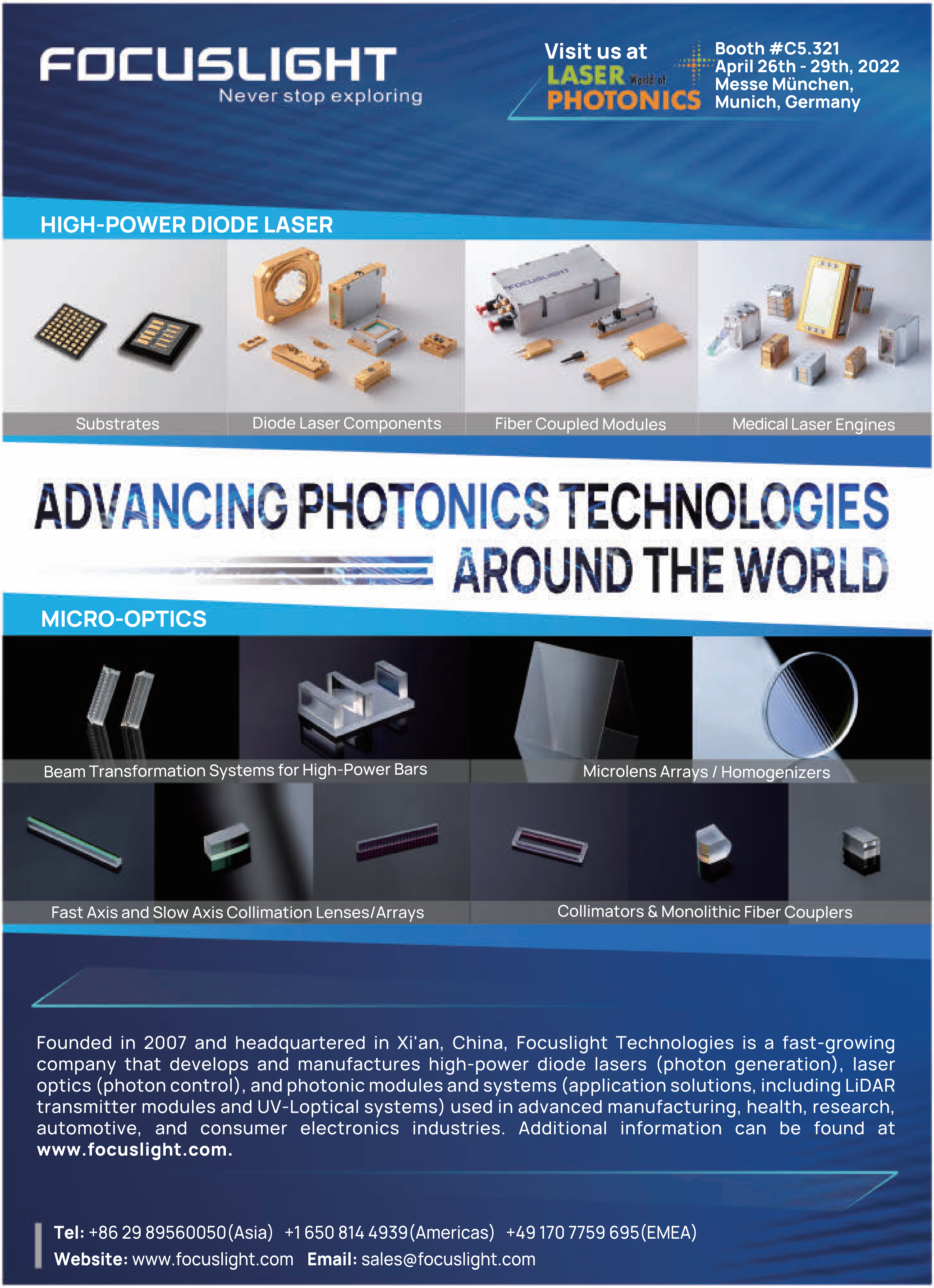
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Titanium additively manufactured components are very suitable for biomedical applications, such as facial implants. (Courtesy of TRUMPF)

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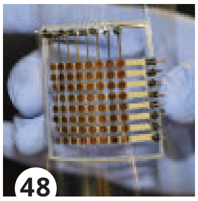

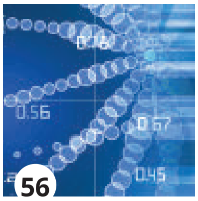

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Uncertainty never fades

HAVING OWNED and operated successful manufacturing operations throughout my career, I have always known strategically dealing with uncertainty is a crucial part of the puzzle. Businesses need to balance lean philosophies with redundancy.

Of course, when the pandemic surfaced, it took the challenges associated with uncertainty to a new level—dealing with mandates, workforce fluxes, and supply chain issues. The pandemic put business strategies to the ultimate test. For those enjoying success, the pandemic spotlighted diligence, agility, and the ability to pivot when needed to capitalize on opportunities to remain stable and in some instances thrive.

As the pandemic becomes an endemic, face-to-face events have resurfaced with LASER World of PHOTONICS taking place this month in Munich, Germany. While not quite "business as usual," most organizations have seemingly figured out how to effectively operate within the new norm.

Photonics companies will undoubtedly leverage the Munich show as a powerful chance to interact with customers and prospects alike. And many companies will use the show floor as an opportunity spotlight innovations and recent successes. The inspiring story of TRUMPF Photonics and SICK's successful collaboration in this issue on page 52 is a prime example.

Unfortunately, even as business is ramping up, the war in Ukraine has once again ushered in a new layer of uncertainty. Beyond the undeniable humanitarian implications, the ongoing battles coupled with an array of sanctions have further crippled already stressed supply chains.

While neither Russia nor Ukraine are big exporters nor importers of photonics components, the turmoil has changed trade routes resulting in the suspension of various logistical services, as well as rapidly escalating costs for air freight that routinely travels over Russia airspace.

With the ongoing restructuring of traditional trade routes not part of the new norm, ING anticipates, "delivery of crucial preliminary products to European manufacturers will be delayed, if they arrive at all. On top of that, scarcity and delays mean further price pressures, resulting in rising prices for producers and consumers."

How the war will impact trade long-term is unknown, but one thing is clear: those businesses keenly focused on innovation will navigate through whatever uncertainties arise.

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WORLD NEWS

Technical advances from around the globe

INTENSE LASERS

Opening up a new realm of extreme laser plasma physics

A group of researchers from Japan and Taiwan recently achieved direct energetic ion acceleration by irradiating a target made of the world's thinnest, strongest material—graphene—with an ultra-intense laser (J-KAREN) at the Kansai Photon Science Institute in Japan.

Theory shows that a thin target is required for higher ion acceleration, but it's notoriously difficult to directly accelerate ions in an extremely thin target regime because noise components in the light from an intense laser destroy the targets before the main peak of the laser pulse arrives.

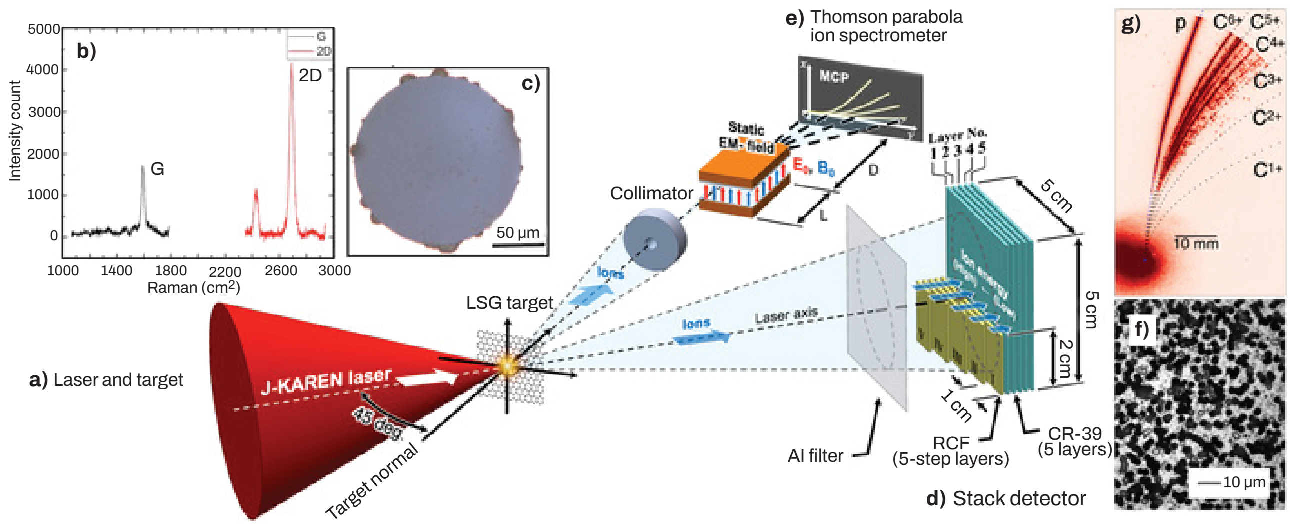
"We've been working on a laser-driven ion acceleration with intense lasers, and when I wanted an ion beam for electromagnetic field diagnostics for a laboratory astrophysics experiment, one of my colleagues warned me of a serious problem: radioactive contamination of the target chamber when they'd shot a relatively thick target," says Yasuhiro Kuramitsu, an assistant professor at Osaka University's Institute of Laser Engineering.

Normally, researchers use lead to stop radiation from the laser-target interactions. In this case, they were dealing with "a relatively small laser system built within the physics department, which was already using many lead blocks for the electron acceleration experiment," Kuramitsu adds. "But the floor couldn't tolerate any more weight."

So they set out to suppress the radiation itself. "The radiation comes from interactions between hot electrons heated by the intense laser and the nuclei within the target material," says Kuramitsu. "We needed to reduce the number of nuclei and target thickness."

The solution came in the form of graphene, which happens to be the thinnest 2D material. Monolayer graphene is transparent, highly electrically and thermally conductive, lightweight, and ideal for laser-driven ion sources.

One day while Kuramitsu and Wei-Yen Woon, a researcher who specializes in graphene, were waiting in line for their daughters at kindergarten, Kuramitsu asked him: "Can you make a free-standing large-area graphene?" Woon said it would be easy and he'd bring a large, suspended graphene (LSG) sample over.



(IMAGE CREDIT: KURAMITSU/OSAKA UNIVERSITY)

Schematics of the experiment are shown; by irradiating a large-area suspended graphene target (LSG) with the ultra-intense J-KAREN laser, energetic ions are generated (a). (b) and (c) show the Raman spectrum and microscope image of graphene, respectively; (d) and (e) show a schematic drawing of a stack detector using solid-state path trackers and a Thomson parabola spectrometer (TPS), respectively; and (g) and (f) show the typical data from TPS and stack, respectively.

"To date, graphene has a variety of applications, including in transportation, medicine, electronics, and energy," says Woon. "We were able to demonstrate another disruptive application of graphene within the field of laser-ion acceleration, in which the unique features of graphene play an indispensable role."

The researchers accomplished this via the J-KAREN ultra-intense short-pulse laser used with an optical parametric chirped-pulse amplifier (OPCPA) and a short-focal-length off-axis parabolic mirror (OAP) tight-focus beam, which results in an intensity of ~10^{22} W/cm^2 (see figure). They were stunned to realize energetic protons and carbon ions at such a high intensity—without requiring a plasma mirror irradiating the graphene targets. A plasma mirror is usually necessary to remove noise components.

Direct irradiation of LSG targets generates MeV protons and carbon ions from subrelativistic to relativistic laser intensities, from low- to high-contrast conditions without a plasma mirror. This demonstrates how durable graphene is. "No one believed the results at first glance, even some of our collaborators," Kuramitsu notes. "Laser plasma physics researchers aren't familiar with graphene."

Pre-pulses and pedestals always accompany an intense laser pulse; these destroy the thin targets before the arrival of the main pulse. "Normally, a double-plasma mirror is necessary to remove the pre-pulse and pedestal when an extremely thin target is irradiated by an intense laser," Kuramitsu explains. "We conducted many experiments with different types of lasers, and we realized graphene is quite different from 3D materials we normally use for laser targets."

While the researchers' work shows extremely high carbon-ion energies, they still don't understand how the carbon ions are accelerated. "We believe graphene and the intense laser are opening up a new realm of extreme laser plasma physics," says Kuramitsu. "We're also planning to use graphene as a mount to accelerate other materials that can't be suspended by themselves, such as extremely thin metals, nanostructure targets, and so on."

Their findings may help develop compact and efficient laser-driven ion accelerators for cancer therapy, laser nuclear fusion, high-energy physics, and laboratory astrophysics. They published their initial work in *Scientific Reports*,[1] and say they will share more results soon.—SALLY COLE JOHNSON

REFERENCE

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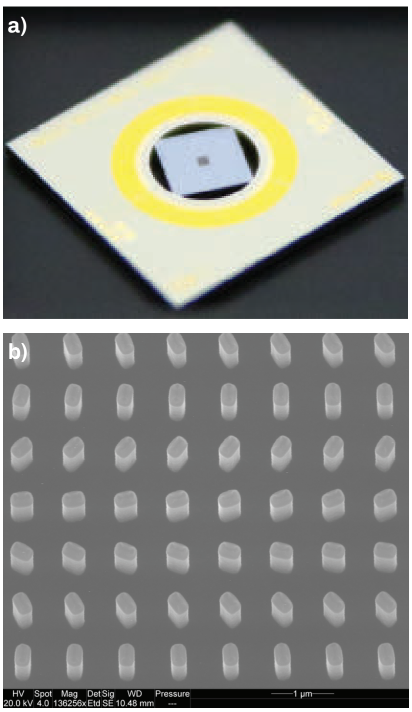
METASURFACE OPTICS

New MEMS metasurface technology allows tunability, adaptability

Electronics and handheld devices such as wearables, smartphones, and tablets continue to get smaller, lighter, and more compact. Optical devices, however, have been slow to follow suit, as the working principle of refractive optical components such as lenses hasn't deviated much from their inception. A team in Norway is now working to change that with a new tunable lens.

In their study, the team from SINTEF Smart Sensors and Microsystems (Trondheim, Norway) used metasurfaces—ultrathin planar optical components composed of subwavelength nanostructures that manipulate light—to develop a MEMS (micro-electro-mechanical system) tunable dielectric lens.[1]



(COURTESY OF CHRISTOPHER DIRDAL, SINTEF SMART SENSORS AND MICROSYSTEMS)

In developing their new tunable lenses, SINTEF researchers suspended a metasurface on a square silicon chip in a thin-film PZT MEMS-actuated ring (yellow; a). An electron microscopy image shows the nanostructure of the metasurface located at the center of the suspended silicon chip (b); the spacing from pillar to pillar is 835 nm, around 50 times thinner than a strand of hair.

Metasurfaces are ideal for ultracompact optical devices because they can be subwavelength-thin and with micro- and nanofabrication techniques, according to the researchers, are easily integrated into the manufacture of smaller devices.

The new MEMS-tunable dielectric metasurface lens works similar to the lens within the eye, bringing objects at different distances into focus. "While the lens within your eye achieves this through deformation by muscular straining or relaxing, our device does this by shifting the distance between two metasurface lenses," says Christopher Dirdal, a research scientist at SINTEF Smart Sensors and Microsystems. Thin-film piezoMEMS (piezoelectric MEMS) architecture made this shift possible. "Tunable metasurfaces offer a range of new possibilities and piezoMEMS is an excellent platform to harness those," he says.

The focal length changes when applying low voltage—a quarter of that used in existing similar technology. The researchers did this to lead zirconate titanate (PZT) membranes, causing them to deform. Tunability in traditional optical systems requires bulky, power-consuming components.

To get to this point, the researchers fabricated a metasurface chip and inserted it into a MEMS actuator designed for piston and tip/tilt movements (see figure). They used nanoimprinting, in which a mask of nanostructures is pressed and the resulting pattern transfers to a silicon substrate via deep-reactive ion etching, explains Dirdal. "The metasurface structure is designed to act as a lens," he says.

The team measured the focus shift through the distance the objective lens needed to be moved to regain focus upon full-range MEMS displacement of the metalens. By applying 23 V, they achieved a ~250 μm focal length shift by placing the metasurface 7.2 μm away.

MEMS metasurfaces can also act as a varifocal lens doublet. To demonstrate this, a second metasurface lens was placed after the MEMS metasurface. The two were held in place by separate holders that can be moved relative to each other for ease of alignment. And the separation distance between the lenses is varied by the MEMS displacement, which allowed the team to tune and adapt the focal point of the lens doublet.

"Most systems incorporating metasurfaces so far are static, meaning the optical functionality is locked after fabrication," Dirdal says. But tunability and adaptability are necessary for cameras, 3D-mapping lidar systems, drone-based mapping, and holographic displays. The MEMS metasurface technology also shows potential for biomedical applications because it allows imaging of tissue at different depths to better see and study things like neurons and blood vessels.

Dirdal says his team is now looking to further optimize its MEMS architecture to develop a commercially relevant tunable lens device. —JUSTINE MURPHY

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1. C. A. Dirdal et al., *Opt. Lett.*, 47, 1049–1052 (2022); doi:10.1364/ol.451750.

BIOSENSORS

Optically pumped single-mode laser enables integrated device biosensor

Interferometry is a sensitive optical detection method quantifying changes in optical path length and is useful for biological and biochemical detection, because biological specimens tend to be optically transparent.

One general interferometric sensor design approach involves monitoring output intensity as the refractive index changes when a target analyte is introduced to one interferometer leg. An interferometer, though, requires precision optical alignment, generally of a laser source. "Precision optical alignment" is a term that doesn't conjure images of rapid and inexpensive clinical testing.

A team of Austrian researchers has developed a diode-pumped lab-on-a-chip design capable of sensing analyte concentrations under a microgram per milliliter, using an inexpensive, misalignment-tolerant diode laser as a pump.

Building on previous work,[1] the team uses the diode as an optical pump for a single-mode organic solid-state laser (OSSL) integrated into a silicon dioxide/silicon nitride (SiO_2/SiN) photonic circuit combined with a microfluidic device.[2] With the laser output coupled into a Mach-Zehnder interferometer (MZI), the device provides high sensitivity with speed and ease of use, opening the door for future clinical applications.

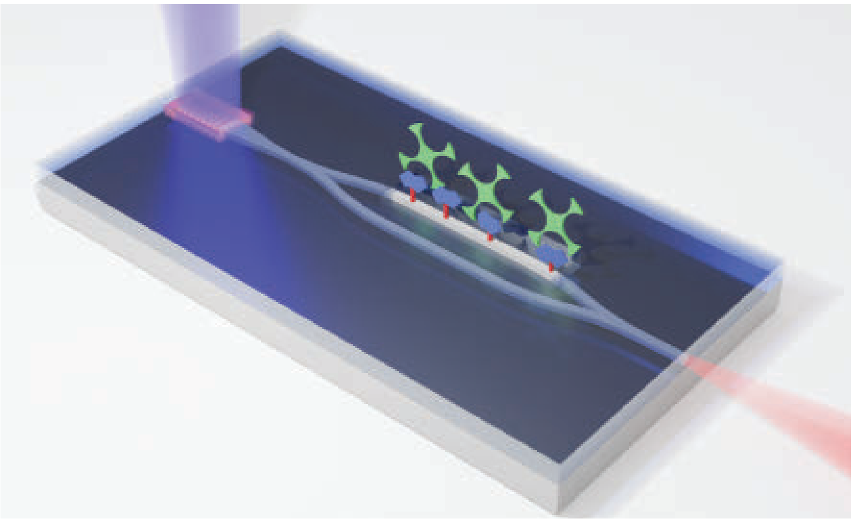
Medical treatment decisions are driven by knowledge, often obtained through laboratory testing of biomedical samples—fluids or tissue. Ideally, an analytical method would be capable of detecting low analyte concentrations in small samples, and doing so rapidly, inexpensively, and easily.

As is often the case, these requirements are somewhat contradictory. For example, optical interferometry can detect very small changes in the index of refraction, so a typical sensor architecture relies on capturing an analyte in one interferometer leg while monitoring the transmitted intensity change at the interferometer output. The analyte's presence modifies the index of refraction, so the phase difference between the measurement beam and the reference beam varies, resulting in an intensity change.

To achieve maximum sensitivity with a small sample, this approach requires accurate and efficient coupling of a single-mode laser into a miniaturized interferometer. This, in turn, demands either integrating a single-mode semiconductor laser directly into the miniaturized device, or precise alignment of an external laser source to the interferometer input. These approaches add cost or both cost and difficulty, respectively, to the analysis.

A research team led by the Austrian Institute of Technology (AIT; Vienna, Austria) has overcome those challenges by incorporating a single-mode OSSL into an integrated photonic/microfluidic device.

The optical waveguide is fabricated by plasma-enhanced chemical vapor deposition of SiN on a SiO_2 layer built on a silicon wafer substrate, which is then topped with another SiO_2 layer—except in two regions: the laser cavity and one leg of the MZI. A 300 × 75 μm region over the laser cavity is then filled with dye-doped polymer. A distributed feedback



A new photonic integrated circuit uses an inexpensive diode laser to pump an on-chip single-mode laser through a silicon nitride waveguide interferometer. With one leg of the interferometer biofunctionalized, the device becomes a rapid and accurate biosensor.

grating structure is built into the laser cavity to constrain to single-mode operation at 605 nm. The output is coupled to a tapered waveguide 375 × 160 nm in cross-section, which links to a Y-branch separating into two interferometer legs, which are then recombined through another Y-branch structure. A 10 mm length over one of the interferometer legs is left uncovered; when mated with the microfluidic channels, the analyte can be introduced right onto the MZI waveguide. The output is coupled into a multimode optical fiber and sent to a detector.

OSSLs are relatively insensitive to the angle of optical pumping, so the organic dye in the cavity can be excited by an inexpensive multimode blue diode laser. The key here is the incorporation of the distributed-feedback structure into a silicon nitride photonic integrated platform, which effectively converts the short coherence length pump laser into an in-device coherence length long enough to ensure high contrast at the interferometer output. This configuration is the first dye-doped single-mode laser suitable for coupling directly into an optical waveguide.

After calibrating the device with various concentrations of sodium chloride solution in the analyte arm, the researchers functionalized this region with a streptavidin/biotin complex and then introduced a complementary analyte. They monitored the phase changeover for periods of up to 20 minutes, demonstrating the ability to measure concentrations as low as 0.5 μg/mL. "Our multidisciplinary team was gratified to see theoretical work, design efforts, and material development result in a real biofunctionalized device that performs as predicted," says Florian Vogelbacher, an AIT team member now at the Chinese Academy of Sciences in Beijing.

Rainer Hainberger, senior scientist at AIT, notes their next steps will include optimizing the laser resonator to reduce the lasing threshold and decrease the dye photobleaching. "Now that we've demonstrated a cost-efficient solution to create coherent light on an integrated photonic sensor platform," he says, "we believe photonic integrated devices will be more attractive for real-world biosensing applications."—RICHARD GAUGHAN

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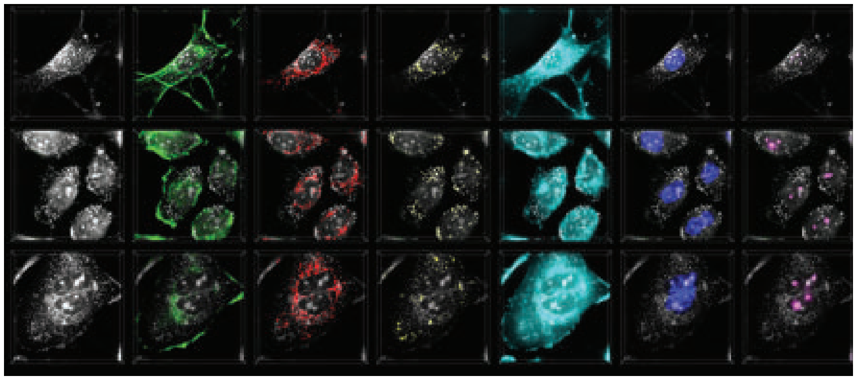
MICROSCOPY

Deep learning technique replaces fluorescent labeling in cell imaging

Fluorescence microscopy, a popular approach to cell imaging, offers very high biochemical specificity. The technique requires the manipulation or staining of cells with fluorescent labels to best extract proteins when imaging. Of course, it poses challenges. For instance, labeling impacts the basic structure of the cells, often resulting in several hours of delay before the cells can be observed. It also prompts photobleaching and phototoxicity.

Using a laser technique known as 3D holographic microscopy or holotomography to measure the 3D refractive index tomogram of microscopic biological cells and tissues, a team from the Korea Advanced Institute of Science and Technology (KAIST), in conjunction with Tomocube, has demonstrated the quantitative imaging of live cells in real time without using staining or labeling. In addition to quickly and accurately measuring the morphological and structural information of cells, holotomography provides limited biochemical and molecular information as well.

In their work, the researchers conducted measurements using a refractive index—an intrinsic quantity



(COURTESY OF KAIST)

Artistic rendering of the AI-based holographic microscopy concept.

governing light/matter interaction.[1] Specifically, they encoded 3D refractive index tomograms. Next, that information was decoded with a deep learning (AI)-based model that implies multiple 3D fluorescence tomograms from the refractive index measurements of the corresponding subcellular targets, which achieves multiplexed micro-tomography.

The quantitative relationship between the spatial distribution of the refractive index, discovered via AI and the major structures in cells, helped decipher the spatial distribution of the refractive index. The process avoids making subsequent changes to the cell structures, photobleaching, and phototoxicity, while still observing various types of cellular structures in their natural state in 3D and at the same time as fast as one millisecond. The researchers say this also allows long-term measurements over several days.

Fluorescence images can be "directly and precisely predicted from holotomographic images in various cells and conditions," according to the researchers. The team's new concept microscope "combines the advantages of several microscopes with the multidisciplinary research of AI, optics, and biology," says YongKeun Park, professor at KAIST.

The researchers note that "full 3D modeling of absolute and unbiased [refractive index] improves generalization, such that the approach is applicable to a broad range of new samples without retraining to facilitate immediate applicability."—JUSTINE MURPHY

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OPTICAL IMAGING

New imaging, software better assess 3D-printed metal

A new imaging technique could potentially boost additive manufacturing, simply by better analyzing and assessing the quality of metal alloy parts.

3D-printed metal alloys comprise various microscopic crystals differing in shape, size, and atomic lattice orientation. The new fast, low-cost method, developed by a team at Nanyang Technological University (NTU) in Singapore, allows a better understanding of those properties—among them, strength and toughness.

Matteo Seita, an assistant professor in NTU's School of Mechanical and Aerospace Engineering and School of

(COURTESY OF NTU SINGAPORE)

Unique crystal patterns are shown on the surface of a 3D-printed metal.

Materials Science and Engineering who co-authored the study, explains how the mapping compares to examining wood grain, which is strongest when the grain is continuous in the same direction.

A novel combo

The new optical method performs grain orientation mapping and uses machine learning and "smart software" to measure the crystal orientation from acquired optical signals. A convolutional neural network is used to predict the crystallographic orientation from the optical signal acquired through directional reflectance microscopy (DRM), which is a method that quantifies surface reflectance as a function of illumination angle.

"Currently, it is impossible to tell the difference between good 3D-printed metal parts and the faulty ones unless we assess the material's microstructure in detail," Seita says.

With current optical orientation imaging, quality assessment results have been attainable only on pure crystalline solids, and measured optical signals indexed using only material-specific, physics-based models. Expanding beyond such imaging to the area of engineering metal alloys was a challenge, the researchers say, because "the complex, multiphase microstructures of these materials give rise to optical signals that are difficult to decode using physics-based models."

> **Results demonstrate optical orientation mapping on a metal alloy is achievable.**

In their study, the researchers used directed energy deposition—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited—to produce specimens that exhibited different microstructures.[1] With an optical camera, the microstructure samples were imaged and illuminated from different angles. Some were highly textured, while others appeared finer with randomly oriented grains (see figure).

Such a process for analyzing and assessing 3D-printed metal alloys has, to date, used scanning electron microscopes, which is time-consuming and expensive. This new technique delivers the same information in just minutes, by using machine-learning software also developed by the NTU team and hardware costing only a fraction of those used in current methods.

"Our results demonstrate optical orientation mapping on a metal alloy is achievable," Seita says. "And since our method is data-driven, it can be easily extended to different alloy systems produced using different manufacturing processes."—JUSTINE MURPHY

REFERENCE

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OPTICS

Optical nanoantennas control light electrically via conducting polymers

Linköping University (Sweden) researchers built a dynamically tunable plasmonic nanoantenna using a conductive polymer that can switch between metallic and dielectric properties at frequencies in the near-infrared optical range (see figure). This advance has implications for future dynamic flat metaoptics and tunable smart materials.[1]

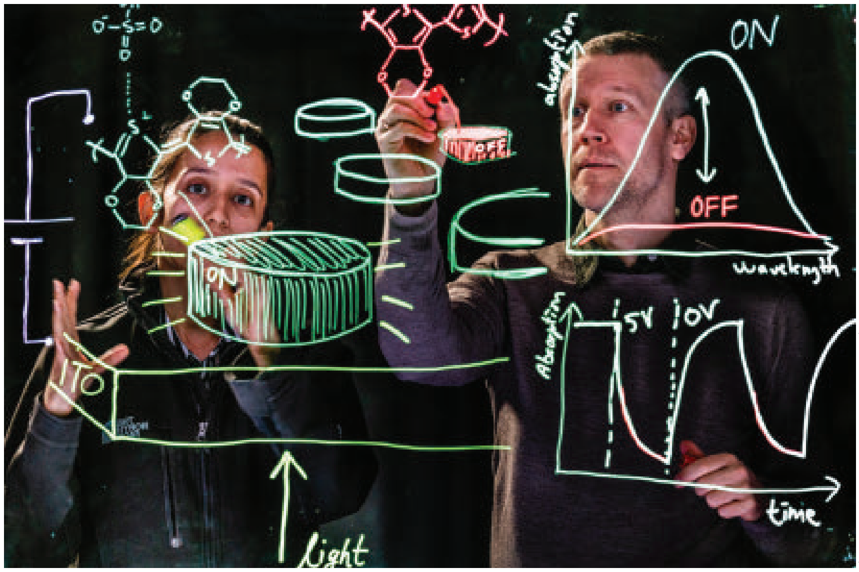
Metallic nanostructures interact strongly with light, which transforms the light into collective charge oscillations, or plasmons. "These nanostructures act as tiny antennas for light," explains Magnus Jonsson, a professor of applied physics and principal investigator of the Organic Photonics and Nanooptics group within the Laboratory of Organic Electronics. "Our organic nanoantennas behave in the same way, but for slightly longer wavelengths at which the conducting polymer is optically metallic."

Jonsson has worked with conventional inorganic plasmonics for many years and understands their limitations when it comes to active tuning. After first learning about conducting polymers, he wondered whether organic materials could also act as metals within plasmonic nanoantennas. If it worked, it would open up a new type of organic optical nanoantennas that could be turned on or off. His group went on to demonstrate it in 2020.

"By fabricating conducting polymer nanoantennas on a transparent electrode and coating them with ion-conducting gel, we can control their redox state by an external potential," says Akchheta Karki, one of the researchers working on the project.

Beyond repeated on/off switching, the group demonstrated the possibility of gradual tuning of the nanoantennas, controlled by the external bias potential.

To gain a better understanding of the underlying mechanisms of the tuning process, they're comparing their results with optical simulation and calculations. Results show both density and mobility of charge carriers within the nanoantennas vary during tuning, and the process is reversible.



(PHOTO CREDIT: THOR BALKHED)

Akchheta Karki and Magnus Jonsson show how they developed dynamically tunable plasmonic nanoantennas made of a conducting polymer, which can be switched between metallic and dielectric properties within the near-infrared wavelength range.

Many strategies for dynamic nano-optics based on conventional gold-based plasmonics have already been explored, Jonsson points out, such as stretchable systems and tuning by modifying the properties of other materials close to the nanoantennas.

"While interesting, such systems cannot be completely turned off because metallic structures are always present within the device during tuning," he adds. "An interesting aspect of our concept is we don't use any conventional metals at all; the nanoantennas are instead made from a tuned material."

Since the material the researchers are using can be tuned all the way from metal to dielectric and back again, it provides a large tuning range.

"In previous work, we showed polymeric nanoantennas could be tuned by exposure to gases and liquids," Jonsson says. "With our present work, we extended the concept to tuning by electrical potentials, which will be much more practical for real applications. One challenge was ensuring all other parts of the devices are sufficiently transparent to light within the near-infrared region at which these nanoantennas have their resonances."

Conducting polymers "form an interesting new type of materials for dynamic nano-optics, thanks to the possibility of varying their properties between metallic and dielectric," adds Jonsson. "The transition in the field from static to dynamic nano-optics is important for many future applications, including steerable metaoptics and dynamic smart windows."

While the researchers are excited about introducing a new materials platform for dynamic nano-optics, they note that there are still many important studies to perform and applications to develop. "We demonstrated nanoantennas with resonances down to a wavelength of 1270 nm in our current study, and one remaining challenge is to further tune the resonances into the visible region," says Jonsson. "Exploring other organic conducting materials for dynamic nanoantennas and improving the efficiency of the nanoantennas are important topics for future work."—SALLY COLE JOHNSON

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Laser surface modification of a titanium sheet

Laser surfacing creates implantable microstructures in titanium and provides color changes to titanium surfaces used for permanent identification of parts and components.

ELIANA FU, DANIEL HUERTA MURILLO, ALONZA BROWN, AND **CLINTON COLEMAN**

During the past several decades, power beam processes such as laser technology successfully demonstrated cutting, welding, and marking capabilities. Now, surface structuring or modification can occur through electron beam and laser processing.

Titanium is a very widely used material in a variety of industry sectors, from aerospace, automotive, and consumer products. In biomedical applications, it is suitable for implants within the human body because it is a biocompatible metal that lends itself to numerous processing options, from forging, casting, machining, and additive manufacturing.

The most popular titanium alloy, Ti-6Al-4V, has long been established as the primary metallic material for orthopedic implants, as well as stents, sutures, tools, and instruments. Its derivative, Ti-6Al-4V ELI, is another popular biomedical alloy, where ELI refers to "extra low interstitials" (chemistry variation from Ti-6-4 where oxygen, iron, and carbon are kept as low as possible). An example of titanium implant components produced by 3D printing (laser additive manufacturing) is shown in Figure 1.

By using a laser to perform surface structuring of titanium, microstructures can be created that produce an increased surface area by forming unique profiles and shapes as a result of melting and rapid solidification. The profile shapes and structures encourage both hard and soft tissue growth, resulting in mechanical keying of implants to the implanted regions in the body. For instruments and tools, a grippier surface is also frequently desirable for ergonomics and handling.

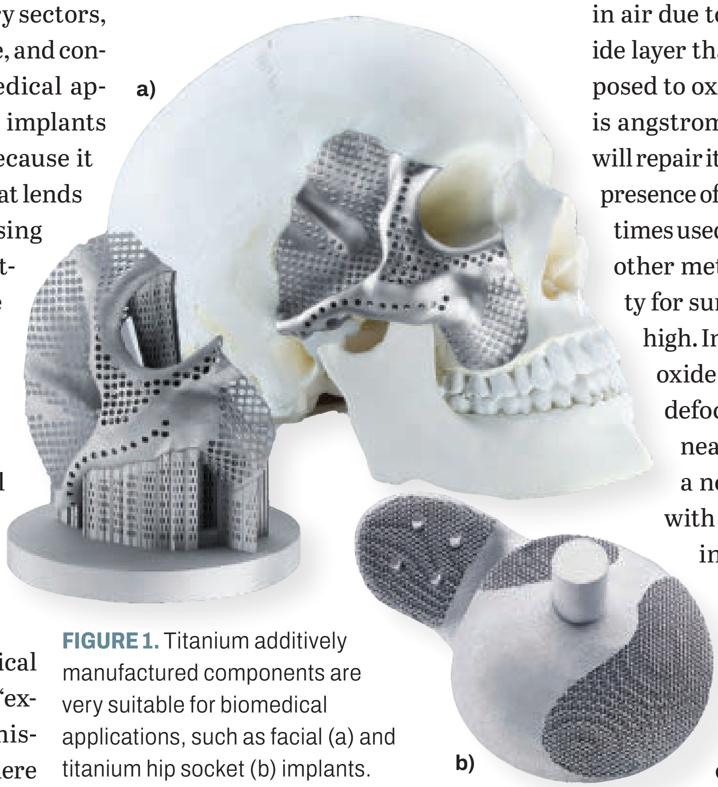


FIGURE 1. Titanium additively manufactured components are very suitable for biomedical applications, such as facial (a) and titanium hip socket (b) implants.

How it works

Laser surface structuring of sheet metal involves using a highly focused laser beam to impinge on the surface of the metal, creating a molten pool that solidifies rapidly. Structures can be created as the beam rasters quickly through the molten pool. Titanium is a highly reactive metal, though stable in air due to the highly tenacious oxide layer that forms readily when exposed to oxygen in the air. This layer is angstroms thick and, if damaged, will repair itself almost instantly in the presence of oxygen. Titanium is sometimes used as a getter in heat treating other metallics, because its affinity for surface oxygen is incredibly high. Interestingly, this tenacious oxide layer is removable with a defocused laser beam. An annealing effect is observed as a new oxide layer is formed, with a color developed according to the thickness of the oxide layer, similar to heat tinting of titanium using furnace treatment.

The creation of surface features and color change using a laser is interesting for medical applications such as tissue sticking, or using color for identification purposes or for go/no-go gages.

TRUMPF performed some laser surface modification trials using a TruMark 5020 (ytterbium fiber) nanosecond laser with a 1064 nm infrared wavelength and average power of 20 W, in a TruMark station 5000. A SCANcube 10 2D galvo scanner with a 160 mm focal length f-theta lens is used for beam focusing and delivery. This optical setup creates a scan field size of 110 × 110 mm with a spot size of 67 µm. The material used was Ti-6Al-4V with sheet thickness of 1 to 3 mm. The laser beam parameters can be changed and adjusted in terms of pulse frequency and duration.

Figure 2 shows how structuring created a pyramid that increases surface area and interlocking surface structuring, which could be used for tissue bonding. A scripted program is used to raster the red lines (Y-direction; top left of image), followed by the blue lines, and repeated X number of times to achieve a desired depth. Surface structures range from 1 µm (finer) to 500 µm (coarse).

Figure 3a shows a structure developed that resembles a metal Velcro. The laser beam is rastered across using "X" target shapes to denote the position where the laser hits the metal (right side of image) resulting in the spikes shown (left side). The process is similar to the percussion drilling method—each X target is hit with a single pulse multiple (up to 100) times. Figure 3b shows the results when the laser is rastered across in 45-degree lines; an interesting shape is obtained where the laser crisscrosses a previous line (additional energy from laser impinging on the metal surface).

As mentioned, titanium easily creates a new oxide layer when the existing one is damaged or removed. Heat introduced by the laser creates an annealing process similar to heat tinting by traditional furnace methods. Color is seen as the light refracts through the thickness of the oxide layer. To produce different colors, the laser beam is slightly defocused to give a larger spot size and control the energy density deposited in the material. The resultant energy density is below the melting point of titanium. After laser processing, a new oxide layer is formed, and colors produced are temperature-resistant to 200°C.

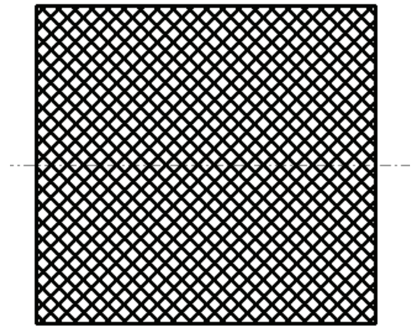
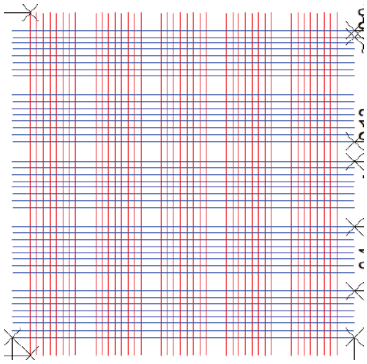


FIGURE 2. Pyramid structures created.

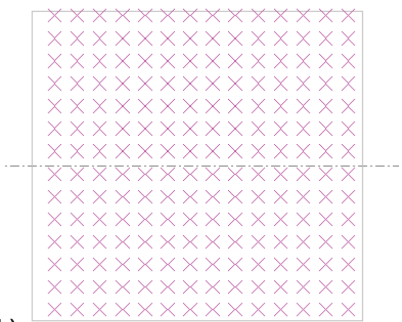
Additional capability

Laser processing can also provide color changes to titanium surfaces from the refraction of light, based on the thickness of the tenacious oxide layer found on all titanium surfaces exposed to air. The color change depends greatly on material chemistry. But on an experimental basis, it can be used to provide permanent identification on parts and components. With further parameter optimization, other colors can be achieved that would be difficult by traditional titanium anodizing.

Although traditional anodizing of titanium and its alloys is well established, the process cannot achieve certain color values the human eye interprets as deep reds (vermillion to scarlet), deep blues, and emerald greens due to the thickness of the oxide



a)



b)

FIGURE 3. Adhesion structures (a) and 45-degree patterns (b) created.

layers formed simply skipping over these wavelengths. In Pantone colors, these are typically reds from 185–187, 192, and 199–200, and blues from 280–282, 286, 287, 288 and 294–295, 541. In greens, these could be from 315–316, 322, 323, 330, 335, 336, 564, and 662, for example, and are almost impossible to achieve with anodizing. However, with further laser parameter optimization, it might be possible to produce these and other desired colors difficult to obtain by traditional anodizing. As we look to the future, it might also be of interest to see how colors develop as a function of increasing beta alloying content (comparing CP titanium to a near-alloy such as Ti-6242 to Ti-6-4, which is an α-β alloy, to a heavily β-stabilized alloy such as Ti-15-3-3-3).

Laser surface colorization and surface structuring also open up a whole realm of possibilities for the aerospace industry. For particularly large structural components, such as a titanium wing spar, where it is extremely difficult to dunk a huge part in an anodizing tank, the ability to colorize or texturize only a small area is attractive. Whether used to create microstructures or color changes, laser technology offers a lot of exciting potential in the processing of titanium and its alloys. ◎

Eliana Fu, Ph.D., is industry manager of aerospace and medical; **Daniel Huerta Murillo**, Ph.D., is a laser applications engineer; **Alonza Brown** is head of pulsed laser applications; and **Clinton Coleman** is TruMark product and project manager, all at the TRUMPF Laser Technology Center, Plymouth, MI; e-mail: eliana.fu@trumpf.com; www.trumpf.com.

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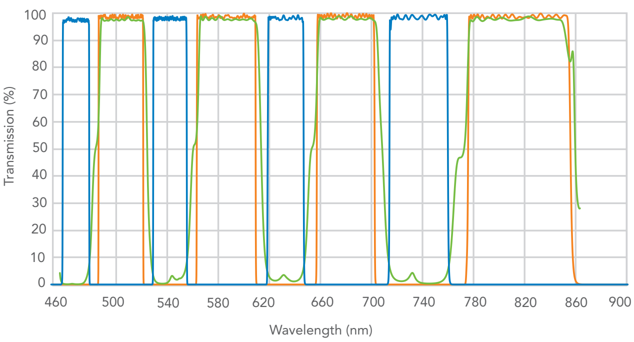

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'Impossible theory' leads to discovery of new photonic effects

Ventsislav Valev's team at the University of Bath demonstrates physical effects of 'Impossible theory' at second harmonic, and continues on to show chiroptical third-harmonic Mie scattering.

SALLY COLE JOHNSON,
SENIOR TECHNICAL EDITOR

Back in 1979, David Andrews, now immediate past president of SPIE, figured out that the way the intensity of light scatters at higher harmonics must depend on the chirality of its scatterers. He realized it would be a new physical effect, wrote about it, and published it in the *Journal of Chemical Physics* with the appropriate math to support it.[1] But for 40 years, no one was able to demonstrate this physical effect.

Laurence Barron, the inventor of Raman optical activity and winner of the 2011 Chirality Medal, also considered it in his 1969 PhD thesis, but didn't develop it mathematically and publish it.[2]

Researchers began to suspect the effect might be too weak to observe or some other effect was preventing its observation. Andrews himself began referring to his work as an "Impossible theory."

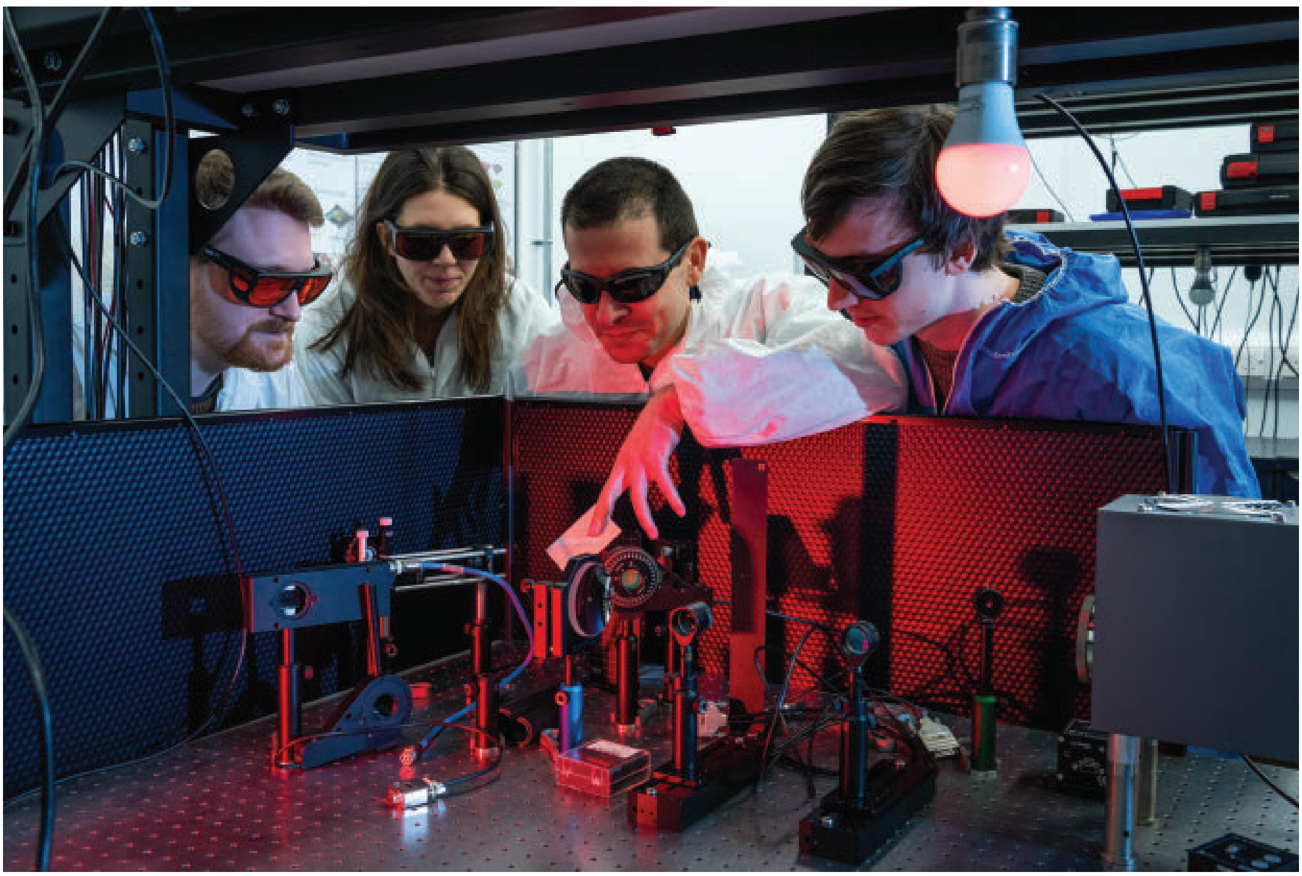

FIGURE 1. In 2019, Ventsislav Valev's team used a physical effect, the changing color of light scattered from chiral molecules, to measure the chirality present. L-R: David Hooper, Kristina Rusimova, Ventsislav Valev, and Joel Collins.

Fast forward to 2009, Ventsislav Valev, now a physics professor at the University of Bath in the UK, had the same idea—without any knowledge of David Andrews' work. He immediately discussed it with his supervisor at the time, Thierry Verbiest at KU Leuven University. "Verbiest told me he and his team had the same idea themselves and even tried it experimentally in the 1990s," he says.

Unfortunately, they were unable to observe the effect. From that point on, Valev focused on developing very sensitive experimental equipment. "Verbiest and his team used some of the best candidates among organic molecules, so I started searching for a material that could give a stronger signal than any molecule," he says.

In the mid 2010s, Valev found metal nanohelices being made by Peer Fischer of Max Planck Institute for Intelligent Systems in Stuttgart. These miniscule metal springs are deposited as an ordered array on a silicon wafer.

"We started by having a look at their nonlinear chiroptical properties and found out they're very strong indeed," says Valev. "I remember asking Fischer how easy it would be to disperse these nanohelices within a liquid environment. I was expecting an elaborate procedure, possibly involving hydrofluoric acid etching of the helices from the substrates. But Fischer gave the most unexpected answer to my question: very easy! All we had to do was to sonicate the samples within a solution of stabilizing molecules."

The quest for chiroptical harmonic scattering

Following Fischer's instructions, in 2019 Valev's team experimentally demonstrated the chiroptical harmonic scattering effect for silver nanohelices at the second harmonic (see Fig. 1).[3] Chirality describes the direction a molecule twists—akin to a right-handed or left-handed curl—and chiral compounds are usually optically active.

"Not only did we observe the effect we were looking for, it was huge!" Valev says.

His team achieved this via an experimental geometry with nanosprings dispersed randomly in water within a glass container, and then aimed a laser at them. The twist—circular polarization—of the laser was switched periodically and light scattered from the container at 90° was analyzed to determine the chirality of the nanosprings.

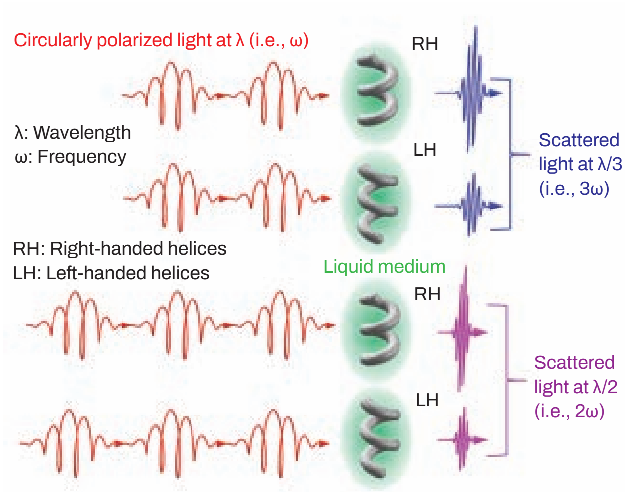

FIGURE 2. Harmonic scattering optical activity: chirality describes the direction a molecule twists.

Valev was still elated when he first presented the results at a conference in Paris. "At the end of my talk, to my great surprise, one of the attendees arose from the back benches of the lecture hall, saying, not without emotion: 'Ventsi, I think you have shown an effect I predicted 40 years ago.' It was David Andrews," he recalls (see Fig. 2).

Valev's team was delighted the experiment was a success—but given how elusive the effect was the last 40 years, Valev feared the newly found effect might only be observable in this one case.

As a next step, the safest bet was to keep the setup as it was, but change the material. "Only after we successfully demonstrated the effect in twisted gold nanocubes as well, did we feel confident trying for the third harmonic," he adds.[4]

Going for the third harmonic

Second and third harmonic scattering are entirely different effects—their physical origins are different, so there was no guarantee of success pursuing the third harmonic. "David Andrews wrote his theory only for the second harmonic, so we were in uncharted waters," says Valev.

For the third harmonic experiments, Valev's team again used Fischer's silver nanohelices and it was an immediate success—once again, they recorded a very strong effect.

The results were reported in 2021, but what made the resulting paper special for Valev is that Andrews wrote its theory.[5] "Although rare, there are well known stories of experimentalists demonstrating theoretically predicted effects after many decades," points out Valev. "Much rarer are cases where the theorists and experimentalists then join forces to make further discoveries together. This scientific work has spanned generations, and I am fortunate and humbled to be part of it."

So far all of the team's work had involved plasmonic, metal nanoparticles. Naturally, they wondered if whether it might be present in other types of materials.

Earlier this year, Valev's team, working with Nicholas Kotav's lab at the University of Michigan, discovered a new photonic effect: chiroptical third-harmonic Mie scattering.[6] When circularly polarized light at a wavelength of 1100 nm illuminates cadmium telluride (CdTe) nanohelices, light at the third harmonic streams out on the opposite side from where particles are illuminated (see Fig. 3).

Chiroptical harmonic scattering opens up new fields of investigation, where researchers can reveal the nonlinear chiral optical polarizabilities of inorganic nanoparticles and molecules. "This is important at the fundamental level because it helps us to understand the light-matter interaction beyond the first order approximation of linear optics," says Valev.

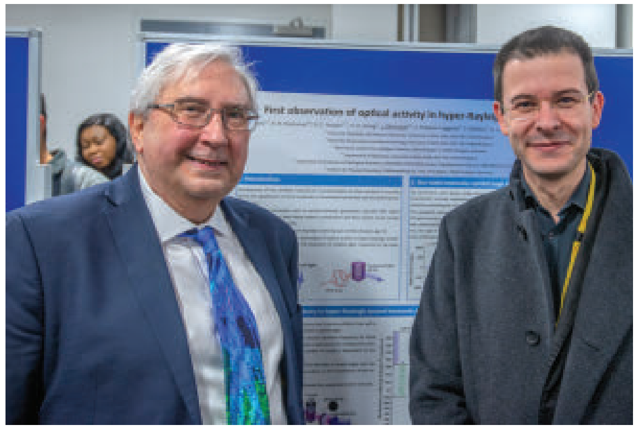

FIGURE 3. Ventsislav Valev and David Andrews meet after Valev's team demonstrates Andrews' Impossible theory.

As far as applications, the new effect can probe chirality in tiny volumes—typically the focal volume of a lens or a microscope objective (see Fig. 4). Such small volumes are of interest for high-throughput chemistry, where the wells on microplates can hold less than a microliter but also in the case of studying natural products, where the available quantities of chemicals are often very small.

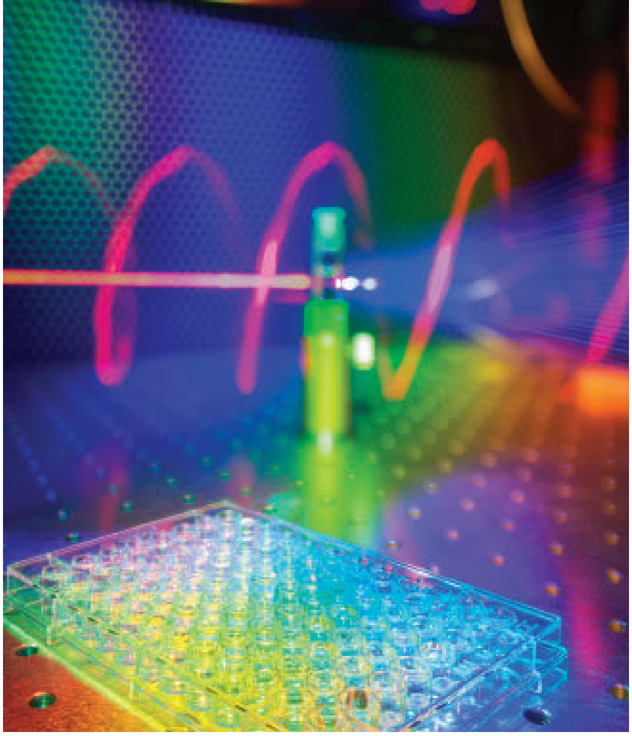

FIGURE 4. Ventsislav Valev and David Andrews meet after Valev's team demonstrates Andrews' Impossible theory.

Valev's lab is currently in an exhilarating phase, "where virtually everything we try is new and exciting," he says. "For instance, we'd like to measure plasmonic-dielectric hybrid nanoparticles, quantum dots, atomic clusters, and many organic molecules."

To do this, they need to expand their wavelength range and start producing chiroptical harmonic scattering spectra, similar to the current circular dichroism spectra available in most chemistry departments around the world. "Sooner or later, we'll discover the limits of applicability of our effect, and then it will be time for the technology to mature toward realistic applications," Valev notes.

In nonlinear optics, "we look at the interactions between light and matter beyond the linear regime," he adds. "There are terms at the second, third, fourth harmonic, and so on. Within each harmonic, there are electric dipole, quadrupole, and octupole contributions, so there are also magnetic dipoles, etc. All of these terms are usually very small, but with increasingly sensitive detection equipment and decreasing prices of lasers suitable for nonlinear optics, we're gaining access to them. Consequently, discovery of new effects is bound to happen." ◎

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Core alignment for splicing large mode area fibers

As fiber lasers proliferate and designs evolve, goals for higher laser power and efficiency are increasingly more important, making the need for better quality splices critical.

DOUG DUKE AND **CRAIG MACMILLAN**

Large mode area (LMA) double-clad fibers have a design optimized for use in fiber lasers. Since the core diameter of an LMA fiber is generally larger than the mode field diameter (MFD), LMA fibers can carry a few higher order modes (HOMs). The core diameters of LMA fibers are typically quite large compared to conventional single-mode fibers, and alignment of LMA fiber cores is challenging. Most fusion splicers in the market today are designed for telecom splicing applications.

While some of these telecom fusion splicers are only capable of aligning the fiber cladding (e.g., ribbon splicers incorporating a fixed V-groove passive alignment system), true core alignment telecom splicers are available. These core alignment splicers are in widespread use and provide the capability of aligning the cores of SMF fibers to a submicron accuracy. However, as these splicers are designed for telecom network applications, the core alignment capability only functions properly with standard telecom single-mode fiber types. For LMA fibers, using existing core alignment algorithms results in either an error message, or random, inconsistent, unreliable core alignment.

Octagonally clad LMA fibers have been developed to meet specific needs for the "active" fiber in high-efficiency fiber lasers. Octagonal LMA fibers are now predominant for nonpolarized active LMA fibers because the octagonal shape promotes effective coupling of all cladding pump power modes to the LMA core. If the active LMA fiber is nonpolarized, any pump power in a helical cladding mode may not couple to the doped LMA core unless at least one flat surface is provided on the surface of the cladding. Various cladding shapes have been tried, such as two flat surfaces on opposite sides of the cladding, hexagonal cladding shapes, etc. However, the octagonal shape is now almost an industry standard. Unfortunately, the octagonal shape presents additional challenges for core alignment.

For telecom fibers, modern industry standards dictate that the core-to-cladding concentricity error (CCCE) of standard SMF may be no greater than 0.5 µm. Such a tight CCCE tolerance is difficult to achieve with LMA fibers, because cladding diameters are generally larger (e.g., 250 µm or 400 µm) and fiber production volumes are low. Controlling the CCCE of active octagonal LMA fibers is further complicated by the octagonal cladding geometry. As a result, it is not uncommon for

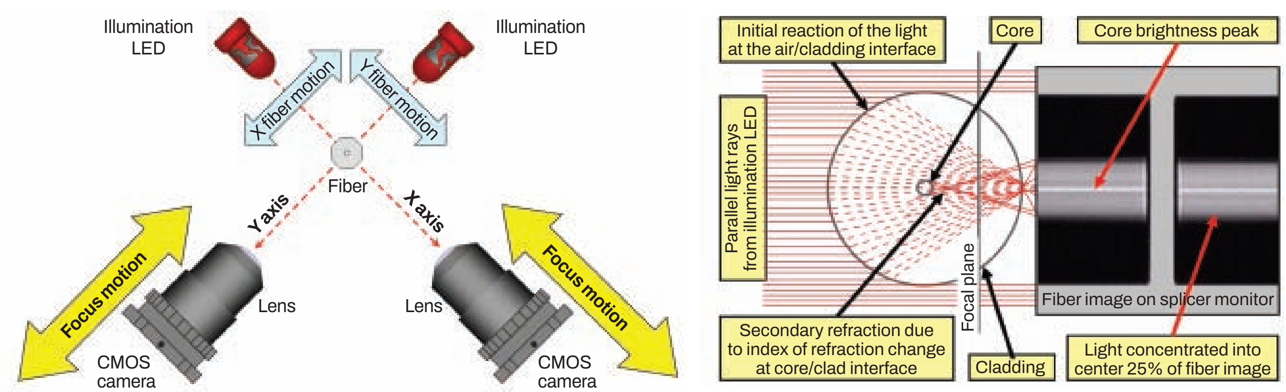

FIGURE 1. The profile alignment system (PAS; a) and refraction of illumination light in a PAS optical system (b).

The repeatability error of the core offset after cladding alignment

Fiber type	CCCE (µm)	Rotation angle (°)	Measured core offset (µm)	Repeatability error (µm)	Sample number
SMF28 (G.652) 9/125 µm	L=0.2, R=1.3	L=0°, R=0 to 360°	Min=1.1, max=1.5, avg=1.4	STD (sigma)=0.10	63
LMA (G.654) 12/125 µm	L=0.1, R=0.7	L=0°, R=0 to 360°	Min=0.5, max=0.9, avg=0.8	STD (sigma)=0.25	26
LMA GDF 20/400 µm	L=0.7, R=1.5	L=0°, R=0 to 360°	Min=0.8, max=2.3, avg=1.5	STD (sigma)=0.23	91
LMS GDF 25/400 µm	L=0.6, R=0.6	L=0°, R=0 to 360°	Min=0.1, max=1.3, avg=0.8	STD (sigma)=0.25	240

LMA fibers to have a CCCE of 1.5 µm, and sometimes the CCCE is significantly higher. The implications of the core/cladding concentricity error are that when the claddings of two LMA fibers are aligned, the result may easily be a core misalignment of 3.0 µm or more, whereas cladding aligned standard SMF can have a maximum resulting core offset of 1.0 µm.

If LMA fibers are spliced together using cladding alignment, negative performance characteristics may be introduced at the splice point. Effects of core misalignment at the splice point present themselves via coupling of the core signal to cladding modes or, more likely to higher-order modes withhin the core. Since LMA fibers are double-clad, cladding modes may continue to be guided by the (inner) cladding. This cladding power may result in downstream heating of the fiber and present thermal management problems if the misalignment of the cores is particularly bad. and if the power level is high. In any case, such cladding modes are undesirable at the output of the fiber laser and should typically be eliminated by a cladding mode stripper. Higher-order modes are a more significant problem because they may degrade the fiber laser beam shape and result in application-specific performance problems. For example, higher order modes may focus on a different point from the primary mode in the output of the fiber laser, degrading performance in a cutting or engraving application. These issues make LMA fiber core alignment highly desirable.

For general telecommunications network splicing of SMF, the principal concern is attenuation of the optical signal and splice loss. For splices of LMA fibers in a fiber laser, attenuation or splice loss may be difficult to measure. Important performance considerations for fiber lasers are thermal management, laser output power, and beam quality. While a typical expectation or requirement for telecom network core alignment splicing with SMF might be 0.2 µm, a more common goal among many fiber laser manufacturers is to align the cores of

LMA fibers within 1.0 μm, especially for larger diameter LMA fibers. Such performance would be almost equivalent to that achieved with common SMF when considered as a percentage of the total CCCE that might otherwise degrade core alignment.

Profile alignment system, IPA, and IPA2

The Profile Alignment System (PAS) was developed to detect and align the cores of standard SMF and is commonly used for telecommunications network splicing.[1] It has matured into a technology with the ability to analyze the rotational position of a fiber, identify its type, and compare it to the fiber to which it is being spliced.

A PAS fusion splicer is arranged on an (X, Y, Z) coordinate plane where high-resolution cameras are aligned on the X and Y axes, and the fiber occupies the Z axis. Each camera has a corresponding LED along its axis on the far side of the fiber, which provides collimated light that passes through the fiber and is detected by the camera. This PAS system arrangement is shown in Figure 1a. The collimated light that passes through the fiber refracts wherever a difference in refractive index is encountered. As the light passes from the air into the cladding of the fiber, it bends inward toward the center of the cladding. Some of that light encounters the core of the fiber, where it is refracted inward again by the difference in refractive index between the core and the cladding. In Figure 1b, the refraction of the illumination light is shown for a standard G.652 telecommunications SMF along with the resulting fiber image.

The inward refraction of the collimated LED light results in an image unique to each fiber construction. At the extreme edges, the background brightness of the splicer's LED is visible where the illumination light from the LED is unimpeded by the presence of the fiber. This defines the outline of the fiber and enables the splicer to measure the cladding diameter, the cleave angle and shape, and the angle of the fibers relative to one another. In addition to collecting data measured through observation of the fiber cladding, the PAS system adjusts the camera focus plane for optimal detection of the SMF fiber core position (see Fig. 1b).

To succinctly define the focal plane location, an observable focus ratio is created. This is the ratio of the width of the bright center region of the fiber image relative to the fiber's diameter. For example, when the width of the bright center region occupies 1/4 of the total fiber diameter from cladding edge to cladding edge, the focus ratio is said to be 0.25.

At an optimal focus ratio, this bright inner region displays a set of recognizable lines that serve to indicate the location of internal fiber geometry. A dataset is then extracted from the optimally focused image wherein the brightness intensity of the image pixels is plotted against the lateral pixel position across the fiber. The resulting data can be plotted as a brightness intensity profile (see Fig. 2), where the horizontal axis of the graph is the lateral position across the diameter of the fiber and the vertical axis is the corresponding brightness intensity of the image at that point.

In the case of standard telecom SMF, the position of the fiber core within the cladding is easily determined by detection of a brightness peak within the bright central area of the fiber image. This bright core peak is easily observable when the camera focus position is optimized and reveals the location of the core within the cladding. The core brightness peak is identified in the PAS camera image in Figure 1b and can be easily seen at the center of the blue brightness intensity profile plotted at the bottom of Figure 2. In practice, the optimum focus ratio may be determined experimentally for a given fiber type and entered into the splicer as a parameter, or the splicer can use a search routine to adjust the focus and find the position that results in the most clearly identifiable core brightness peak.

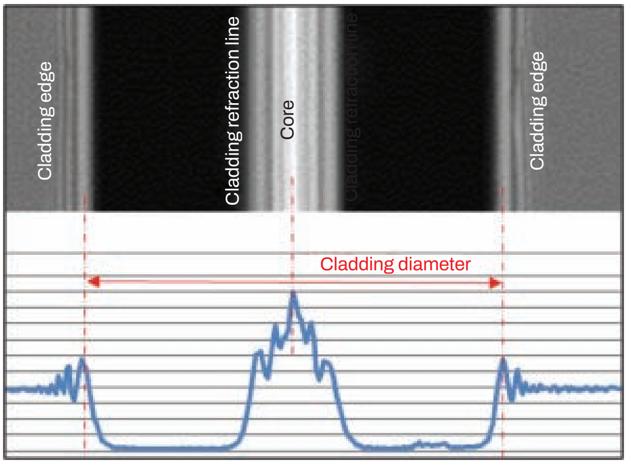

FIGURE 2. Brightness intensity profile of standard SMF.

Analysis of a fiber's brightness intensity profile is the essence of PAS and serves as the basis for further developments to enable the application of PAS for purposes other than alignment of the cores of single-mode fibers. If the PAS dataset is plotted against the fiber's rotational position, a new set of functionalities is realized. If a perfectly symmetrical fiber is rotated in view of a PAS camera, its brightness intensity profile will not change—regardless of rotational position. By contrast, if a fiber having any refractive index or other asymmetry (such as a polarization maintaining fiber) is likewise rotated, its brightness intensity profile will change as a function of the changing rotational position. The light refracting through the rotating internal geometry of the fiber generates a different brightness intensity profile for each angular position, highlighting internal symmetries and differences of the fiber. This effect is highly pronounced in fibers with well-defined planes of symmetry.

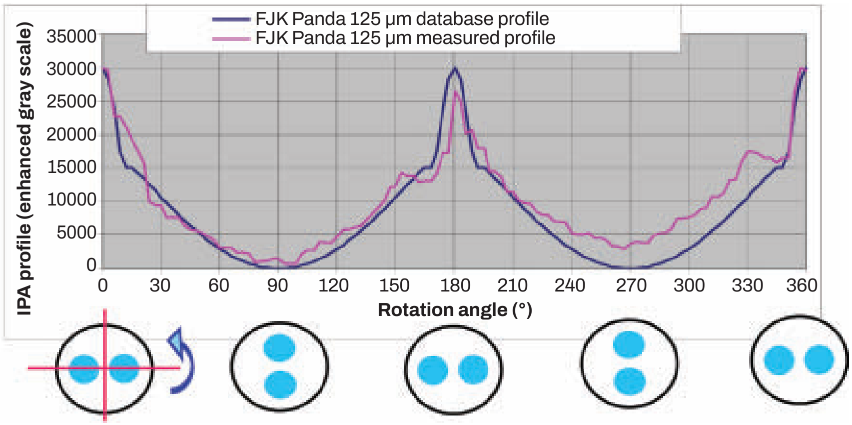

FIGURE 3. IPA profile for Panda fiber.

While the brightness intensity profile at different rotational positions can be used in many ways, one effective method is to interrelate the PAS data with the fiber's rotational position. Observing some characteristic from the PAS brightness intensity profile at successive rotational positions produces a new set of data that can be used to interpret the rotational position of internal features of a fiber. This method is formally referred to as Interrelation Profile Analysis or IPA.[2] It should be noted when IPA is used, there may not be an observable core peak within the bright central area of the fiber image.

With most polarization-maintaining (PM) fibers, the core position is not detectable regardless of the fiber's rotational orientation. However, other data within the brightness profile may be collected and plotted relative to rotational position. Precisely which characteristic from the brightness intensity profile is used for IPA is proprietary and will not be discussed here.

A characteristic IPA data plot for a Panda PM fiber is shown in Figure 3, and the corresponding rotational orientation of the Panda fiber is shown underneath the IPA data. The IPA profiles for the left and right PM fibers can

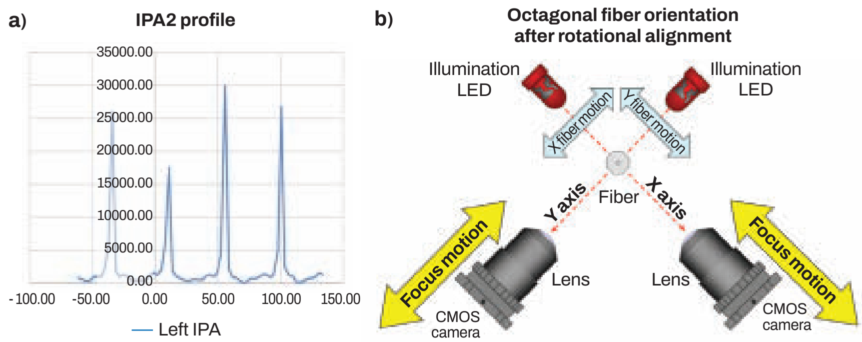

FIGURE 4. IPA2 rotational profile for octagonal fiber (a) and orientation relative to splicer cameras after IPA2 alignment (b).

be compared and correlated to each other directly (in the case of similar left/right PM fibers) to determine how far to rotate one or both fibers to ensure the best alignment of the polarization axes of the two fibers. If the two PM fibers to be spliced have different characteristic IPA profiles, the IPA data for each fiber may be indirectly correlated to IPA profiles stored within the splicer's IPA database.

Using IPA as a method of aligning asymmetrical and other rotationally sensitive fibers is tremendously powerful and enables a wide array of splicing possibilities. But the originally developed IPA did not work well for alignment of some PM fiber types. More recently, a new version of IPA, IPA2, was developed. IPA2 operates in a manner analogous to IPA, but the way data is observed and plotted and how fibers are observed during rotation is different. IPA2 provides improved rotational alignment accuracy for many types of PM fibers.

Application of PAS and IPA2 techniques to LMA fibers

While LMA fibers are similar in structure to common telecom SMF (with a pure silica cladding surrounding the higher index of refraction core), there are significant differences. The major design differences between SMF and LMA fibers are not only the large diameter of the LMA core, but also the lower refractive index difference between the core and inner cladding of the LMA fiber.

In the case of a standard SMF, a well-defined brightness peak is easily observable in the PAS image near the center of the bright area, and this reveals the core position. The large core diameter of the LMA fiber results in a PAS image with two dark parallel lines, but without a well-defined core brightness peak. The lower refractive index difference of LMA makes the core refraction line much dimmer than the SMF structure and more difficult to distinguish from the background noise. To accurately locate the core of LMA fibers, the focus ratio should be carefully chosen to avoid camera saturation—while also providing adequate resolution to differentiate the core refraction line from background noise. But even with precise optimization of the focus position, the core peak for LMA fibers is still more difficult to accurately detect. Since the core detection methods adequate for common SMF are unreliable for LMA fiber, it is necessary to develop new proprietary core alignment algorithms to enable LMA core position detection.[3]

Passive LMA fibers are quite similar in structure to standard SMF, having a round pure silica cladding containing a higher index core. The new LMA core alignment algorithm enables core alignment of the passive fibers, but a further problem arises with fibers of a noncircular cladding shape. Random rotational orientation of the noncircular fiber shape relative to the splicer's camera system results in random refraction of the illumination light that passes through the fiber, and no consistent or discernable image will be achieved.

IPA2 provides a solution for octagonally clad fibers. While IPA was originally developed as a method to rotationally align the polarization states of PM fibers, an IPA2 alignment mode is provided to rotationally align an octagonally clad fiber such that flat surfaces of the octagon are perpendicular to the orthogonal X and Y camera observation axes of the splicer. This enables the PAS system to observe a consistent fiber image. An IPA2 profile for an octagonal fiber is shown in Figure 4a. The IPA2 data is clearly periodic to 45 degrees of rotation, which enables simple rotational alignment of the octagonal fiber relative to the splicer's camera system.

While PAS core alignment capability was previously only applicable to cylindrically clad fibers, with the introduction of the new IPA2 rotational alignment mode for octagonal fibers, it's now possible to apply core alignment to octagonal active LMA fibers. Once IPA2 is used to rotate the octagonal fiber such that flat surfaces of the octagon are perpendicular to the camera axes (see Fig. 4b), a useful PAS image is available. This permits the light to travel through the fiber and displays a brightness intensity profile that allows detection of the core location via the new LMA core recognition technology. And this enables the core of an octagonal active LMA fiber to be aligned to the core of the cylindrically clad passive LMA fiber. Regardless of the random angular rotational orientation in which the octagonal fiber has been loaded into the splicer, IPA2 enables the cladding to be rotated to the correct position for core alignment.

In Figure 5, the brightness intensity profile of an octagonal active LMA fiber was overlaid over the passive (round) LMA fiber to which it is being spliced. IPA2 was first used to rotate the octagonal fiber to the proper position relative to the splicer's cameras. By using the new LMA core alignment technique, a core brightness peak is observable near the center of the bright region of the brightness intensity profile of both octagonal and round LMA fibers.

Core alignment and verification for LMA fiber splicing

The core offset repeatability test is a frequently used method for quick analysis of the quality of a core alignment algorithm. Using identical fiber types on the left and right of the splicer, alignment data is collected by either (a) performing core alignment while measuring cladding offset (misalignment) or (b) performing cladding alignment while measuring resultant core offset.

Repetition (without re-cleaving or reloading the fibers) enables verification of the consistency and repeatability of readings. For this test method, at least one fiber in the pair should have sufficient CCCE to enable measurements not within the noise level of the measurement system. Moreover, one of the fibers should be rotated to search for the maximum core offset between the left and right fibers. Test results are shown in the table for four LMA fiber types.

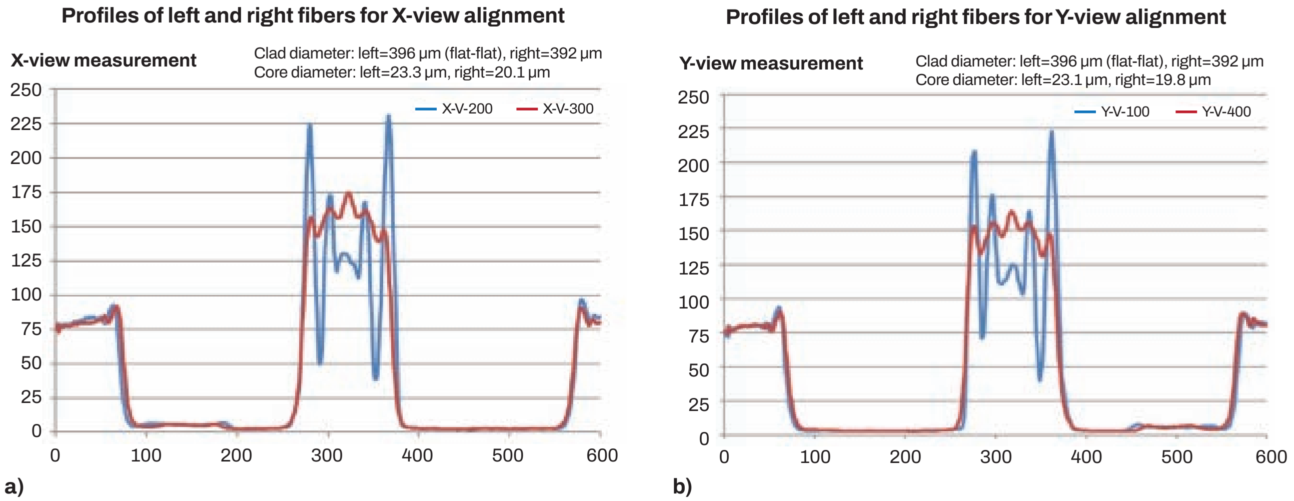

FIGURE 5. Brightness intensity profiles for octagonal LMA TDF 20/400 µm (left fiber, blue data plot) and round LMA GDF 20/400 µm (right fiber, red data plot) after core alignment for both X (a) and Y (b) camera views.

The data in the table (p. 30) shows alignment repeatability for round passive LMA fibers. For splicing an active octagonal LMA fiber to a round passive fiber, it is not possible to use the same method as above because the octagonal fiber cannot be rotated to search for maximum core offset. This is due to the need to use IPA2 to rotate the octagonal fiber to the specific angle required to enable PAS core observation. When tested in the lab, the repeatability of the angular alignment of the octagonal fiber was within a few tenths of a degree, indicating the rotational orientation of the octagonal fiber by IPA2 is repeatable. Subsequent core alignment using the new LMA core alignment capability showed results consistent within 1 µm when cladding misalignment of nearly 4 µm was required to align the LMA cores.

It's significantly more difficult to align cores of LMA fibers compared to cores of standard SMF. The greater variability of CCCE in LMA fiber, the

LMA core alignment provides improved thermal management.

low contrast between core and cladding, and issues concerning cladding geometry present significant challenges to core alignment with PAS. Accordingly, the same submicron core alignment accuracy typical for splicing common SMF fiber isn't achieved with LMA fibers. Nevertheless, by using LMA core alignment algorithms, optimizing the camera focus position, and rotationally aligning the cladding of active octagonal LMA fibers using IPA2, laboratory testing demonstrated core alignment performance for LMA fibers with good repeatability. While the precision of LMA fiber core alignment does not match that for common SMF, it is similar as a percentage of possible CCCE.

Although the magnitude of the benefits need to be quantified by implementing these LMA core alignment capabilities in fiber laser production, the LMA core alignment capability should provide benefits for fiber laser manufacturing such as improved thermal management, better beam quality, and generally, better and more consistent fiber laser performance. The new LMA core alignment capabilities will be further refined as more experience and user feedback is gained via implementation in fiber laser production applications. ◎

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Laser therapy for pain relief: current and future trends

An increasing demand for noninvasive laser devices to treat chronic pain is prompting strong market growth, and a boost in the development of innovative technology.

ANTONIO RASPA

Unlike high-power surgical lasers designed for cutting or ablating tissue or destroying tumors, low-level laser therapy (LLLT) is a noninvasive treatment that works by stimulating the body's natural healing mechanisms in the area where the light is applied. Body tissues then absorb the light and release nitric oxide (NO)—a key signaling molecule that promotes blood flow and increases lymphatic drainage—which in turn inhibits inflammation processes, reduces swelling, and stimulates healing of the surrounding tissues. The light in question is in the red and near-infrared (near-IR) spectrum in 600–950 nm wavelengths, sometimes referred to as cold light because it produces virtually no heat. Low-energy lasers, which induce minimal temperature elevation (0.1 to max. 0.5°C) with powers of 50 to 500 mW and treatment energies of a few joules per square centimeter, can penetrate ~0.5 to 2.0 cm^2 and have surface treatment areas of ~0.3 to 5 cm^2.

Treatments that require greater penetration depths and larger surface treatment areas often require high-intensity laser therapy (HITL), which uses lasers with higher power levels between 5 and 10 W per wavelength that can penetrate up to 10 cm^2 and provide surface treatment areas of 70 to 80 cm^2. However, as the mechanism of action is the same, LLLT and HITL are both painless and noninvasive procedures with little or no adverse effects. More importantly, they reduce the need for analgesic medication with its associated side effects, and in many cases, they heal the source of inflammation or pain, rather than simply providing relief from it.

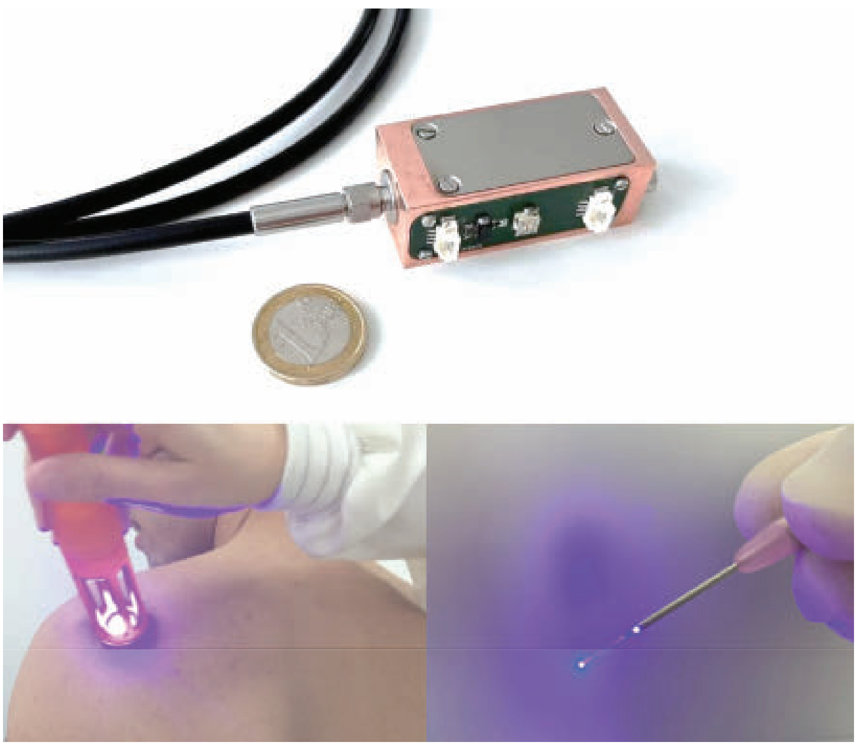

FIGURE 1. The core technology of laser therapy devices is based on diode lasers, as they provide unique levels of power and wavelength scalability that combine to support a very wide range of medical applications. *(Courtesy of Lyocon)*

Pathologies amenable to laser therapy

Following clinical trials in the U.S. and across Europe on laser therapy for pain relief, there is now a wide range of FDA-, UK-, and EU-approved laser-based devices for pain and inflammation relief in relation to the following pathologies:

Osteoarticular disorders. A group of pathologies that can highly impact

FIGURE 2. A combination therapy approach from Electro Medical Systems (EMS) incorporates a high-power laser to provide fast relief for patients with musculoskeletal disorders *(Courtesy of EMS)*

the quality of life and which mainly affect the mature population, such as osteoarthrosis and joint pain in general. The aim here is to reduce inflammation in the articular capsule; relieve pain symptoms; reduce functional disability (by acting on the muscles); reduce periarticular edema, thereby contributing to maintaining a good standard of quality of life; and controlling the use of pain relief through medication.

Neuromuscular disorders. These affect, in particular, a young and active population, often associated with neurological and muscular fatigue, or which originate from sports injuries. These include neuromuscular diseases impacting the lumbar and cervical area of the spine that are very common and recurring, to the extent they can compromise the quality of life and the work capability of patients. Laser therapy can be used to reduce pain through muscle relaxation and improving microcirculation.

Tendinopathies. A family that groups together painful issues affecting tendons and related areas. These diseases are very common in athletes, who require short recovery times and a quick return to high performance. In the field of sports traumatology, the anti-inflammatory, anti-edema, and analgesic effect of laser therapy can help to resolve painful symptoms and local swelling, assisting recovery, and accelerating the return to competitions.

Edema/hematoma. These are respectively linked to pathological conditions of the lymphatic and circulatory system. An edema is the result of an imbalance in the filtering system between interstitial spaces and capillaries, while a hematoma is an anomalous collection of blood outside the blood vessels, which occurs after damage to vein, artery, or capillary walls. The action of laser therapy on promoting microcirculation and lymphatic drainage can provide a valuable contribution to treating these issues, often associated with traumatic events.

Tissue damage. In this area, laser therapy can promote tissue healing and functional recovery thanks to specific biological mechanisms that occur both at tissue level (i.e., remodeling extracellular matrix, modulation of inflammatory processes, induction of myogenesis) and at cellular level (induction of differentiating processes, release of growth promoters, and other substances).

The technology

The core technology of laser therapy devices is based on diode lasers. Thanks to their relatively simple monolithic semiconductor architecture, they are able to directly convert electrical energy into laser light. Diode lasers also provide unique levels of power and wavelength scalability that combine to support a very wide range of medical applications (see Fig. 1).

Different semiconductor compositions enable selected wavelengths, achieved by setting the output wavelength to the blue, green, red, or near- and mid-IR ranges—these generally offer the required power levels. In this way, most medically interesting wavelengths can be produced, and the wide choice of output wavelengths allows the laser system to be tailored to best match the needs of each specific application; for example, to maximize blood coagulation, tighten collagen, maximize tissue ablation, maximize penetration depth in soft tissue or limit it to surface treatment, burst target cells, etc. For every application, there is one or more optimum wavelength that delivers the best selectivity; that is, where the laser produces a maximum effect while minimizing any unwanted side effects.

There are currently 23 randomized controlled trials in the Physiotherapy Evidence Database (PEDro)—a bibliographic database containing randomized trials, clinical practice guidelines, and systematic reviews in the field of physical therapy—regarding the treatment of musculoskeletal disorders with 904/905 nm pulsed, high-power lasers alone. This evolution of laser devices will make available more effective and penetrative treatments with longer lasting effects, which in combination with other therapeutic technologies will lead to even greater clinical outcomes.

In comparison to IR, blue laser surgery ensures shorter operating times.

Swiss manufacturer Electro Medical Systems (EMS), for instance, has developed a combination therapy concept incorporating a high-power laser (see Fig. 2). It touts fast relief for patients with musculoskeletal disorders thanks to a guided multimodal therapy, which has since proved extremely effective in helping Swiss bobsledders return to competition after injury.

Another new technology developed for physical therapy comes from Mectronic Medicale (Italy). Based on a temperature-controlled, high-energy, adjustable multimode emission laser, the technology makes possible the modulation of the energy in a selective manner, creating a mix of wavelengths and emission modes; this allows specific pathological situations to be treated selectively, maximizing therapeutic results (see Fig. 3).

FIGURE 3. Mectronic Medicale's laser therapy technology is based on a temperature-controlled, high-energy, adjustable multimode emission laser to enable modulation of the energy in a selective manner, creating a mix of wavelengths and emission modes; this allows specific pathological situations to be treated selectively, maximizing therapeutic results. *(Courtesy of Mectronic Medicale)*

Future trends

According to a report by Future Market Insights,[1] the global LLLT market is expected to grow from \$104.0 million in 2020 to \$165.4 million by 2031, at a CAGR of 4.4%. Drivers include the rising prevalence of chronic diseases, surging demand for noninvasive equipment to treat chronic pain, innovations in the technology, and increased optimism in getting faster approvals from the regulatory authorities for innovative products.

Germany accounted for over 24.3% of the market share across Europe in 2021 and both China and India are poised to expand at over 6% CAGR for the forecast period due to the rising incidence of chronic musculoskeletal pain, improved installation of cold laser therapy devices in home care settings, and improved healthcare infrastructure.

The development of medical devices based on diode lasers emitting in the blue area of the spectrum (450 nm) is targeting applications such as dentistry. Unlike conventional IR lasers, which use the hot end tip of the laser to vaporize tissue, blue lasers use the ultra-high absorption in human tissue to increase the tissue temperature and directly cause tissue vaporization. Blue radiation is not absorbed by water and therefore grants better comfort and minimum pain to patients during treatment. In comparison to IR, blue laser surgery ensures shorter operating times, as well as simultaneous cut and coagulation, a cleaner and disinfected operating area, and a faster healing process.

Another technological development is in the area of power supply and cooling, where constant, optimal temperature and thus fast-response cooling are of great importance for wavelength stability, maximum output power, and lifetime of diode lasers. Until now, for cooling heat loads up to about 200 W, thermoelectric (TEC) chillers have been considered the ideal solution, despite their low efficiencies; more efficient compressor-based chillers are often perceived as less comfortable and acoustically annoying due to compressors rattling the enclosure or noise caused by hot gas bypass discharge.

Chillers based on compressors are helping overcome these problems. Such technology developed by UK-based AMS Technologies, for example, includes wide-speed-range inverters and environmentally friendly refrigerant. Designed in compact form factors, these chillers target cooling applications for laser surgery and therapy and are typically integrated into the laser device.

The future for laser therapy for pain relief looks promising. Testimonials from athletes note laser therapy is perfect for treating sports injuries, as it is fast, effective, and being noninvasive, and avoids the side effects of traditional drug-based treatments.

Other notable developments in laser technology include single-emitter, highly customizable diode lasers and blue diode lasers. ◎

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Terahertz imaging advances toward medical diagnostics

Commercial terahertz imaging has made great strides in recent years, progressing toward biomedical applications.

VALERIE COFFEY-ROSICH, CONTRIBUTING EDITOR

The field of terahertz (THz) imaging based on time-domain spectroscopy (TDS), a versatile technique for gathering images that enable us to "see through" plastics, textiles, and cardboard, has made enormous progress during the past two decades. Terahertz wavelengths—ranging from approximately 30 μm to 3 mm—are strongly absorbed by liquids and metal material, which makes terahertz imaging ideal for use identifying such materials in applications like airport security scanners and food inspection.

Unlike x-rays, terahertz waves have low photon energies in the range of 0.4 to 40 meV, which is not harmful to biological tissue. The ability of THz-TDS systems to acquire x-ray-like images without dangerous ionizing radiation makes it particularly compelling for their potential in living tissue (*in vivo*) applications. Terahertz waves are absorbed by water, so they are handy for distinguishing varying water content in different objects. Plus, using the unique spectral fingerprint of many biological organisms and molecules, terahertz can provide spectral information about each pixel within an image, like hyperspectral imaging cubes, which adds to the exciting potential of terahertz technology for medical diagnostics, such as cancer detection and diabetes screening. Furthermore, imaging with terahertz sources can provide sensitivity in soft tissues comparable to that of x-rays.

FIGURE 1. Sensitive GaAs Schottky diode detectors allow nondestructive, passive terahertz imaging systems to detect concealed weapons using the thermal contrast up to 30 feet away without the damaging high energies of x-rays. *(Courtesy of Thruvision)*

Commercial, portable passive terahertz systems have been on the market for more than two decades, thanks to the advent of very sensitive detectors, such as fiber pigtailed antennas. Systems using gallium arsenide (GaAs) Schottky diode detectors, superconducting multiple-quantum-well antennas, and planar detector arrays have also found widespread use in a variety of nondestructive, noninvasive applications, including security, food inspection, manufacturing, and art conservation. In recent years, terahertz stand-off detection has been used by major transportation hubs in 18 countries. For example, London's Underground and the LA Metro use the technology to scan passengers for concealed weapons or other contraband as they proceed through terminals. One such device, the VariView tactical awareness camera, licensed by Thruvision (Abingdon, UK), uses thermal contrast to detect potential weapons on the body, speeding up security screening of passengers (see Fig. 1).[1] But these systems don't gather spectroscopic information, so they aren't as useful for biomedical applications.

Likewise, the advent of new terahertz sources in recent years has combined with these sensitive detectors to enable the first commercial, portable THz-TDS systems that actively illuminate the target to acquire spectroscopic information.

Typically, to create terahertz waves for TDS, the source is a pulsed, mode-locked fiber laser, often at femtosecond frequencies. Fiber lasers offer compactness that enables portability. Other types of terahertz sources proven in the lab with promise for commercial medical applications include photoconductive antennas, powerful gyrotrons with both continuous-wave (CW) and pulsed modes, and quantum cascade lasers.

Although terahertz imaging has yet to reach commercial viability within the medical field, according to Qiwu Shi, professor of Material Science and Engineering at Sichuan University (Chengdu, China), research in pursuit of *in vivo* applications has greatly accelerated in recent years.

"Advanced terahertz imaging systems are becoming higher resolution, smaller in size for better portability, and faster in imaging," says Shi. "Also, the commercial development of numerous advanced terahertz sources has rapidly reduced the cost."

Barriers

One of the biggest limitations of terahertz is its long wavelengths and weak light-matter interaction, which means it can only penetrate a few hundred microns through live tissue. At 0.5 THz, the penetration depth of fat is only a few millimeters, but only a few hundred microns in fibrous tissue or cancer. The strong absorption of terahertz by water *in vivo* causes deterioration of the reflected information and the image. Clinicians can get around this problem using external (*in vitro*) techniques, such as freeze-drying, endoscopy, or studying slices of tissue.[2]

Another emerging solution to reduce image deterioration in high-water-content tissues in terahertz imaging is the use of contrast agents. Nanoparticle contrast agents have been developed in a technique called terahertz molecular imaging, which increases the reflective index of the terahertz water near the nanoparticles. Gold nanorods (GNRs) are the most commonly used contrast agents in terahertz imaging experiments, thanks to their ability to create surface plasmon resonance absorption in response to near-infrared lasers. The enhanced light absorption can cause photothermal conversion and then lead to increased terahertz reflection amplitude. In live cancer cells enhanced with GNRs, terahertz reflection showed a 20% increase over those without GNRs. Other contrast agents with potential in terahertz medical imaging include superparamagnetic iron oxide nanoparticles and gadolinium oxide nanoparticles.

"The most promising point for terahertz medical imaging is the emergence of contrast agents, but more study is needed on their biotoxicity before they can reach clinics," says Shi.

Ultimately, *in vivo* terahertz imaging works well when the area to be imaged is literally (and only barely) skin deep. In *Scientific Reports*, an interdisciplinary team demonstrated that direct terahertz time-domain imaging can be used as a safe and effective diagnostic test for diabetic foot syndrome.

Physics postdoctoral researcher Goretti Hernandez-Cardoso at the Philipps-Universität Marburg (Germany) and colleagues at the Center of Investigations in Optics, Instituto Mexicano del Seguro Social, and Hospital Angeles Leon (all three in Guanajuato, Mexico) used a terahertz spectrometer from Advanced

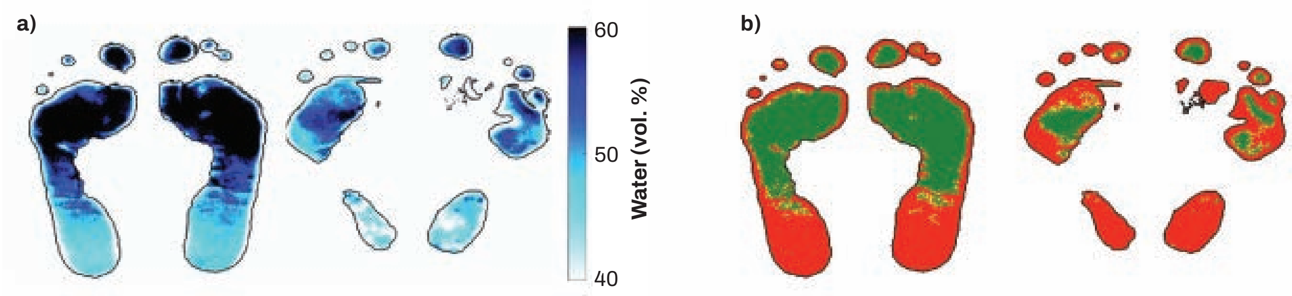

FIGURE 2. (a) Terahertz imaging of foot sole hydration in (left) a diabetic patient without complications and (right) a diabetic patient with a noticeable ulcer on the right metatarsal area. (b) Red pixels indicate hydration levels below 51.7% in the same two patients, which indicate lower deterioration risk (left) and higher ulceration risk (right). *(Courtesy of G. Hernandez-Cordoso et al.)*

Photonix (Camarillo, CA; now Luna Innovations, Ann Arbor, MI) coupled to an imaging platform to raster scan and image the soles of healthy vs. diabetic patients. The spectrometer used a Yb:fiber femtosecond-pulsed laser, photoconductive antennas, and a sophisticated algorithm to map hydration levels of the skin. The team analyzed the water content of the patients' feet to predict deterioration in early stages of the disease, which can help prevent ulcers that can lead to amputation (see Fig. 2).[3] This was the largest human population to ever be imaged using terahertz technology. The findings also provided evidence of a link between the presence of neuropathy, common in diabetic foot patients, and the dehydration of their feet, possibly due to the failure of the nervous system to help regulate hydration.

How about if the target to be imaged is, say, as wide as a tooth? Could terahertz imaging replace x-rays in the detection of dental caries? A group of scientists at Hubei Polytechnic University and Nanjing University in China set out to show terahertz equipment can do just that. Dr. Nagendra Paradad Yadav and colleagues constructed a terahertz parametric imaging system to examine teeth in 2D and 3D. The team used a Tera-1024 terahertz camera from TeraSense (San Jose, CA), and a fixed-frequency 100 GHz (0.1 THz) pulsed diode at various power settings ranging from 80 mW to 400 mW.[4] The setup revealed terahertz imaging can provide rapid diagnostic information on enamel, dentine, and caries. Future studies will work on increasing terahertz imaging resolution to better than 1 mm.

Another advance toward biomedical use of terahertz imaging is machine learning to assist in processing the large amount of digital information obtained via images and spectra. Commercial detector arrays used for terahertz imaging can measure 1024 × 1024 pixels and larger, and if every pixel contains spectroscopic information, the resulting hyperspectral cube is too large for the average non-superhero to analyze efficiently. Pattern recognition algorithms can help identify opaque objects with clear boundaries, a goal for reconstructing 3D terahertz tomographic image cubes both *in vivo* and *in vitro*. Machine learning can compare large amounts of spectral information quickly to recognize, for example, cancerous vs. healthy tissue.

A barrier to terahertz in medical applications is the lack of standards. The increasing use of terahertz in dermatology, cosmetology, and communications could increase the incidental exposure of humans to high-energy terahertz sources. Small to moderate periodic doses of terahertz exposure from CW sources cause no damage to live tissue, but lengthy exposure (≥1 hr) to higher-peak-power pulsed terahertz sources, such as those that might be used in cosmetology or cellular phones, could potentially cause DNA damage and changes in gene expression. Even a few seconds of exposure from a high-power terahertz laser can induce thermal injury because intercellular water molecules vibrate within skin. Before *in vivo* terahertz medical diagnostic equipment can find its way into clinics and labs, more research is necessary to quantitatively define safe and optimal exposure times and dosages.[5]

"It may be some time before we see commercial terahertz equipment for cancer dental screening," says Shi, "but it's exciting to see researchers so focused on the goal." ◎

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Photonics offers a solution to latency issues for AI

Researchers are looking beyond electronics and exploring in-memory computing using optical combs to overcome latency issues for demanding computational problems, including artificial intelligence (AI) applications.

SALLY COLE JOHNSON, SENIOR TECHNICAL EDITOR

Existing technologies and computers aren't able to keep pace processing the sheer volume of data the world is generating. This inspired a group of researchers led by IBM Research Europe, in Switzerland, to look into alternative computer paradigms—and completely rethink how they should work.

To do this, IBM started working on the concept of in-memory computing.

How is in-memory computing different than standard computing? "In-memory computation occurs at locations where the data is stored," explains Ghazi Sarwat Syed, IBM Research Europe staff member. "At no point does data move between memory and a logic unit, which creates bottlenecks. In-memory computing allows us to avoid bottlenecks by computing within the memory."

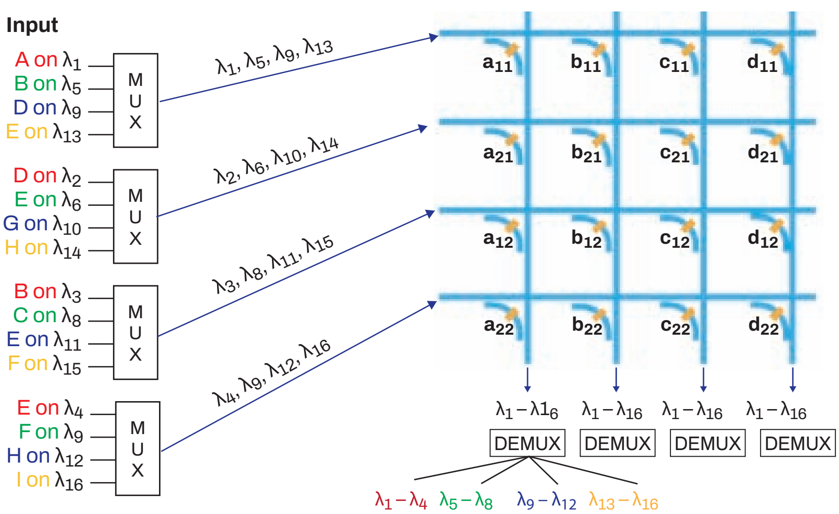

FIGURE 1. A first on-paper sketch of the photonic computing idea the researchers conceptualized. Individual inputs, represented as vectors, are encoded in distinct optical wavelengths. Using wavelength-division multiplexing, a parallel matrix-vector multiplication operation is performed on all input vectors as they traverse through the photonic crossbar.

Moving beyond electronics to photonics

The group has researched integrated in-memory computing technology for several years, and demonstrated the world's first fully integrated in-memory computing chip based on nonvolatile phase-change memory devices in 2021.

"In parallel with efforts within the electronic domain, with our academic collaborators at the University of Oxford, University of Manchester, and University of Exeter, we initiated an investigation into photonic in-memory computing to assess the potential for more efficient and faster computing," says Abu Sebastian, distinguished research staff member and manager of the research program for IBM Research Europe.

"Our idea was to do what we were doing within the electronic domain—but with light instead of electricity," says Syed. "We overcome the latencies notorious within the electronics domain by the physical loss and delays of electricity, which are bottlenecks to speed, with photons."

The electronic domain relies on electricity, or fermions, which are fundamental particles, a.k.a. electrons. Fermions interact with each other as they pass through a copper wire, so they scatter and generate heat, causing latencies or lag times for computing.

But the photonics realm involves bosons, a different type of particle. Bosons don't interact with each other at different frequencies and interact only marginally with most materials they pass through.

"Photonics doesn't experience the latencies you get within the electronic domain," says Syed. "And since the wavelengths aren't interacting with each other, multiple wavelengths carrying lots of information can flow through a common channel at once."

IBM researchers and their academic partners are embracing the concept of photons at multiple wavelengths going at the same time, "but to compute," adds Syed. "Each wavelength will perform a set of computations and with multiple wavelengths within the same time instant, so you're performing multiple computations at the same time. This is wavelength-division multiplexing, which isn't possible in a straightforward way in electronics."

Optical computing for AI

The second piece of the researchers' work focuses on deep learning applications and involves inputs of light at different wavelengths.

One of the biggest challenges was figuring out how to generate light on-chip. While interest in optical computing got its start back in the 1960s, the field experienced a renewal with the advent of integrated photonics—essentially, the optical analog of the electronic silicon integrated circuit.

Working with silicon photonics involves silicon waveguides. "Silicon can't generate light," notes Syed. "It can sense but not efficiently generate it. So the first thing we did was to find a component to generate light on-chip, which is a silicon nitride (SiN) optical frequency comb."

Another challenge was building a crossbar with photonic elements. A crossbar is common within the electronic domain—with a topology of memories. "The advantage of a crossbar is it's insanely dense," Syed says.

Theirs is designed within the optical domain of a crossbar and combined with optical combs, which results in very low latencies for computations (see Fig. 1). This was implemented with academic collaborators at the University of Oxford, University of Muenster, Swiss Federal Institute of Technology, and the University of Exeter.

"The throughput is light," explains Syed, "and in between is a black box, which in our case is a photonic memory crossbar made of waveguides and all-optical components."

This crossbar is special because a germanium-antimony-tellurium (GST) phase-change material sits at every junction and stores the value of an optical matrix with multiple elements (see Fig. 2). "The storage is nonvolatile, meaning if I store this element within the phase-change material it will stay there," notes Syed. "And it doesn't need a constant supply of energy to maintain a certain element weight, it's fixed."

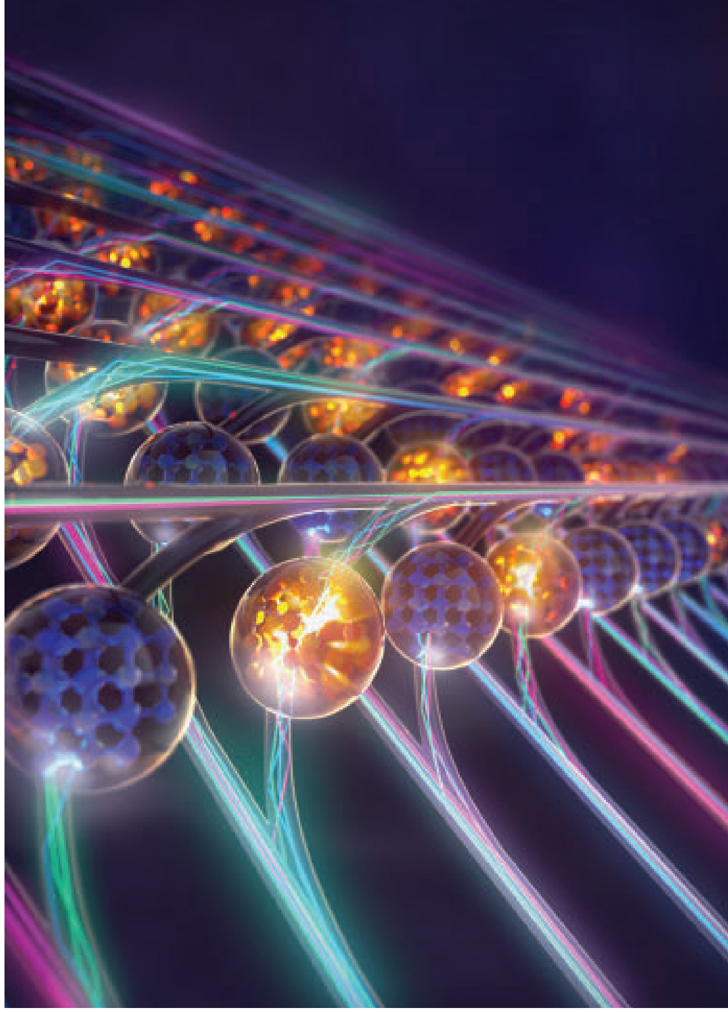

FIGURE 2. This rendered image of the crossbar shows a phase-change material (GST) at each crosspoint and input signals of light in different colors.

Multiple inputs come in via the crossbar, and then there's output. "The beauty of our project is we achieve this by combining two different modules—one component is the photonic memory crossbar, which does the optical matrix part, and the optical combs are an on-chip source of light," he says. "This is a big advance because a huge challenge for photonics is generating and computing with light on a chip."

By using a single optical comb to generate multiple lights, they can get around 200 individual wavelengths at the same time, which serves as the input to the matrix.

Surprises along the way

The biggest surprise for the researchers was things worked the way they'd imagined. "We were amazed by the throughput and the speed," says Sebastian.

The group achieved a throughput of around 2 TOPS, which means two trillion multiply accumulate operations per second. This result is striking because it was accomplished at a whopping 14 GHz input/output speed, with a crossbar encoding a tiny matrix—the number of operations scale with the matrix size. “A laptop or your mobile phone works at 1 GHz, or 1 billion operations per second,” he adds. “We’re talking about trillions of operations per second without the chip ever becoming heated.”

And they reach this speed via a single crossbar. “Right now, it’s the speed of deep learning in AI,” Syed says. “You can buy activation-specific accelerators to speed some AI tasks, but they use tens of computational cores to achieve the same throughput.”

Autonomous applications ahead

Self-driving vehicles are one obvious application in need of fast speeds and low latencies for image recognition tasks. “If your car is looking at an image possibly in the road ahead of you, you want it to process it as fast as possible,” Sebastian points out. “You don’t want any latencies. And typically the images self-driving cars capture are large in size, so you’ll want a photonic computer to do this.”

Along the same lines, photonic computers can be used for machine language translation or natural language processing. “Companies can make predictions about things like what movie you’ll want to watch next,” he adds, “and it can be done much faster with photonic computers than now.”

How long before we see photonics-based computers for AI? “We’re still in the evaluation phase of innovation,” Syed says.

It’s important to note IBM Research isn’t alone within this realm—many startups are exploring photonics-based computers for AI, and some already have off-the-shelf products. One company in France, Light On, was able to integrate an optical computer into an AI supercomputer in December 2021.

What’s next?

IBM Research is exploring other interesting computational problems within the optical domain—like how to find the best timetables for planes or even exploring complex protein folding and how its structure changes.

“It takes a long time to compute these things today, even on supercomputers. Our hope is to assess such computational tasks using photonics,” says Syed. “Another direction we’re looking into is applications for computation of live data, which involves performing statistical operations for processing big data to see how we can best leverage photonics.”

Display technology sees swift advancement

From flexible smartphones and laptops to head-up displays for autonomous vehicles, the future of displays is here.

JUSTINE MURPHY, SENIOR EDITOR

Reality is changing. School, work, even doctor visits can happen today without leaving home. Technology needs to keep pace with today's ever-changing world, so continuous progress is crucial.

The future of laptops, smartphones, and now automobiles relies, in part, on advances in displays. And the market is growing, with an estimated value of $186 billion globally by 2023.

During the next several years, experts predict a nearly 4% compound annual growth rate (CAGR), citing various driving factors: the surging adoption of organic light-emitting diode (OLED) displays expanding use of LED displays for things like "video walls, TVs, and digital signage applications, a growing demand for interactive displays, and rising demand for display-based medical equipment, including ventilators and respirators."

OLED displays

Researchers at the University of Minnesota, Twin Cities have developed a 3D-printed, flexible OLED display—the first of its kind. Its introduction could pave the way for lower-cost displays "that could be widely produced using 3D printers by anyone at home, instead of by technicians in expensive microfabrication facilities."

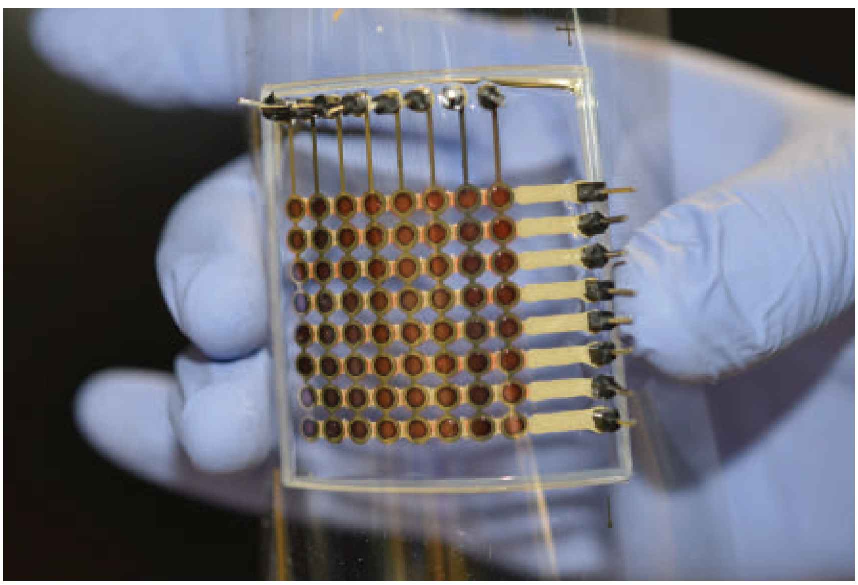

FIGURE 1. This fully 3D-printed flexible OLED display prototype is about 1.5 inches on each side and has 64 pixels, each of which displays light. *(Courtesy of McAlpine Group, University of Minnesota)*

Their study says OLEDs are competitive alternatives to liquid crystal displays (LCDs)—the current standard for flat-screen TV screens.[1] OLEDs tout self-emission and higher contrast ratios than LCDs, as well as fuller viewing angles, higher power efficiency, and mechanical flexibility.

This new technology is based on the conversion of electricity into light using an organic material layer, which allows OLEDs to be high-quality flexible digital displays for use in TV screens and monitors as well as smartphones and other smaller, handheld devices. Such displays, the researchers note, are also lightweight, more power-efficient, and thin. Producing them, however, is challenging because OLED displays are typically manufactured in large, expensive fabrication facilities.

"We wanted to see if we could basically condense all of that down and print an OLED display on our tabletop 3D printer," says Michael McAlpine, a professor in The University of Minnesota's Department of Mechanical Engineering.

Among initial obstacles with the 3D printing process was with nonuniformity of extrusion-printed active light-emitting layers. The researchers describe the creation of repeatable and stable polymer-metal junctions

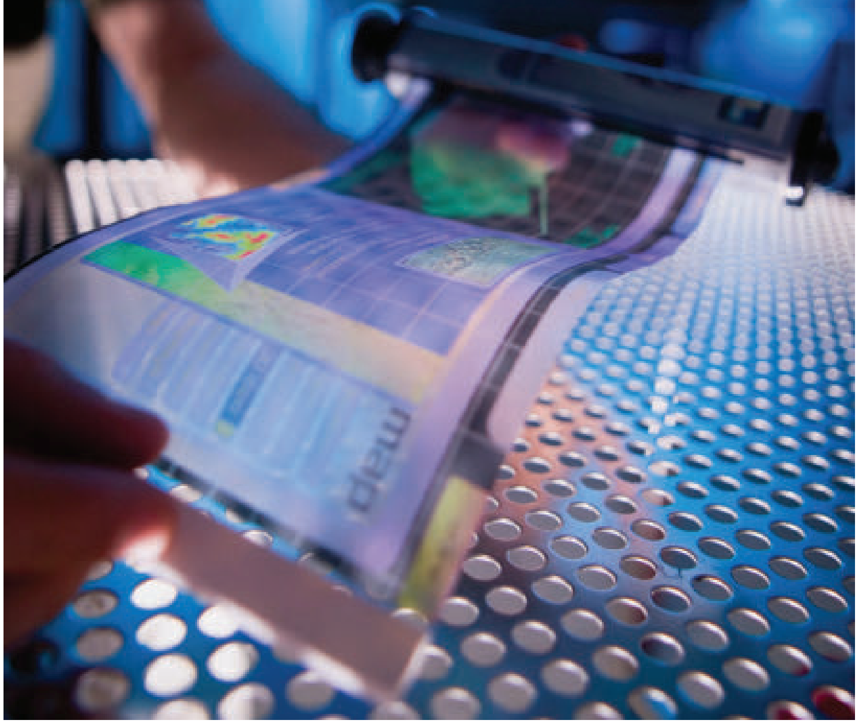

FIGURE 2. Flexible displays are already being used in smartphone designs and other devices. *(Courtesy of U.S. Army RDECOM)*

between the active layer and the cathode using the 3D printing approach at room temperature as "difficult."

The OLED display comprises six device layers created by combining two different modes of printing. Extrusion printing enabled researchers to overcome issues relating to printability, electrodes, interconnects, insulation, and encapsulation—the active layers were then spray-printed using the same 3D printer at room temperature. The display prototype measured 1.5 in. on each side, and 64 pixels of light (see Fig. 1).

"The device exhibits a relatively stable emission over 2000 bending cycles," says Ruitao Su, who earned a Ph.D. from the university and is now a postdoctoral researcher at MIT. He notes the displays could be packaged in an encapsulating material, opening up a variety of potential applications such as wearable displays. And the entire fully 3D-printed process could prompt "futuristic concepts" including displays "interwoven with soft robotics for electroluminescent body parts and three-dimensionally structured pixel matrices for holography."

A team in South Korea is also exploring the use of OLEDs for advanced displays. In work published by Springer—*Advanced Display Technology: Next-Generation Self-Emitting Displays*—authors Byeong Kang, Ph.D. (former CTO of LG Display, Korea and a fellow of The Society for Information Display); Chang Wook Han, Ph.D. (a chief research fellow and VP at LG Display); and Jae Kyeong Jeong, Ph.D. (a professor in the Department of Electronic Engineering at Hanyang University (Seoul, South Korea) and a member of the *Scientific Reports* and *Journal of Information Display* editorial board) report: "OLEDs today can be manufactured at 8K resolution on a large scale, and with remarkable efficiencies, color purity, and long lifetimes."

Many of the imaginative possibilities for OLED technologies are finding their way into commercial devices, they say, including foldable devices, transparent displays, and rollable televisions.

OLED displays are also boosting smartphones. Companies including Samsung and Motorola have already rolled out smartphones with flexible screens. The IEEE Computer Society says this "new breed called 'flexphones' feature flexible substrates, unique materials, and ultrathin displays that can be folded multiple times without creasing." Nearly all flexphones feature OLED displays (see Fig. 2).

Sri Peruvemba, CEO of Marketer International Inc. (California) and board director of Summit Wireless Technologies Inc. (San Jose, CA), notes foldable phones will ultimately become even thinner and feature a longer battery life.

Micro-OLEDs have the potential to bring augmented reality/virtual reality (AR/VR) technology to the next level. Unlike LCD displays, and even OLED displays, micro-OLED screens are directly mounted to single crystal silicon wafers, enabling the production of thinner, more power-efficient, self-illuminating displays. This suits AR/VR wearable technology, according to TechNews, a source used by technology companies worldwide.

Companies including Apple, Sony, and Samsung are currently developing displays featuring micro-OLEDs.

Smart glass displays

Also called switchable glass, smart glass touts light transmission properties that are altered when voltage, light, or heat is applied. It can also alternate between transparent and opaque, and is now finding applications in marketing and advertising. When opaque, the smart glass display acts as a projection screen on a traditional glass storefront. When transparent, it features that same type of display but allows an unobstructed view into the store.

Smart glass has proven ideal for privacy in homes (bathroom and bedroom windows as well, and other settings such as hospitals.

Autonomous vehicles

The automotive smart display market is booming. By 2025, it's expected to reach $10.9 billion, increasing at a CAGR of nearly 10%. Global market analysts Research and Markets attribute such growth to the advancement of autonomous vehicles.

Smart displays used in autonomous vehicles are referred to as head-up displays (HUDs). Karlheinz Blankenbach, a professor at Pforzheim University (Germany) and founder of the school's Display Lab, discussed the future of this technology at this year's SPIE Photonics West.

"Autonomous cars should communicate by exterior displays with other road users to increase safety," he says. Such displays can show information such as visualization of the vehicle's driving mode, the current speed limit, visual detection of other vehicles and nearby pedestrians, and navigation instructions (see Fig. 3). He and his Display Lab team note there are ongoing challenges in implementing this technology into vehicle designs, given their current novelty, but they're continuing their research.

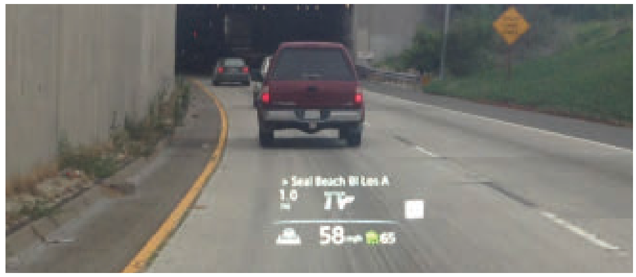

FIGURE 3. An active driving display with traffic sign recognition. *(Courtesy of Mazda)*

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Noncontact laser measurement for everyone

Optical measurements of speed, position, and length in production systems are better than tactile ones—but, unfortunately, also much more expensive. SICK and TRUMPF revisited this old conundrum and discovered it is no longer true.

ALEXANDER WEIGL

When Heiko Krebs, senior vice president of product management at SICK (Waldkirch, Germany), reached out to Ralph Gudde, vice president marketing and sales for TRUMPF Photonic Components (formerly Philips Photonics; Ulm, Germany), he was interested in collaborating.

Specifically, Krebs wanted to establish a new technology in the world's conveyor systems: noncontact optical capture of production data such as speed, position, or length. The reason? Until now, these were much more expensive than standard measuring wheel encoders, which involve a wheel rolling over the passing goods and components and calculating their dimensions and speed. "The benefits of noncontact measurement would usually not outweigh the higher purchase price," says Krebs.

SICK's customers come from all sectors, because industrial companies everywhere want to automate their process and production systems, which requires reliable, real-world data from their systems to control their processes and ensure quality. This includes knowing: Are all sheets/polystyrene sheets/packaging materials cut to the correct length and width? How fast and in what position do they run through the conveyor systems? At what distance from each other?

They accomplish this via measuring wheel encoders. Other existing sensors, in which laser light scans parts and calculates this information from the runtime of the light, are technically complex and too expensive for many applications. There are also additional costs because they require high laser power and fall into the laser class 3 category. This makes structural safety precautions necessary in and around the system and personnel needs special training to be able to work on the system. This can all be avoided by using the tried-and-tested measuring wheel.

Contactless by nature

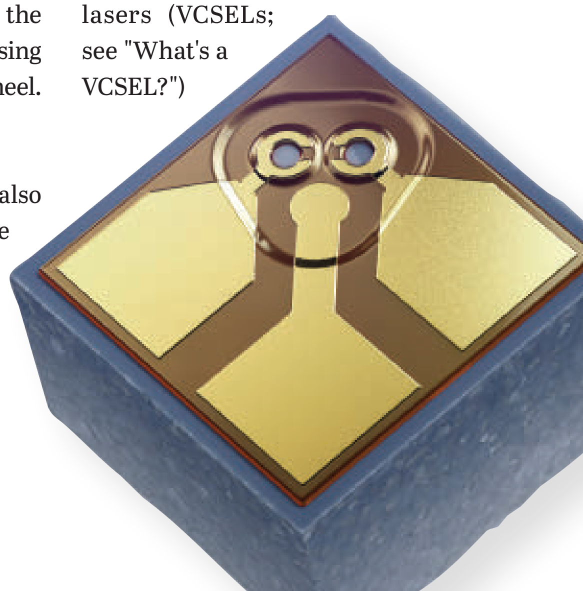
Tactile measuring wheel encoders also have real disadvantages, which are quite significant depending on the application. "They touch goods and components to be measured," he says.

This is irrelevant for many materials, such as thick sheets. But with thin, delicate materials such as films, the wheels leave undesirable grooves and marks that disrupt the subsequent process. Or the wheels do not get enough grip. This can happen on soft surfaces such as polystyrene or insulation materials. The wheels struggle with slip and measure inaccurately. This is why one centimeter is added when cutting wool insulation, to be on the safe side.

Over time, this represents a lot of extra material that could be saved with a more reliable measurement. "The second major disadvantage of measuring wheels is that they wear out," notes Krebs. Neither trace nor wear problems are inherent to an optical sensor.

VCSEL illumination

With a goal of being competitive, this is where the engineers at TRUMPF fit into the equation. The engineers produce tiny vertical-cavity surface-emitting lasers (VCSELs; see "What's a VCSEL?")



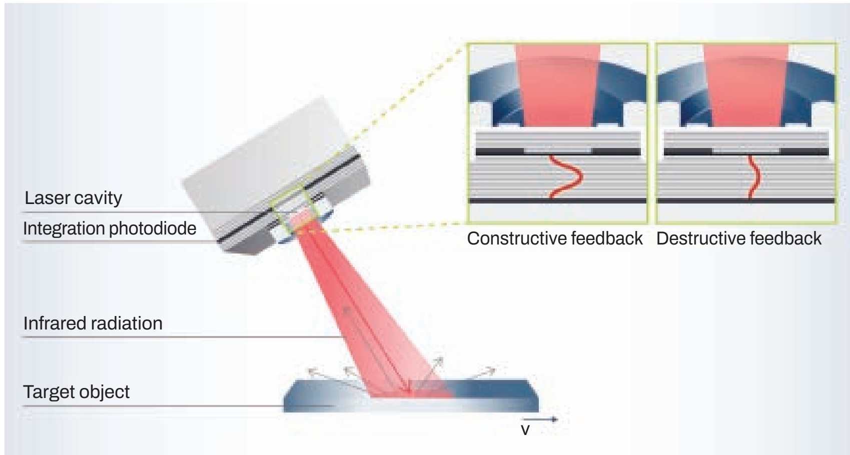
A multimode VCSEL with integrated photodiode for infrared light.

and photodiodes, fully integrating all components, such as the lens, into the entire system. When this project kicked off, VCSELs were mainly used for consumer goods such as smartphones, office printers, and optical computer mice. “VCSEL products were created for the mass market, where every penny counts, and TRUMPF already offered to these markets high volume with excellent quality at low cost,” Krebs recalls.

Krebs understood VCSELs would solve the restrictions associated with laser class 3. But would it also work technically?

“We immediately proposed a different measuring procedure,” says Gudde. “With the VCSEL diodes, we were able to use so-called self-mixing interference technology (SMI). It’s been used in millions of products for around 20 years and proven itself.”

With SMI, a VCSEL projects an infrared laser beam onto the surface of a passing part, whether it’s metal or plastic. An optical resonator catches the reflection of the laser beam and mixes it with the light in the resonator. A photodiode measures the interference and the system calculates the movement speed from the frequency difference. The modulation of the wavelength can be used to determine the direction. And the sensor directly detects speed and direction, as well as the indirect position and expansion of the part.



With self-mixing interference technology (SMI), a VCSEL projects an infrared laser beam onto the surface of a passing part. An optical resonator catches the reflection of the laser beam and mixes it with the light in the resonator. A photodiode measures the interference and the system calculates the movement speed from the frequency difference.

Joining forces

Krebs and Gudde decided to tackle the revolutionary project together and launch a development partnership. TRUMPF contributed the core technology, while SICK contributed the application expertise and market access.

The path was clear, but several challenges remained. “At the time, we had little insight into the requirements an integrated industrial sensor had to meet,” Gudde says. “We didn’t even know what markets and niches existed within the industry.”

One challenge was to develop an integrated field-programmable gate array (FPGA) circuit to handle all the different surfaces the laser could encounter. “With light diffusion, for example, it makes a big difference whether it comes from sheet metal or packaging film,” Gudde adds.

Krebs also reflects on the many years of development work, noting that “with project partners oriented toward the fast-paced consumer market and us focusing on industry specifications, two worlds collided. We first had to find a common language, a common way of thinking about some things. The colleagues at TRUMPF sometimes helped us maneuver our way out of impasses with their approach.”

Consider, for instance, the case of industrialization, as the two teams considered how they wanted to manufacture the sensor, and which specifications it needed to comply with. “For the sensor, we wanted to achieve a temperature rating of 0 to 70°C out of habit,” says Krebs. “This is the same range the measuring wheel encoders have.”

But the VCSEL requires consistently stable temperature control. Maintaining this, including at very high ambient temperatures, increased the structural and technical requirements placed on the sensor. “It would have led to a much higher price,” says Krebs. However, TRUMPF engineers noted by stopping at 45°C, it could achieve over *continued on page 55*

What’s a VCSEL?

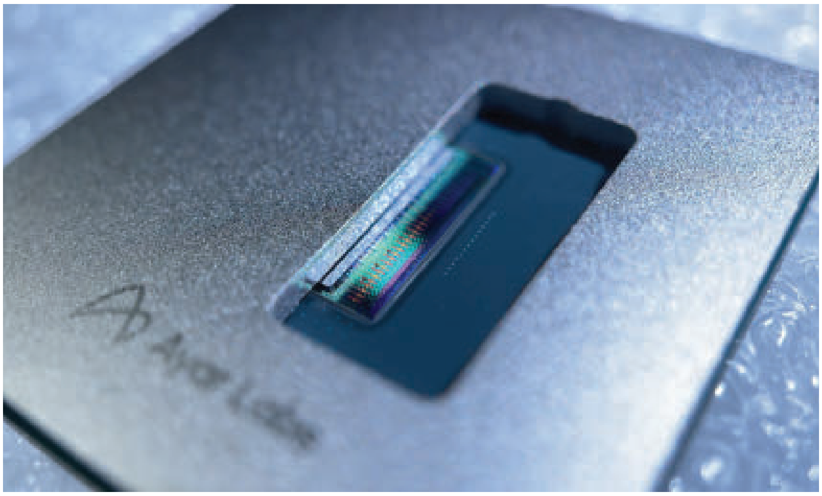
Vertical-cavity surface-emitting lasers (VCSELs) are diodes that generate laser light with very high beam quality. They are efficient and can be reduced to almost any size. Integrated VCSELs not only emit radiation, they also capture signals and process them. This makes them particularly appealing for industrial encoders to monitor processes.

Strategic collaborations fuel future photonics growth

PETER FRETTY, Editor in Chief

As companies within the evolving photonics space embrace the idea of integrated offerings designed to meet specific applications, the need for strategic partnerships will intensify—often as an alternative or sometimes as precursor to a merger or acquisition.

A quick look at recent activity at Santa Clara, CA-based Ayar Labs shows the producer of chip-to-chip optical I/O technology is aggressively pursuing collaborative opportunities—the type of relationships capable of positioning the organization to thrive in the future.



Phoro Credit: Ayar Labs

For instance, on March 9, Ayar Labs announced a strategic collaboration with Lumentum to deliver CW-WDM MSA-compliant external laser sources in high volume. These light sources are critical to power Ayar Labs' optical I/O solution.

This news came on the heels of another collaboration involving Ayar Labs' ongoing work with Global Foundries, which expands to include Broadcomm, Cisco Systems, Marvell, NVIDIA, Lightmatter, PsiQuantum, Ranovus, and Xanadu. Chips built on the resulting technology will power automotive (LIDAR), quantum computing, consumer optical networks such as fiber-to-the-home (FTTH), 5G networks, telecommunications, data center transmissions, time-of-flight (TOF) sensors, aeronautics, and defense applications.

In late February, Ayar Labs also announced its strategic arrangement with computing giant Hewlett Packard Enterprise (HPE), to revolutionize computing by moving data with light, better enabling high-performance computing (HPC) and artificial intelligence (AI) solutions.

Optical I/O uniquely changes the performance and power trajectories of system designs by enabling compute, memory and networking ASICs to communicate with dramatically increased bandwidth, at a lower latency, and at a fraction of the power of existing electrical I/O solutions.

Read on as Marten Terpstra, senior director of product management for the high performance networks, HPC and AI business groups at Hewlett Packard Enterprise and Hugo Saleh, senior vice president of commercial operations and managing director of Ayar Labs UK discuss their strategic collaborations.

Laser Focus World: How do you see this technology effectively impacting HPC?

Saleh: As the industry enters the exascale era, electrical-based networking offerings will eventually reach bandwidth limits, creating challenges in latency and overall application performance. At the same time, future data-intensive HPC and AI workloads will continue to demand increased flexibility, efficiency, performance, and throughput. Optical I/O is foundational to enabling emerging heterogeneous computer systems, disaggregated/pooled designs, and unified memory architectures that are critical to accelerating future innovation.

With the combination of Ayar Labs' optical I/O and HPE's Slingshot, the teams are well positioned to design next-generation, high-performance networking solutions and novel disaggregated system architectures that are critical to meet these demands.

LFW: As HPE integrates this technology into its offering, what applications will it enable?

Terpstra: We are about 1–2 generations away from reaching a limitation to run high-speed signals over electrical paths, over required distances and power utilization. Optical I/O provides an alternative to addressing the limitations of electrical, copper-based I/O by delivering integrated optical technology that uses light instead of electrical signals to transmit data.

This will allow longer distance, higher speed, and lower power and latency communications that enables disaggregated memory and GPU architectures. These, in turn, will improve application performance overall to create far more effective HPC and AI training model performance, with systems that are more cost-effective and flexible in how they are being used, and how resources, such as memory and GPU/CPU cycles, are being dynamically allocated.

LFW: What challenges remain?

Saleh: Building the right products at the right time for customer consumption. Ultimately, we want to build the product that meets the customers' needs and that the customers will buy. Working together, we need to figure out the optimal solution.

For broad adoption of optical-based technology that will allow the industry to flourish, we need to ensure there are standards in place and build out an ecosystem for adoption. We believe the combination of the industry leader in servers with the leader in chip-to-chip optical communications is the right team to build the ecosystem needed to make the shift to the optical era of computing.

LFW: What do you see as key to reaching the next level?

Saleh: The combination of Ayar Labs' optical technology ecosystem partnerships with HPE's advanced system architecture supply chain is key to accelerating the adoption and delivery of optical I/O at scale, leading to unique, disaggregated system architecture design for the future of HPC and AI. ◎

continued from 53 80% of all possible applications. "It was a decisive breakthrough," says Krebs.

"The development partnership with SICK was a kind of baptism of fire for the projects with industrial customers," says Gudde. "When TRUMPF took over our company in 2019 as an industry expert, we were already able to demonstrate our expertise." So the two companies finalized the product development and set a global technical benchmark for optical sensors made in Germany.

Soft surfaces? No problem

Together, TRUMPF and SICK initiated a process algorithm to evaluate signal quality on the FPGA quickly and with extreme precision. At object speeds of ten meters per second, it achieves a resolution of 4 μm and a measuring accuracy of 0.1%. This enables measuring a length of 1 m to the millimeter. The sensors, now known as SPEETEC, measure a length of 1 mm to the nearest millimeter—regardless of what's underneath the laser diode, including wool insulation. "And the price is significantly closer to tactile solutions than previously available on the market," says Krebs with satisfaction. With this technology, they entered the market as pioneers.

This optical sensor is attractive for companies looking to exchange previous solutions for more precise laser sensors. For example, plastics manufacturers whose products were coming hot from the extruder and were simply too soft for wheels. Or cable manufacturers where wheels had always caused problems with accuracy issues.

"We receive many requests for applications we didn't even have in mind during development," says Krebs. "With SPEETEC, companies can now solve measuring tasks for which there were previously no suitable sensor systems. This is also so exciting because the noncontact process can be very easily adapted to special requirements using software." ◎

Alexander Weigl is product manager at TRUMPF Photonic Components, a fully owned subsidiary of the TRUMPF Group, Ulm, Germany; e-mail: photonic.components@trumpf.com; www.trumpf.com/s/vcsel-solutions.

Lasers light the way toward quantum computing

Advances in high-purity, low-noise laser sources are facilitating the development of practical quantum computer hardware, but frequency control and phase noise management challenges exist.

CASIMER DECUSATIS

While the idea of using quantum mechanics principles such as superposition and entanglement to perform computations is at least several decades old, it's only within the past few years that the technology to implement practical quantum computers became available. High-purity, low-noise laser sources are among the key enabling technologies for emerging quantum computing architectures. Advanced laser systems will play a pivotal role as quantum hardware disrupts the field of computer science.

The interest in building laser systems suitable for quantum computation is tied to the inherent benefits of quantum computing itself. Just as bits are the fundamental building blocks of modern digital computers, two-level systems called qubits form the foundation of quantum computers. A qubit can exist in coherent superposition of two binary states (zero and one), so it can be used to perform certain calculations much more rapidly than conventional computers.

Many practical problems in physics, chemistry, and biology, as well as problems in such diverse fields as accounting[1] and automotive design,[2] could benefit from quantum computing techniques. These and other fields face problems currently requiring exponential execution times, which could take decades to solve on even the fastest conventional supercomputer. Such computations could be performed much faster (in polynomial time) on a suitable quantum computer. These range from simulations of the world around us to optimization and sorting problems, factoring large prime numbers (the basis for modern encryption techniques that support a trillion-dollar global electronic commerce system), and improving existing algorithms such as artificial intelligence and machine learning. While quantum computers won't replace conventional systems anytime soon, there are enough high-value problems within this category to drive multi-million-dollar investments in the development of practical quantum computers.

It's useful to think about quantum computing as being in the earliest stages of its development, much like conventional computers. Indeed, before

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Charles Babbage and Ada Lovelace developed the first modern computer or difference engine to calculate logarithms, performing such computations was done by skilled humans whose job title was "computer" (just as someone who works with paint was called a painter).

There are many historical examples of such "computers," including Katherine Johnson, Dorothy Vaughan, and Mary Jackson who played a vital role in the early days of the U.S. space program.[3] Babbage's difference engine used mechanical gears to execute programs developed by Lovelace using punched holes in paper tape—arguably the first implementation of bits in a mechanical computer. Subsequent computer architectures found new ways to represent bits, including voltage and current fluctuations in vacuum tubes, polarized photons, and electron states within silicon chips.

Implementing qubits

There are also many ways to implement qubits, and it's likely we haven't yet found the optimal way to achieve this in a quantum computer. For example, commercially available systems such as the IBM Q System and similar hardware from Google and Intel rely on superconducting wires cooled to near-absolute zero to realize qubits. The success of these systems has led researchers to investigate alternative quantum computing architectures that could operate under less extreme environmental conditions. Laser systems with specific properties are critical to many of these recent efforts because of the role it plays in multilevel physical systems.

A qubit is a two-level system, in which two states can exist in a stable superposition. For example, consider two internal energy states within an atom—a ground state and an excited state (see Fig. 1). There is a discrete energy gap separating these states, and they can be coupled together using laser radiation at a specific frequency (where the laser energy and frequency are related by Planck's constant, *h*). The atom's state evolves in a well-defined phase relationship with the laser radiation (in other words, coupling between the laser and the atom is coherent). By applying laser pulses with a controlled frequency and duration, it's possible to create a superposition state between the two atomic energy levels, effectively controlling the probability of finding the atom in the excited state or the ground state.

This process shows whether an atom is in the ground state, excited state, or both simultaneously (analogous to the famous Schrodinger's Cat experiment). When measuring the qubit, it collapses into either the excited or ground state with some probability and can be reverted to a conventional zero or 1 value. By combining multiple two-level systems, it's possible to create entangled states, in which the value of one qubit affects the value of another. Precisely tuned laser pulses that control the coherent interaction are used to construct quantum logic gates, just as conventional computers use Boolean logic gates to process bits.

In a quantum computer, a sequence of quantum gates operating on one or more qubits is used to implement quantum algorithms. We can measure the probability that a quantum gate is working as designed (or more generally, the probability of achieving a target quantum state) as the fidelity of a quantum logic gate. Fidelity is essentially the probability that entanglement between two states has been successful. If the fidelity drops below a threshold level, gate errors will occur and the quantum calculations will be corrupted. Quantum gate fidelity is limited by how well we can control the parameters of laser pulses used to interact with qubits. This means very high-purity, low-noise optical sources are fundamental to the construction of practical, scalable quantum computers.

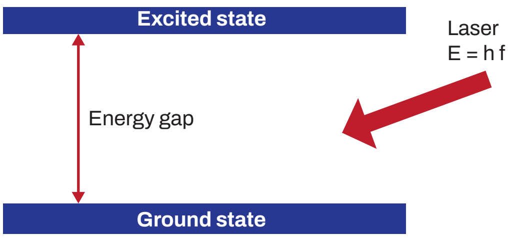

FIGURE 1. Two-state energy gap with laser excitation.

One type of qubit based on single trapped atoms are known as optical qubits. In a design known as an ion trap, the atomic energy levels are chosen such that the excited state lasts for as long as possible (on the order of a second or two using current systems). There are significant research challenges to overcome when realizing practical optical qubits. One of the most significant is laser linewidth, which sets an upper limit on the coherence time for interactions between the laser source and the qubit. To take advantage of properties such as superposition, a quantum computer must perform all its calculations before the system loses coherence. This is analogous to using the calculator function on your cell phone when the battery is running out; you only have a limited time to complete your work before the phone dies and your calculation is forced to stop.

It's desirable to maximize coherence time in a quantum system to enable performance of more lengthy calculations. Achieving a long-excited state lifetime requires laser sources with extremely narrow emission linewidths, on the order of perhaps 1 Hz.[4] This is well below the range of many standard laser systems, which operate with linewidths between a few hundred kilohertz to several megahertz. Significant linewidth reduction and stabilization is required for high finesse laser cavities, which are insensitive to even small vibrations and other noise sources.

Advanced linewidth reduction systems have been developed using Ti:sapphire lasers at 729 nm center wavelength, with a 1 Hz linewidth and feedback stabilization from a high finesse external optical cavity. This makes it possible to create high-fidelity entangled qubit logic gates (see Fig. 2). More specifically, ion traps can be constructed using a steel vacuum chamber cooled to nearly -450°F. A dozen lasers at slightly different frequencies are directed into this chamber ionizing a combination of calcium and strontium atoms, which are held in an electric field and brought together to form a crystal.[5]

The frequencies required for laser cooling calcium and strontium ions, entangling them, and reading out the results all fall within the same portion of the optical spectrum, which simplifies the laser system requirements. This material system can also be manipulated by infrared light, for which there are a wide range of available laser sources, as opposed to other materials that require ultraviolet frequencies to excite and trap ions. While device specifications vary, output power on the order of hundreds of milliwatts to a watt or more should be possible in the short-term using these devices. Strontium and calcium energy states can become entangled, so that reading the state of one qubit (for example, by interrogating the crystal with a laser wavelength that will only interact with the calcium ion) will also yield the state of the strontium qubit. A fidelity of 94% has been measured in the calcium/strontium crystal, sufficient to prove this concept is viable for quantum computations; variations on this structure have achieved fidelity of nearly 99%, among the highest gate fidelities yet reported.

An alternative approach known as hyperfine qubits encodes information in two sub-levels of the ground state of alkali-earth materials. Two laser frequencies separated by a few gigahertz (the energy gap of the qubit) provide coherent coupling through stimulated Raman transitions. In this case, the ability to control coherence isn't determined by the linewidth of each laser, but rather the relative phase noise between the two sources. Typically, these two sources can be implemented by phase locking two lasers to maintain a precise frequency offset. It's also possible to use electro-optic modulation to produce two frequencies through sideband generation. Raman transitions are non-resonant, meaning relatively high optical power is required to achieve high-fidelity logic gates. Such a system requires both low phase noise and high power, typically at ultraviolet wavelengths.

One recent implementation for calcium ion hyperfine qubits uses two phase-locked and frequency-doubled Ti:sapphire lasers, operating at 397 nm wavelength with a frequency offset of 3.2 GHz. The combined system can deliver over 3 W of total power. This approach is suitable for high-fidelity quantum gates, because it features low phase noise (7 mrad rms between 10 kHz and 1 MHz).

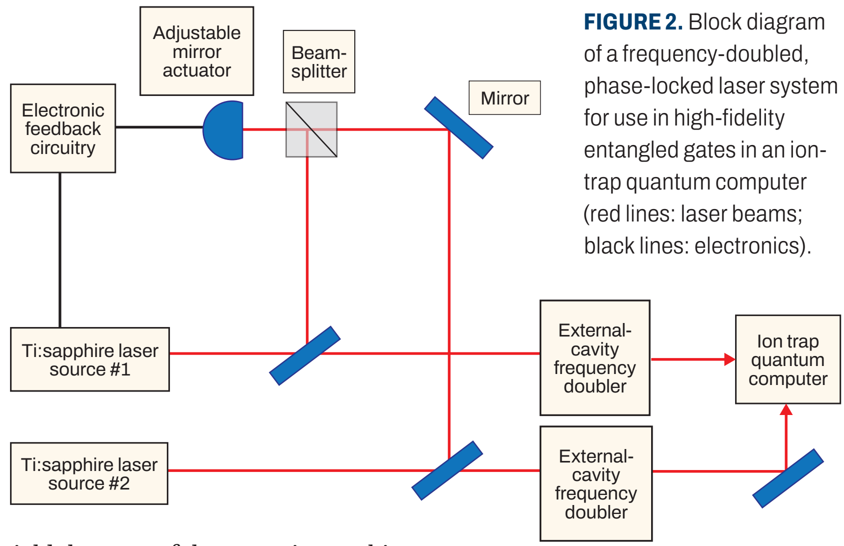

FIGURE 2. Block diagram of a frequency-doubled, phase-locked laser system for use in high-fidelity entangled gates in an ion-trap quantum computer (red lines: laser beams; black lines: electronics).

Technical challenges

Many technical challenges remain, including scaling these systems to large enough numbers of qubits for practical calculations. Systems such as those described earlier have only been demonstrated for a few qubits at a time; hundreds or thousands of qubits are desirable for many applications. This will require greatly increasing laser output power—on the order of several watts to tens of watts or higher—while maintaining low noise and fine line widths. Precision alignment of optical components in future systems may also benefit from advances in integrated optics and modulators.

Further, there are proposed implementations of qubits that do not use ion traps, but instead encode qubits into two optical modes of a single photon (such as light polarization).[6]

In principle, photonic qubit systems would not need to be cooled near absolute zero to function and could facilitate transmission of qubits over long distances using fiber-optic cable, provided the cable preserves the optical mode property during qubit propagation. This is a significant challenge, since many optical fiber systems exhibit photon attenuation and loss rates much larger than the coherence time of the associated qubits.

Experimental setups operating at wavelengths near 780 nm have been demonstrated using this principle, and modified photonic quantum logic gates remain the subject of ongoing investigation by many researchers and institutions.[7-9] For example, recently developed 4 × 10 mm photonic qubit devices that implement an 8-qubit quantum computer have become accessible through cloud-based interfaces.[10] This includes efforts supported by Cisco's new quantum research team to demonstrate optical qubits integrated into photonic circuits using aluminum gallium arsenide (AlGaAs) laser sources.[11]

It's too early to say which of these approaches will emerge as the equivalent of solid-state semiconductor processing for conventional computer chips, but we can expect high-quality laser sources to play a pivotal role in any quantum computing architectures to emerge in the future. ◎

In principle, photonic qubit systems would not need to be cooled near absolute zero.

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Dr. **Casimer DeCusatis** is an associate professor of information technology and systems at Marist College (Poughkeepsie, NY), and former IBM Distinguished Engineer and IBM Master Inventor who holds over 150 patents; e-mail: casimer.decusatis@marist.edu.

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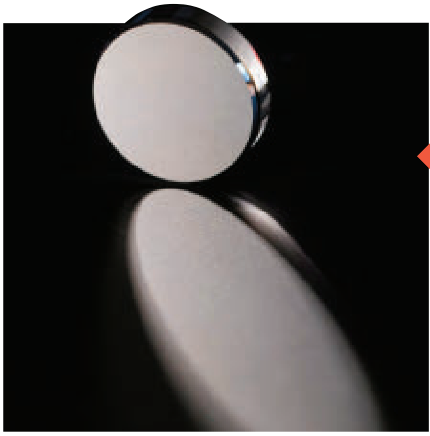

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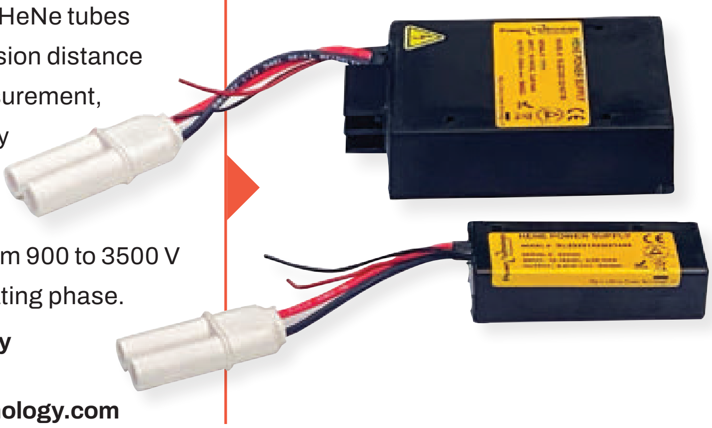

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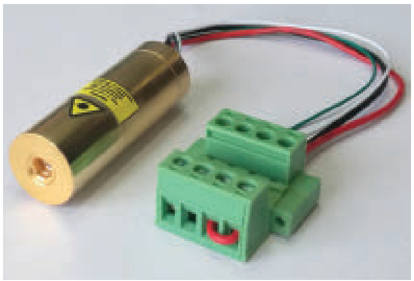

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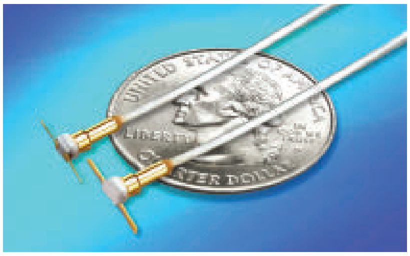

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Andrea Armani of the University of Southern California

JUSTINE MURPHY, SENIOR EDITOR

Andrea Armani leads a mix of undergraduate and graduate students. Pictured here are Hyungwoo Choi, Max Hattem, Samantha McBirney, and Brock Hudnut. *(Courtesy of University of Southern California)*

The Faces in Photonics series spotlights experts from around the world whose work is reshaping the growing photonics community.

Here, we feature Andrea Armani of the University of Southern California (Los Angeles, CA), where she is vice dean for New Initiatives, the Irani Chair of Chemical Engineering and Materials Science, and a professor of Chemical Engineering and Materials Science in the Viterbi School of Engineering. She also leads a research lab in the Viterbi School.

Justine Murphy: What attracted you to photonics?

Andrea Armani: My amazing mentor for my undergrad thesis at the University of Chicago, David Grier (now at NYU). As a classic physics department, UChicago did not offer optics or lasers courses. However, he was incredibly patient teaching me about lasers, free-space alignment, optical tweezers and their potential applications in biology, and automated data analysis of videos. Essentially, in his lab, I learned about "convergent research" before it had the fancy name, and he truly catalyzed my interest in the entire field.

JM: What do you enjoy about the industry, and what do you find challenging?

AA: It never gets boring! Like a firework that shoots into the sky and then bursts into hundreds and thousands of streams, every discovery leads to hundreds and thousands more. The challenge is that I joined the show after it started. This means that I'm a perpetual student—continuously trying to catch up on what came before I started, while paying attention to what is currently happening.

JM: What are you working on now?

AA: So many things. My group combines chemistry, electrical engineering, materials science, and physics to develop photonics-based solutions to biomedical and quantum-based challenges. And yes, I put everything in alphabetical order—I don't have favorites!

In this context, we are making new nonlinear optical materials and new integrated photonic devices and also building new optical systems to advance imaging and diagnostics. We are also collaborating with biologists, oncologists, and neuroscientists to actually test our materials and systems and use them to advance their research.

The best feeling is when something you've discovered shoots out of your lab altogether, becoming a thousand streams of light. ◎