technical University of Denmark, Denmark; **Mai Banawan**, Université Laval, Canada.

Thank You, Volunteers

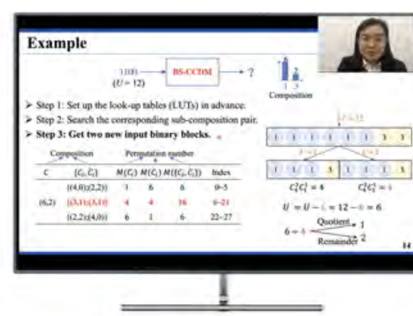
Thank you to the chairs of the OSA Quantum 2.0 Conference: **Ronald Holzwarth**, Menlo Systems GmbH, Germany; **Christopher Monroe**, University of Maryland at College Park, USA; **Michael Raymer**, University of Oregon, USA.

OSA/ Marcia Lesky

Left: David Welch, Infinera, USA, delivers his presentation "How the Future Began." See it here: www.ofcconference.org/keynote. Right: OFC co-chair Jun Shan Wey speaks with attendees about her career path in the Nagel Lounge.

OFC Highlights

OFC was held in San Diego, CA, USA—and virtually, worldwide—in March. Among many dynamic presentations and activities, the event "Celebrating 50 Years of Light-Speed Connections" stood out as a conference highlight. The celebration honored two significant technical achievements in 1970 that led to the development of practical fiber optic communications: the demonstration of low-loss fibers and the first room-temperature semiconductor lasers.

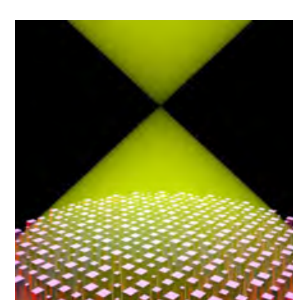


Mengfan Fu presents her prize-winning paper virtually at OFC.

The Suzanne R. Nagel Lounge, an inclusive networking space where attendees could discuss diversity efforts, meet colleagues and explore new business opportunities, was another conference highlight. Professional development sessions ranged from resume writing to navigating the industry, and attendees were encouraged to get complementary headshots taken. Several speakers are offering remote versions of their talks at **www.osa.org/diversity**.

The Corning Student Paper Competition, which was piloted as a virtual competition this year via Zoom, was also held at the conference. The grand prize winner was **Mengfan Fu**, Shanghai Jiao Tong University, China. Fu presented her paper, "Parallel bisection-based distribution matching for probabilistic shaping," at OFC (remotely).

OSA Hosts Flat-Optics Incubator



Vyshakh Sanjeev/ Harvard SEAS

From 26 to 28 February, OSA hosted an incubator meeting on the emerging field of flat optics at OSA Headquarters in Washington, DC, USA. Attendees also participated virtually. The meeting covered topics such as generating, optimizing, fabricating and applying flat optics, with special attention to recent advances in the area of customizable and controllable metasurfaces. Various applications of flat optics were also discussed, including their use in augmented reality/virtual reality (AR/VR) systems. Attendees spoke collaboratively on the appropriate applications for rapidly maturing flat-optics technologies and crafted a roadmap for the future.

OSA/OIDA & OSA Partner Meetings

In light of the COVID-19 (coronavirus) pandemic, OSA is exploring all options for upcoming OSA Events. Please visit the individual meetings pages for updates.

VIRTUAL MEETINGS

CLEO Conference

11 – 15 May 2020, Pacific Daylight Time (PDT), GMT-07:00

www.CLEOConference.org

OSA Imaging and Applied Optics Congress

22 – 26 June 2020, Pacific Daylight Time (PDT), GMT-07:00

- *3D Image Acquisition and Display: Technology, Perception and Applications (3D)*
- *Adaptive Optics: Methods, Analysis and Applications (AO)*
- *Computational Optical Sensing and Imaging (COSI)*
- *Digital Holography and Three-dimensional Imaging (DH)*
- *Imaging Systems and Applications (IS)*

www.osa.org/ImagingOPC

OSA Optical Sensors and Sensing Congress

22 – 26 June 2020, Pacific Daylight Time (PDT), GMT-07:00

- *Applied Industrial Spectroscopy (AIS)*
- *Laser Applications to Chemical, Security and Environmental Analysis (LACSEA)*
- *Optical Sensors (Sensors)*
- *Optics and Photonics for Sensing the Environment (ES)*
- *Propagation Through and Characterization of Atmospheric and Oceanic Phenomena (PcAOP)*

www.osa.org/SensingOPC

OSA Advanced Photonics Congress

13 – 16 July 2020, Eastern Daylight Time (EDT), GMT-04:00

- *Nonlinear Photonics (NP)*
- *Novel Optical Materials and Applications (NOMA)*
- *Optical Devices and Materials for Solar Energy and Solid-state Lighting (PVLED)*
- *Photonics in Switching and Computing (PSC)*
- *Photonic Networks and Devices (Networks)*
- *Signal Processing in Photonic Communications (SPPCom)*
- *Specialty Optical Fibers (SOF)*

www.osa.org/PhotonicsOPC

AS SCHEDULED

OSAF Siegman International School on Lasers

18 – 25 July 2020, University of Warsaw, Chęciny, Poland

www.osa.org/SiegmanSchool

OSAF Innovation School

21 – 25 July 2020, OSA Headquarters, Washington, DC, USA

www.osa.org/Innovation

OSA Incubator on Visual Perception in AR/VR

23 – 25 July 2020, OSA Headquarters, Washington, DC, USA (invitation only)

www.osa.org/VisualPerceptionInc

14th Pacific Rim Conference on Lasers and Electro-Optics (CLEO-PacRim)

2 – 6 August 2020, International Convention Centre Sydney Sydney, New South Wales, Australia

www.CLEOPR2020.org

OSA Frontiers in Optics + Laser Science APS/DLS

13 – 17 September 2020, Washington Marriott Wardman Park, Washington, DC, USA

www.FrontiersinOptics.org

OSA Laser Congress

12 – 16 October 2020, Québec City Convention Centre, Québec City, Québec, Canada

- *Advanced Solid State Lasers Conference (ASSL)*
- *Laser Applications Conference (LAC)*

www.osa.org/LaserOPC

OSA 2nd Annual 5G Summit

21 – 22 October 2020, OSA Headquarters, Washington, DC, USA

www.osa.org/5g

OSA Latin America Optics and Photonics Conference (LAOP)

16 – 19 November 2020, Mar Hotel, Recife, Pernambuco, Brazil

www.osa.org/LAOP

CANCELLED

OIDA Forum on Optics in Autonomy and Sensing

24 June 2020, San Jose McEnery Convention Center, San Jose, CA, USA

OSA Applied Industrial Optics Topical Meeting*

20 – 22 July 2020, OSA Headquarters, Washington, DC, USA

**Three webinars featuring topics from the meeting will be presented over the same time period.*

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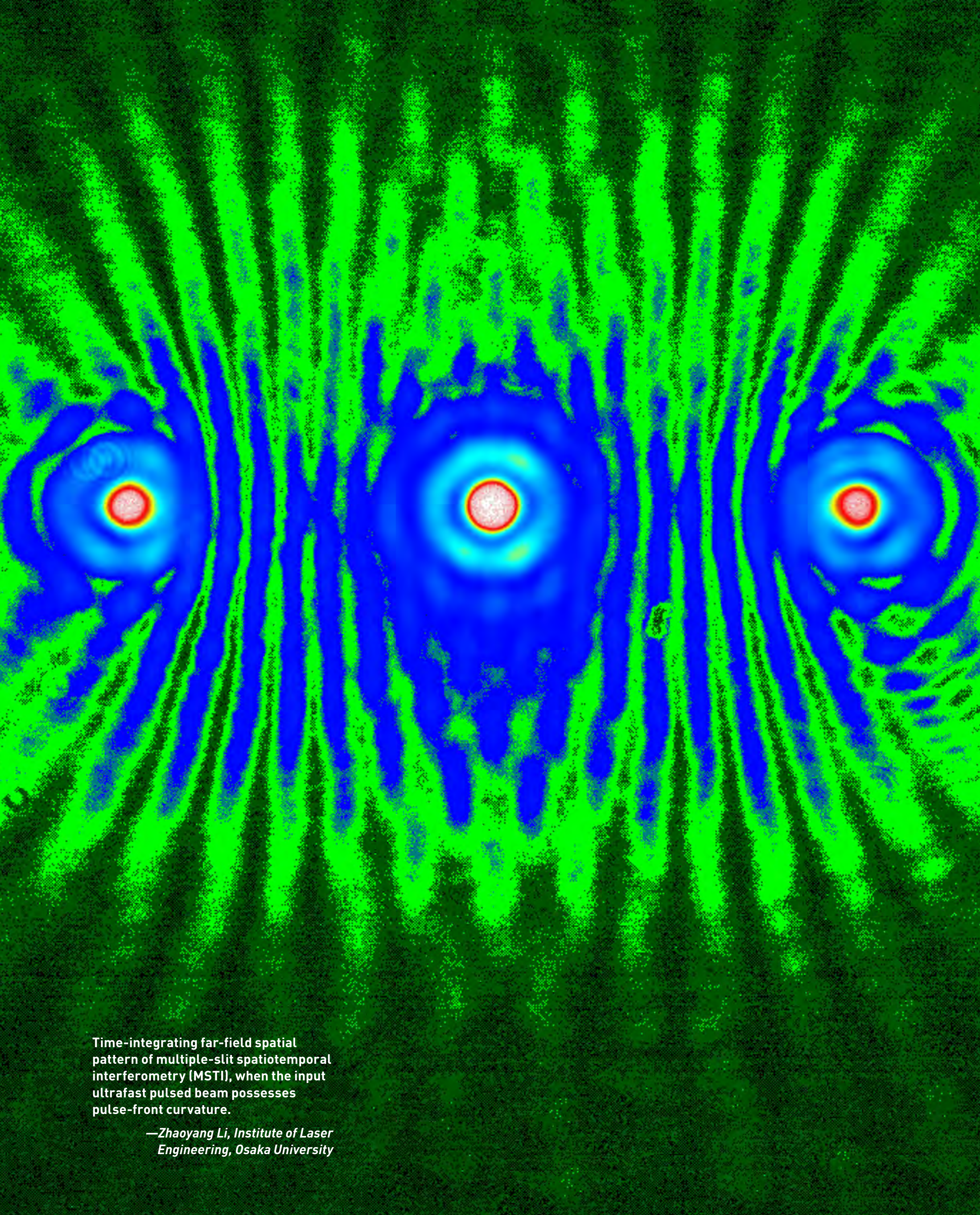

Time-integrating far-field spatial pattern of multiple-slit spatiotemporal interferometry (MSTI), when the input ultrafast pulsed beam possesses pulse-front curvature.

—Zhaoyang Li, Institute of Laser Engineering, Osaka University