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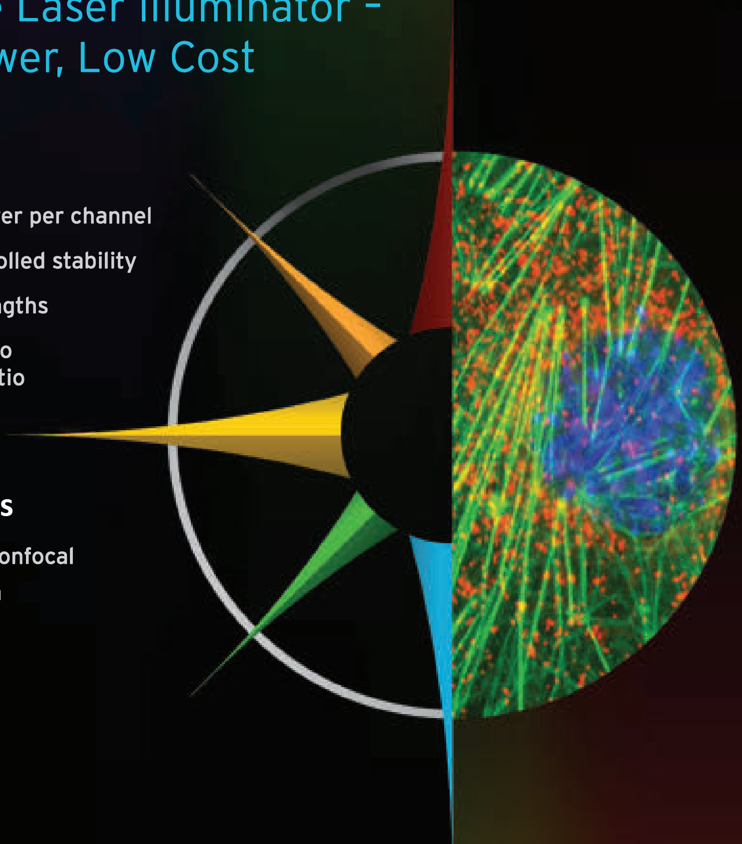


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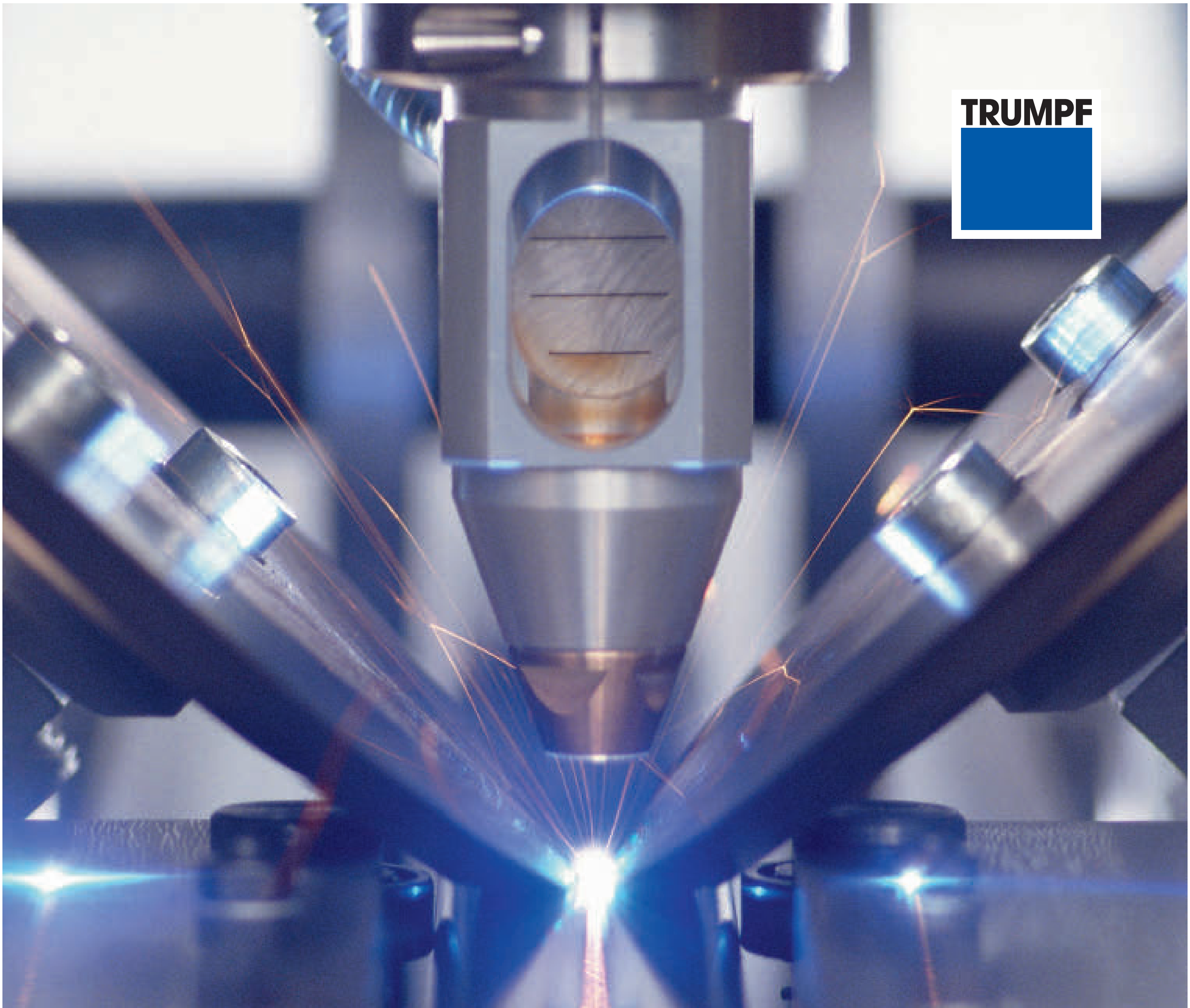
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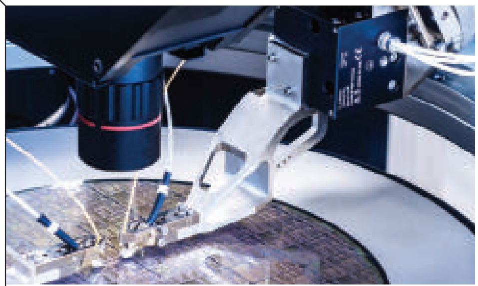

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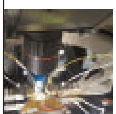

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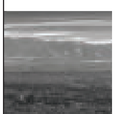

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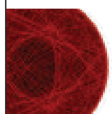

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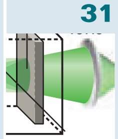

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Optical coherence tomography (OCT) continues to develop, leveraging advances in computing power, innovation in system design, and application of artificial intelligence. *Richard Gaughan, Contributing Writer, BioOptics World, and Barbara Gefvert, Editor in Chief, BioOptics World*

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editor's desk

Laser light sources

As the demands on automotive lighting grow increasingly complex, LED and laser light sources will inevitably play an increasing role. After all, LED lamps have proven durable, long-lasting, and energy-efficient, and single diode laser modules are already proving themselves on the road in automotive headlight applications. In this issue, you can read about the development and production of an innovative laser headlight module that uses a stable, easy-to-manufacture glass-based phosphor converter layer that is much more stable than silicone and less expensive than ceramic (see page 17).

While laser light sources have been exploited in numerous other illumination applications due to advantages such as high brightness and high coherence, the high spatial coherence of laser illumination is not always desirable. In some applications such as laser-illuminated microscopes and other optical systems, high spatial coherence may cause adverse artifacts such as speckle noise. On page 34, you can read about how Hui Cao and her colleagues at Yale University have developed novel laser cavity geometries and alternative feedback mechanisms that enhance laser performance in illumination applications. By tailoring the spatial and spectral properties of cavity resonances, the number of lasing modes, the emission profiles, and the coherence properties can be controlled.

Also in this issue, you can learn about how fully integrated and automated wafer-probing systems enable silicon photonic chip designers to more quickly characterize and qualify their designs (see page 22). Then, Senior Editor John Wallace discusses the advantages of using shortwave-infrared in security and surveillance applications (see page 27). And finally, on page 39, you can learn about the recent progress in metamaterials associated with Mie scattering, and how it's bringing a novel platform into the field of nanoscale optics based on high-index dielectric nanoparticles that can support high-quality resonances driven by the exotic physics of bound states in the continuum, which was introduced by the pioneers of quantum mechanics almost 90 years ago. As always, I hope you enjoy this issue.

John Lewis

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Editor in Chief
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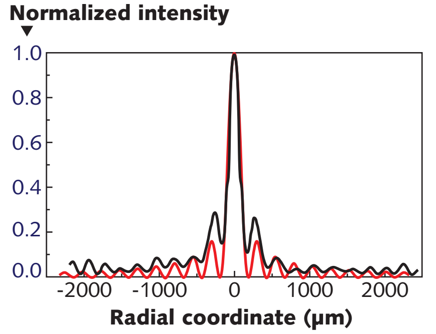
newsbreaks

Fiber-based polymer microtips produce Bessel-like beams



With their nondiffracting and self-healing properties, Bessel-like beams find use in particle guiding, microprocessing, and other applications. Forming axicon lenses on the ends of optical fibers offers a compact way to generate Bessel-like beams without the alignment and stability issues that arise with bulky optical systems. However, previous fiber-based microaxicons produced Bessel-like beams with only several concentric rings (less than five, and with low quality), and other fiber-based methods produce the beams either with low quality or with narrow wavelength range. Now, researchers at Fudan University (Shanghai, China) have developed a novel and efficient approach to generating Bessel-like beams by fabricating self-growing polymer microtips at the facet of single-mode fibers. The method promises an effective, low-cost, convenient, and ultracompact method for generation of Bessel-like beams.

First, a dose-reduction photopolymer droplet is deposited at a precise location on the facet of a fiber to fabricate the creation of a short microtip with optimized shape. The fiber-based microtips can then be tailored by green laser power (of on the order of a microwatt) coupled into the other end of the fiber, laser exposure time (on the order of a minute), and diffused oxygen concentration, enabling all-fiber, high-quality Bessel-like beam conversion. Distributing oxygen in the convex droplet inhibits polymerization when the irradiated laser power is low and can naturally polish the end of the microtip to form a microaxicon. The resulting microtip functions over a broad bandwidth and produces Bessel-like beams with a maximum of more than 30 concentric rings. The researchers verified the self-healing properties of the beams. *Reference: J. Tan, R. Yu, and L. Xiao,* Opt. Lett. *(2019); https://doi.org/10.1364/ol.44.001007.*

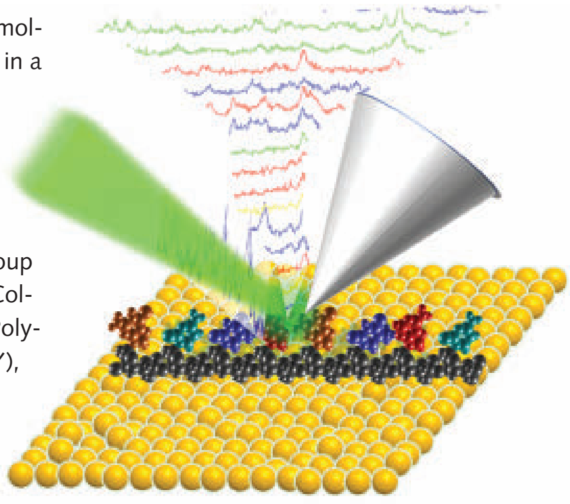
With leads reversed, experimental IR LED can cool things

In a finding that shows coherent light is not needed to optically cool things, researchers at the University of Michigan (Ann Arbor, MI) ran a light-emitting diode (LED) with electrodes reversed to cool another device just nanometers away. The approach could lead to new solid-state cooling technology for future microprocessors. The well-known technique of laser cooling is based on the foundational work of Arthur Ashkin, who shared the Nobel Prize in Physics in 2018. It has resulted in compact all-optical cryogenic devices that are already practical for some uses. The Michigan researchers instead harnessed the chemical potential of thermal radiation. In theory, reversing the positive and negative electrical connections on an infrared (IR) LED won't just stop it from emitting light, but will actually suppress the thermal radiation that it should be producing just because it's at room temperature. In other words, it behaves as if it were at a lower temperature.

However, measuring this cooling, and proving that anything interesting happened, is complicated. To get enough IR light to flow from an object into the LED, the two would have to be at a subwavelength spacing to take advantage of near-field (evanescent coupling) effects. The group proved the principle by building a minuscule calorimeter and placing it next to a small LED about the size of a grain of rice. The two were constantly emitting and receiving thermal photons from each other and elsewhere in their environments, but once the LED was reverse-biased, it began acting as a very low-temperature object, absorbing photons from the calorimeter. At the same time, the nanoscale gap between them prevented heat from traveling back into the calorimeter via conduction, resulting in a cooling effect. The team demonstrated cooling of 6 W/m^2—theoretically, the effect could produce cooling equivalent to 1000 W/m^2.

With improvements in efficiency and cooling rates, the team envisions this approach as a way to quickly draw heat away from microprocessors in devices. It could even stand up to the abuses endured by smartphones if nanoscale spacers provided the separation between microprocessor and LED. *Reference: L. Zhu et al.,* Nature *(2019); https://doi.org/10.1038/s41586-019-0918-8.*

TERS images single-stranded DNA without amplification



Optical imaging at the single-molecule level is often carried out in a low-temperature environment to minimize thermal sensor noise. To achieve high sensitivity as well as ultrahigh spatial resolution in ambient conditions, a joint research group from Texas A&M University (College Station, TX), Rensselaer Polytechnic Institute (RPI; Troy, NY), Friedrich-Schiller-Universität Jena (Germany), and Baylor University (Waco, TX) used tip-enhanced Raman spectroscopy (TERS) to sequence a single-stranded DNA molecule (from the M13mp18 bacteriophage) with an accuracy of more than 90% and a resolution of 0.5 nm.

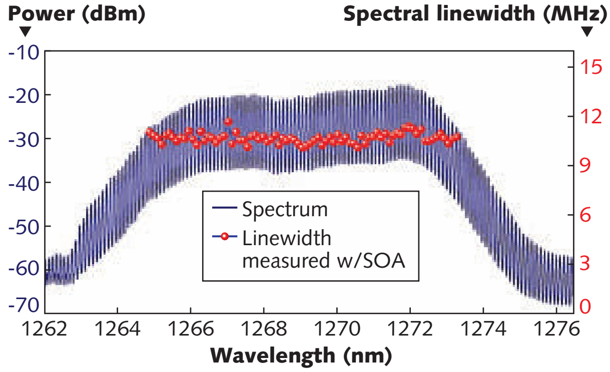
The TERS method relies on surface plasmon effects in noble-metal probe tips. In the presence of the electromagnetic field, when the plasmon is resonant with the excitation wavelength, intensities of the localized electromagnetic field near the tip are greatly enhanced, increasing Raman scattering and overcoming the diffraction limit.

In this study, the researchers used gap-mode TERS in which the tip and a nearby gold film form a plasmonic nanoscale gap, allowing for nanoscale sensing and single-molecule detection based on strongly enhanced Raman signals. The TERS Raman spectra were used to identify the individual DNA nucleotides through careful spectral analysis with correlation coefficients. By resolving single molecules, TERS imaging of DNA can be used to examine its spatial alignment, structure, and sequence in a timely manner (four seconds per base) without the need for fluorescent labeling or amplification. Furthermore, this technology is likely applicable for scanning RNA, providing a route for easy and economical direct RNA sequencing without making complementary DNA (cDNA) or involving polymerase chain reaction (PCR) amplification, which, taken together, could supplant RNA sequencing platforms. *Reference: Z. He et al.*, J. Am. Chem. Soc., *141, 753–757 (2019).*

Quantum-dot mode-locked laser on silicon transmits data at 4.1 Tbit/s

A group at the University of California (UCSB) has created a high-channel-count 20 GHz passively mode-locked quantum-dot laser directly grown—for the first time, to the group's knowledge—on a silicon substrate. With a proven 4.1 Tbit/s transmission capacity, the micron-sized laser leaps an estimated full decade ahead from today's best commercial standard for data transmission, say the researchers, which is currently reaching for 400 Gbit/s on Ethernet. The technology is the latest high-performance candidate using the tried-and-true wavelength-division-multiplexing (WDM) technique. "We want more coherent wavelengths generated in one cheap light source," says Songtao Liu, one of the researchers. "Quantum dots can offer you wide gain spectrum, and that's why we can achieve a lot of channels."

The laser, which is grown on a CMOS-compatible silicon substrate, is passively mode-locked to prevent noise from wavelength competition in the laser cavity and stabilize data transmission. Mode-locking produces a frequency comb with a 3 dB optical bandwidth of 6.1 nm. An external semiconductor optical amplifier (SOA) boosted the signal and suppressed low-frequency mode partition noise. The high transmission rate is achieved by using 64 channels (comb teeth) and a 32 Gbaud Nyquist four-level pulse amplitude modulation format.



The device is intended to become part of silicon electronic and photonic integrated circuits (EPICs). While silicon is a good material for the quality of light it can guide and preserve, and for the ease and low cost of its large-scale manufacture, it's not so good for generating light. "If you want to generate light efficiently, you want a direct-bandgap semiconductor," Liu says. "Silicon is an indirect band-gap semiconductor." The quantum dot laser, grown on silicon molecule-by-molecule at UCSB's nanofabrication facilities, is a structure that takes advantage of the electronic properties of several semiconductor materials for performance and function (including their direct bandgaps), in addition to silicon's own well-known optical and manufacturing benefits. Since John Bowers and his UCSB group a decade ago demonstrated the world's first hybrid silicon laser (an effort in conjunction with Intel), the silicon photonics world has continued to create higher-efficiency, higher-performance technology while maintaining as small a footprint as possible, with an eye on mass production. The quantum dot laser on silicon, Bowers and Liu say, is state-of-the-art technology that delivers the superior performance that will be sought for future devices. *Reference: S. Liu et al.,* Optica *(2019); https://doi.org/10.1364/optica.6.000128.*

Chip microcomb
See page 14

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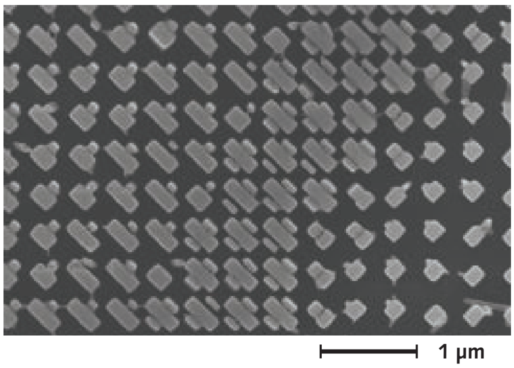
METASURFACE OPTICS

Broadband achromatic metalens focuses all polarizations

Optical metasurface lenses, which are made of subwavelength arrays of nanostructures of varying geometries and thus can form a true flat lens, are looking more and more like they could be practical replacements for refractive lens elements, or even entire refractive lens systems, for some applications. This type of metalens design has had some barriers to overcome, though: one is the difficulty of moving beyond narrowband performance, and another is the fact that designing a metalens to focus both polarizations (and thus unpolarized light) is difficult. Metalenses for general use would need to have both of these characteristics.



These subwavelength anisotropic nanostructures that are arrayed across the surface of a metalens can focus light regardless of its polarization, doubling the efficiency of the lens. The titanium dioxide nanofins were optimized in shape using a "particle swarm" algorithm. (*Courtesy of the Capasso Lab/Harvard SEAS*)

Researchers have believed that symmetric nanostructures such as circular pillars were essential building blocks to develop metalenses that are not sensitive to polarization. Now, researchers from the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) at Harvard University (Cambridge, MA) have developed a polarization-insensitive metalens consisting of nonsymmetric nanofins that can achromatically focus light across the visible spectrum without aberrations.[1] This flat lens could be used for everything from virtual or augmented reality headsets to microscopy, lithography, sensors, and displays.

"By making this lens polarization-insensitive, we have doubled the efficiency of the metalens from previous iterations," says Wei Ting Chen, a research associate at SEAS. "This is the first paper that demonstrates both achromatic and polarization-insensitive focusing in the visible spectrum." The research was led by Federico Capasso, whose group at SEAS has come up with many previous advances in metalenses, including a meta-optical system for handheld spectrometers, a wide-angle, high-efficiency polychromatic metalens, and a metasurface polarimeter on a chip.

In previous research, Capasso, Chen, and their team demonstrated that arrays of titanium dioxide nanofins could equally focus wavelengths of light and eliminate chromatic aberration, but those lenses could only focus a circularly polarized light. "This meant we were essentially discarding half of the incident light which does not possess the right polarization," says Alexander Zhu, a graduate student at SEAS.

Diffraction-limited from 460 to 700 nm

In this latest design, the researchers changed the layout of the nanofins, positioning each pillar so that it is either parallel or perpendicular to its neighbor. "This new design gives us a lot of freedom to tune the geometrical parameters of the metalens, which allows us to better achieve achromatic focusing across the entire visible range," Chen says.

The experimental lens, which has a diameter of 26.4 mm and a numerical aperture (NA) of 0.2, has diffraction-limited imaging quality across the visible wavelength band of 460 to 700 nm (which encompasses blue, red, green, and the colors in between).

The metalens design was created using a finite-difference time-domain (FDTD) solver to obtain each element's phase, group delay, and group delay dispersion, and optimized via a "particle swarm" method that found optimal shifts for phase, group delay, and group delay dispersion (see figure). The lens itself was fabricated from a film of titanium dioxide (TiO_2) using electron-beam lithography. The anisotropic nanofin design is what allowed the researchers to accurately and simultaneously optimize the phase and its higher-order derivatives (group delay and group delay dispersion) with respect to frequency. The result is a device with a diffraction efficiency of 92% at 530 nm and a focusing efficiency that varies by at most 4% over various polarizations.

The 26.4 mm diameter of the lens is limited by the achievable group delay in nanostructure elements—about 5 fs in the 600-nm-tall nanofins used in the lens. To create a larger-diameter lens will require either taller nanofins, hyperbolic metamaterials, or a hybrid diffractive-refractive lens design. "Next, we aim to maximize efficiency and make much larger-size achromatic metalenses to bring them into everyday life for a wide range of applications," Capasso says.—*John Wallace*

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1. W. T. Chen et al., *Nat. Commun.* (2019); https://doi.org/10.1038/s41467-019-08305-y.

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BioOptics WORLD

RAMAN FIBER LASERS

Random laser advances: Fiber optics and lasing vegetables

If you're like most people, when you think of a laser, you think of a device that generates an intense beam of light at a specific wavelength—the kind of device that incorporates an energy source, along with a gain medium and mirrored optical cavity that amplify the light to produce that powerful beam.

But there's another kind of laser, too: the random laser, in which light of various wavelengths is scattered instead of contained in an optical cavity. Because of its relative simplicity and ability to produce a beam containing multiple spectral lines, a random laser is potentially useful for applications such as biomedical imaging. But, random lasers are famously difficult to control.

Furthermore, random lasers normally rely on plasmonic or dielectric scatterers, as well as gain media that are not only toxic and nonbiodegradable (for example, chemical dyes and fluorescent polymers), but also require high energy/power density optical pumping. And while recent research has suggested the potential for biocompatible scattering media, these experiments have still used toxic gain media.

Now, work being done at the University of New Mexico (UNM; Albuquerque, NM) and at the Indian Institute of Technology (IIT)-Madras (Chennai, India) is addressing these limitations.

Control issues

UNM's researchers at the Center for High Technology Materials (CHTM) have demonstrated the ability to reliably harness these extremely powerful random lasers by using a disordered optical fiber they developed using a highly porous glass.[1] When this glass is stretched into fibers, dozens of microscopic air channels form—channels that enable control of the laser by way of a phenomenon known as Anderson localization. When the random laser is filled with a gain medium and then pumped with a single-colored laser, the channels make the output beam highly directional and stabilize its spectrum (see Fig. 1).

While the UNM researchers are considered experts in Anderson localization, CHTM director Arash Mafi says there is still a lot to learn about this phenomenon.

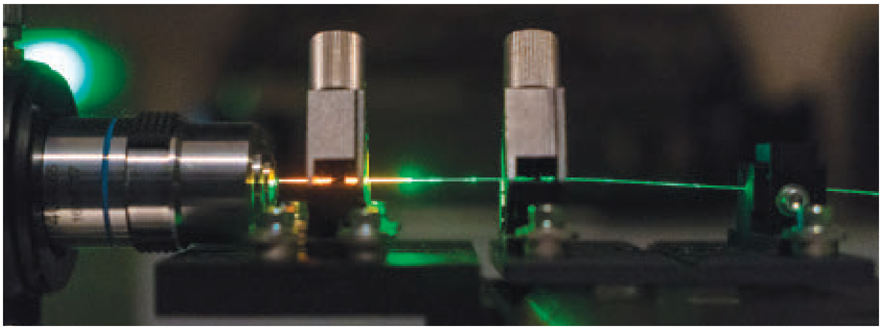

FIGURE 1. When a random laser is filled with a gain medium and then pumped with a single-colored laser, microscopic air channels in the optical fiber make the output beam highly directional and stabilize its spectrum. *(Courtesy of UNM)*

Veggie de-light

Researchers in the Department of Physics at IIT-Madras have proposed that continuous-wave (CW) pumping could be effective and economical for random lasers—and they've demonstrated stable Raman-mode random lasing with a threshold of just 14 μW.[2] The medium they use is something you may well have in your refrigerator: a carrot.

The researchers note that because of their visible light absorption characteristics, organic pigments such as carotenoids and porphyrins make carrots optically active media. And while carotenoids' fluorescence quantum yield pales in comparison to standard organic laser dyes, it is possible to obtain their vibrational spectra to concentrations as low as 10^{-8} M.

The work leverages the natural Raman activity of carotene and the ability of fibrous cellulose to facilitate photon scattering, which contributes to optical amplification (see Fig. 2). The apparent amplification mechanism, the scientists say, is a combination of the multiple scattering and photoluminescence seeding of the Raman mode. The researchers report that

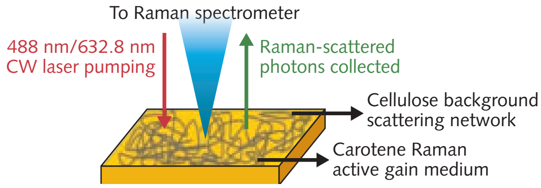

FIGURE 2. A carrot-based random laser takes advantage of carotene's natural Raman activity and the ability of fibrous cellulose to facilitate photon scattering, which contributes to optical amplification. *(Adapted from V. S. Gummaluri, S. R. Krishnan, and C. Vijayan[2])*

photoluminescence threshold and linewidth analysis of the zinc sulfide (ZnS)/beta-carotene showed characteristic lasing action with a threshold of 130 W/cm^2 and linewidth narrowing with a mode Q factor up to 1300. Further, they report that photoluminescence is temperature-dependent, with intensity at 173 K approximately 20X that at 300 K.

The IIT-Madras work hints at untapped possibilities for simple, biocompatible light sources for biological applications involving spectroscopy, imaging, and sensing.—*Barbara Gefvert*

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2. V. S. Gummaluri, S. R. Krishnan, and C. Vijayan, *Opt. Lett.*, 43, 23, 5865 (2018).

OPTICAL FREQUENCY COMBS

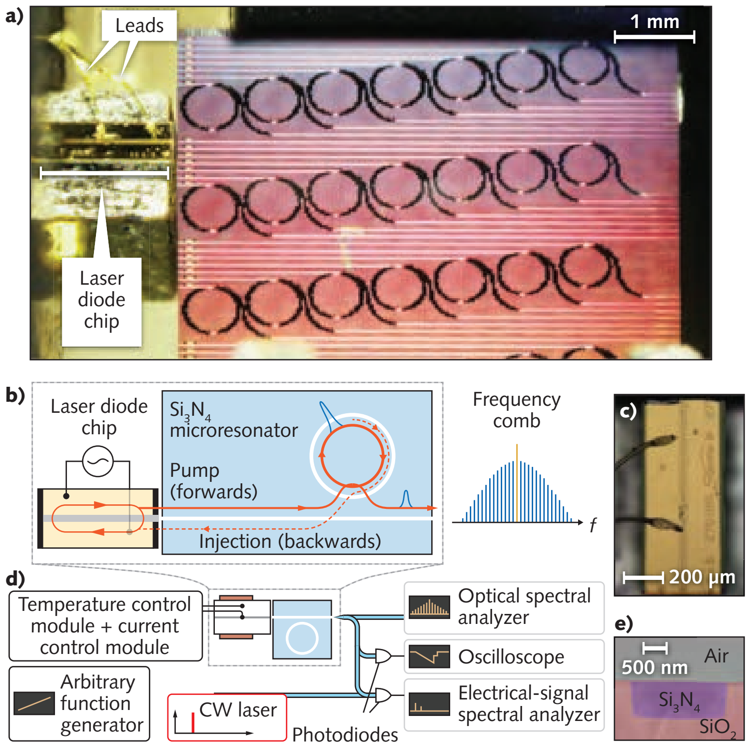
Smallest chip-based 'microcomb' consumes just 1 W in a 1 cm^3 package

While chip-based optical frequency combs operating in the dissipative Kerr soliton (DKS) mode have been demonstrated, these coherent soliton "microcombs" typically require high threshold powers (a few milliwatts) that are difficult to achieve in silicon-photonics-based lasers. As a result, chip-based approaches have previously required optical pumping with external, bulky standalone laser modules. These modules in turn require additional optical amplifiers to counteract the high coupling losses and low quality (Q) factors of the integrated photonic microresonators used to initiate soliton formation.

Building on recent advances in the pursuit of ultralow losses in silicon nitride (Si_3N_4) waveguides, researchers from the Swiss Federal Institute of Technology Lausanne (EPFL) and the Russian Quantum Center (Moscow) have built a compact (1 cm^3), low-power-consumption (1 W electrical), high-performance (sub-100 GHz comb spacing) integrated Si_3N_4 microresonator-based soliton microcomb in conjunction with a commercially available chip-based laser diode.[1] The researchers say it is the smallest Kerr soliton microcomb to date and, unlike a recently demonstrated device, requires no Vernier filters or temperature tuning mechanisms.[2]

Optical frequency generation and self-injection locking

One of the key challenges to achieve soliton microcomb generation at low power was to fabricate the microresonator with ultralow losses. The Si_3N_4 microresonators featuring smooth sidewalls were fabricated using the photonic Damascene reflow process, enabling the high-Q factor (>10 million)



A chip-based, compact laser injection-locked soliton Kerr frequency comb (a) consists of a laser diode chip butt-coupled to a silicon nitride photonic chip with microresonators that create an injection-locked soliton Kerr frequency comb (b). A magnified view shows the indium phosphide laser diode chip (c), which is part of the overall microcomb architecture (d). Also shown is a false-colored SEM image of the waveguide cross-section (e). *(Image credit: EPFL)* used to generate a microcomb operating at electronically detectable repetition rates (<100 GHz) with a commercially available laser diode chip.

A critical injection locking mechanism allows soliton formation to occur with a multifrequency indium phosphide (InP) chip-based laser diode. By tuning the current of the InP laser diode, the lasing frequency coincides with selected resonances of the microresonator and a small fraction of light gets scattered back to the laser diode. This leads to switching from a multifrequency emission to single-mode operation indicating self-injection locking, an important phenomenon to stabilize the laser diode and enable high-coherence lasing (see figure).

The small phase difference between emitting and backscattered light provide the freedom to detune the laser frequency from the microresonator's resonance, which is crucial for Kerr frequency-comb generation due to its existence on the effectively red detuned side. Initially, the self-injection locked state is switched to a chaotic comb (modulation instability), and eventually to coherent soliton microcombs by changing the current of the laser diode. The direct fast optical feedback from the microresonator not only stabilizes the laser diode, but the solitons are generated without any active electronics stabilization or additional modulators, greatly reducing the operational complexity.

Soliton microcombs operating at 149 GHz and 88 GHz have been demonstrated via simple current tuning of the laser diode, eliminating the need for bulky external pump lasers and showing high performance for a chip-based integrated device in such a small footprint. Such an integrated chip-scale device promises myriad applications in future datacenter interconnects, coherent telecommunication, lidar, and spectroscopy.

"The high-losses in Si_3N_4 waveguides prevented the full photonic integration of the optical frequency combs. This longstanding problem was solved by optimizing the Si_3N_4 fabrication using a patented method called 'the photonic Damascene process' developed at EPFL," says professor Tobias J. Kippenberg, the head of the Laboratory of Photonics and Quantum Measurements at EPFL. "The photonic integrated soliton microcomb driven by a chip-scale laser diode with simplified operation will unlock their potential use in everyday applications, which were limited to the laboratory until now."—*Gail Overton*

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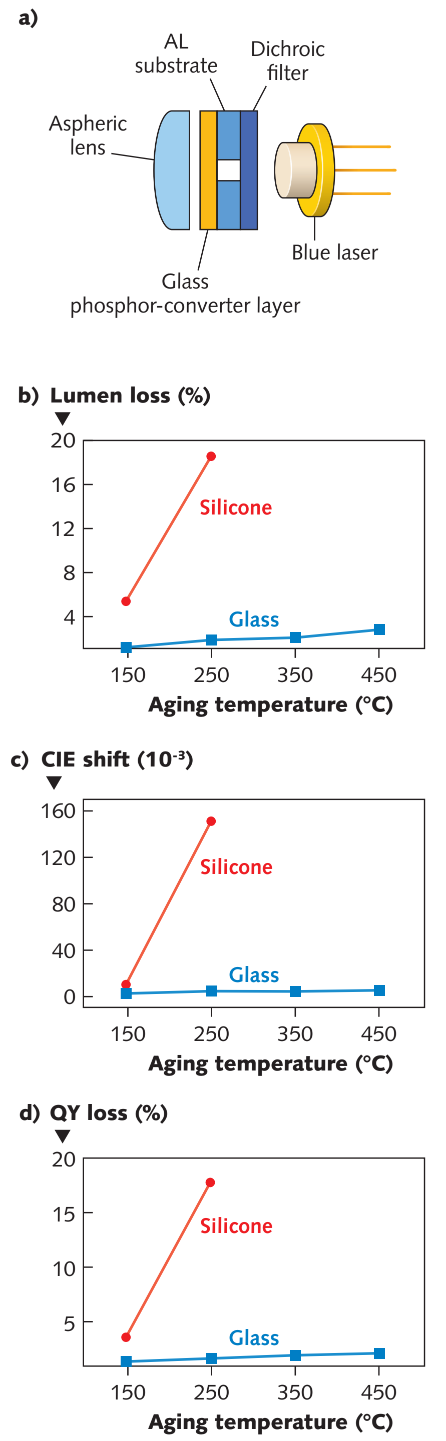
AUTOMOTIVE LIGHTING

Laser headlight module uses stable, easy-to-manufacture glass phosphor

The future is looking good for semiconductor-based vehicle headlights. Commercially, light-emitting-diodes (LEDs) are already displacing traditional incandescent automotive headlights and intermediate-generation high-intensity-discharge (HID) light sources, working their way from the luxury market on down. And solid-state lighting's second wave, laser diodes, is set to enter the commercial automotive market in Europe late this year. (Shuji Nakamura, one of the inventors of the blue LED that has made solid-state lighting possible, has formed a company, SLD Laser, to develop laser-diode-based white-light sources for automotive and specialty lighting; in 2018, the company received a *Laser Focus World* Gold Innovators Award for its LaserLight SMD high-luminance white laser light emitter packaged in a 7 mm surface-mount device.)

A laser headlight populates the visible spectrum with both the blue light from the laser itself and broadband yellowish light from a phosphor converter layer excited by the laser light. As with white LEDs, the laser diode's blue emission combines with the yellow phosphor emission to create white light. While regulatory hurdles still exist for laser headlights, especially in the U.S., applied R&D efforts around the world are ironing out technological issues, including those related to cost and manufacturability. In one example, a group of researchers from National Chun Hsing University and Taiwan Color Optics (both in Taichung, Taiwan) has been developing phosphors that combine high stability and lower manufacturing costs.

The phosphor (usually powdered cerium-doped YAG, or Ce:YAG) that forms part of a solid-state light source is embedded in a stable and transparent matrix. For white-light LEDs, that matrix has often been silicone, which is low in cost and can be mixed with phosphor and molded into its final form at temperatures no higher than about 150°C. While this works well for LEDs especially as indoor light sources, silicone is not thermally stable enough to withstand the temperature extremes experienced by cars and trucks, say the



A glass phosphor converter layer for a laser headlight (a) has high thermal stability and can be made at a relatively low temperature of 750°C. In comparison to a silicone-based phosphor converter layer, the glass-based device, when subjected to thermal aging tests, shows much lower lumen loss (b), much less color shift (c), and a much smaller drop in quantum efficiency (d).

Taichung researchers. As a result, laser headlights have mostly been fabricated using more stable, but more difficult to manufacture materials such as ceramics, and even single-crystal Ce:YAG. The minimum temperatures required to form the phosphor converters into bulk shapes are high: 1200°C for ceramics and 1500°C for single-crystal YAG.

Glass-based phosphor is highly reliable

The Taichung group has developed a laser headlight module based on a highly reliable glass-based phosphor that allows fabrication of the converter layer into its final shape at a lower temperature of 750°C. The researchers took extra care to reduce the formation of bubbles in the glass, which has been a problem with many glass-based phosphors. The end result was a module consisting of a five-unit linear blue laser array, a dichroic filter to pass the blue light and reflect the yellow phosphor light outward, the glass phosphor converter layer, and an aspheric collimation lens (see figure).

The precursor material is created by mixing Ce:YAG powder into melted sodium glass at 1200°C, which is then solidified and ground into a powder. The actual manufacture of the phosphor converter layer consists of sintering the powder at 750°C for one hour, followed by annealing at 350°C for three hours, then cooling to room temperature. The researchers experimented with different concentrations of the Ce:YAG powder, finding that the highest luminous efficiency was reached with a 40% weight concentration. The bulk shape was then cut into disks 25 mm in diameter and 0.35 mm thick, which, when in use in a headlight module, have an external quantum efficiency (EQE) of about 70%.

The thermal stability of the glass-based phosphor layer was compared to that of a silicone-based phosphor layer by subjecting them both to thermal aging tests in which they were both baked at temperatures of 150°, 250°, 350°, and 450°C for 42 days. Results showed a drastic lowering of lumen loss, color shift, and quantum efficiency for the glass-based device.

The resulting laser headlight module built by the researchers had an optical output of 6 W, a luminous flux of 1860 lm, a color temperature of 4100 K, and an extremely high efficiency of more than 310 lm/W (on the order of twice as high as the most efficient white-light LEDs on the market).—*John Wallace*

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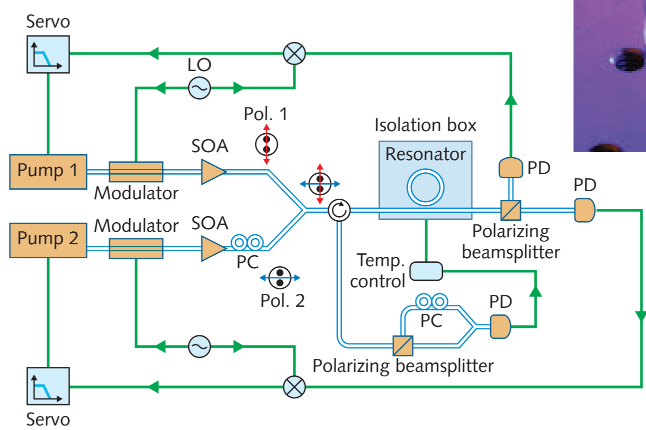
FIBER LASERS

Ultranarrow Brillouin fiber laser has built-in temperature stability

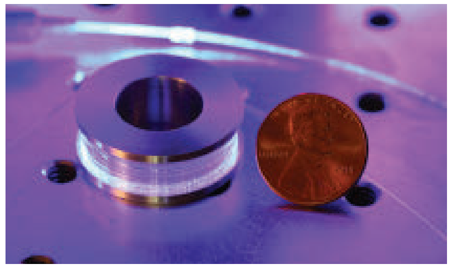
To achieve ultranarrow laser linewidths of 1 Hz or less for applications in precision spectroscopy and metrology, the typical ultralow-expansion (ULE) cavity-stabilized laser meets the linewidth requirements, but falls short of amenability to portable applications due to its large size (a cubic meter or so) and vibration susceptibility. Combining the inherent robustness of a fiber-laser architecture and stimulated Brillouin scattering (SBS) in a high-quality (Q) resonator, Massachusetts Institute of Technology (MIT) Lincoln Laboratory (Lexington, MA) researchers have achieved ultranarrow linewidth lasing in a portable package that provides built-in temperature stability.[1]

High-*Q* temperature stability

The high-Q, temperature-stabilized laser cavity consists of two independent, orthogonally polarized pump laser signals sent into a single resonator, generating two orthogonal polarization SBS signals. Components in the setup include phase modulators and semiconductor optical amplifiers (SOAs) to boost power to around 15 mW (see figure). These two signals then travel backward through the circulator and their frequency beat becomes the temperature-correction signal.



Shown is the SBS lasing setup with independent pump lasers and controlled coupling scheme, with linewidth optimized for a resonant cavity (see inset fiber loop) coupling ratio of around 1.3%. *(Image credit: MIT Lincoln Laboratory)*



Pump light is monitored and stabilized to the cavity resonance, and the optical-fiber resonator is secured to a block of aluminum placed on vibration-dampening foam in order to keep the fibers secure and isolate the system from table vibrations.

To control the coupling ratio of the resonator to generate ultranarrow-linewidth lasing, the transverse offset between two polished fibers in the resonator cavity is controlled. The narrowest lasing linewidth occurs for a coupling ratio of around 1.3%, but the researchers used 5.6% coupling to maximize output power without degrading the laser linewidth (which is around 20 Hz full-width half-maximum for a fairly wide range of coupling ratios). The long lengths of fiber and large mode-field diameter fundamentally increase the optical mode volume.

Dramatic reduction in the long-term frequency drift of the SBS laser (around 1.65 GHz for a 1°C temperature drift in silica glass) is achieved through the polarization-based temperature-sensing technique wherein the change in frequency of the beat signal described previously corresponds to a direct temperature change in the optical resonator. Temperature stabilization is accomplished via a resistive heater—that is, heat is applied to the optical fiber by increasing or decreasing the applied current to the resistive heater in order to keep the SBS beat frequency constant.

The temperature-stabilized SBS laser affords a significant improvement in the rejection of temperature disturbances compared to standard SBS lasers and allows for shifts as small as 85 nK to be corrected. Furthermore, many of the components in the setup could be integrated in an on-chip format for compact assembly and portable applications.

"Many applications in basic and applied science, such as optical atomic clocks, gravitational wave detection, and advanced lidar, fundamentally rely on lasers of extreme frequency precision for their operation," says MIT Lincoln Laboratory staff scientist William Loh. "In order to eventually transition these systems into the field or space, one critical step involves miniaturizing the stable laser source without degrading its precision. By advancing this SBS laser technology, we aim to bridge the wide gap in performance between the scientific-grade but otherwise bulky ULE cavity-stabilized lasers and the rest of the laser technologies in existence today."—*Gail Overton*

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Automated wafer-level probing meets silicon photonics

JOE FRANKEL, KAZUKI NEGISHI, MIKE SIMMONS, DAN RISHAVY, and ERIC CHRISTENSON

Fully integrated and automated wafer-probing systems enable silicon photonic chip designers to characterize and qualify their designs faster than ever.

As chip designers are pressed for ever-increasing data rates, the use of wavelength-division multiplexing (WDM) with infrared photonic signals as a data transfer medium is increasingly finding its way into CMOS silicon-based devices. Termed "silicon photonics" (SiPh), this technology is not only being used to displace traditional electrical interconnects, but also for a broad range of applications, including lidar, quantum computing, and biosensing.

The integration of optical components on a chip creates a host of new challenges and demands for wafer-level probing of SiPh devices, where huge volumes of device-performance data are required to carry a design from concept to qualification and into production. While working in a lab on an initial prototype, it may suffice to spend minutes or in some cases hours to set up and align a single device for measurements. However, such time- and effort-intensive methods are unsuitable for the cycle-time demands of high-volume SiPh manufacturing.

A huge leap forward in throughput is required to quickly get process feedback and take these designs to the next level. In addition, input/output (I/O) measurements must be made with alignment precision on the order of nanometers due to the effective aperture dimensions of optical gratings and waveguides fabricated in silicon—a precision heretofore unheard of with traditional probing systems.

As device technologies evolve from simple transmission lines to optical-to-electrical converters to optical modulators and beyond, manufacturers must keep pace to produce prober platforms that enable chip designers to test and improve their rapidly maturing SiPh designs. Starting in 2017, FormFactor developed a wafer-level probing solution that supports a wide variety of SiPh applications, with a development roadmap to support the rapidly evolving SiPh industry.

Probing applications

Silicon photonics probing applications typically fall into the category of either modeling and characterization, wafer acceptance testing, or production process monitoring. Each of these application categories places its unique relative emphasis on accuracy, throughput, and test flexibility.

Modeling and characterization applications seek to extract model parameters used to design and simulate the device, or portions thereof. In this case, precision is key, but throughput is not

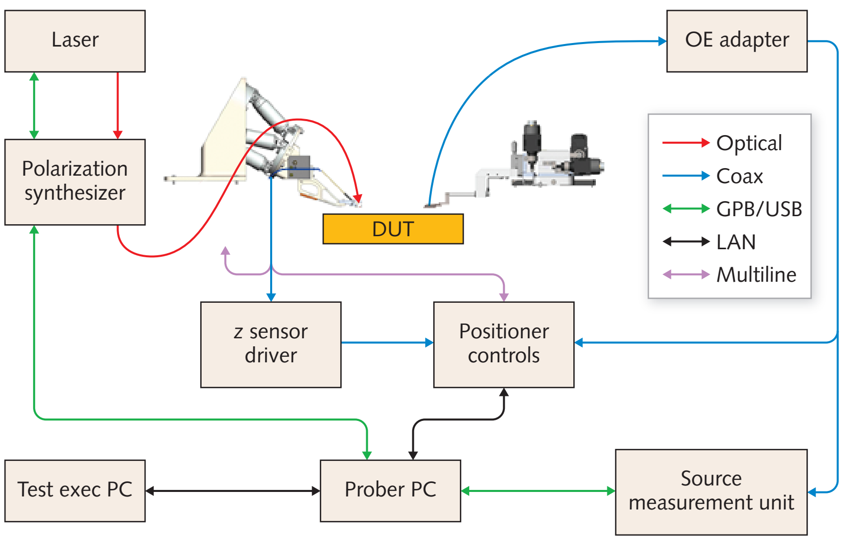

FIGURE 1. This schematic shows the building blocks for a silicon photonics probing system.

Silicon photonics probing parameters

Test parameter	Possible values
Wafer diameter	300 mm, 200 mm, singulated die
Photonic I/O	Vertical coupling/grating couplers
	Edge coupling/trenches/waveguides
I/O configuration	Optical-to-optical (O-O)
	Optical-to-electrical (O-E)
	Electrical-to-optical (E-O)
	Optical-to-electrical-to-optical (O-E-O)
Vertical coupling angle	6°–20° (grating couplers)
Edge coupling angle	0°, 70°, 80°, 90° (waveguides)
Device layouts	Single layout per die
	Multiple layouts/subdie stepping
Wavelength	1260–1625 nm
Frequency	DC, 10 Gbit/s, 40 Gbit/s
Positioners	Dual-sided hexapods (thru)
	Single-sided hexapod (loopback)
	RF positioners, DC positioners (motorized or manual)
Optical probe types	Single fibers, fiber arrays, lensed fibers, faceted fibers
Electrical probe types	RF, DC (for modulation and biasing)
Test temperatures	25°C (controlled ambient), -40°C to +150°C (thermal)
Accuracy	<300 nm
Throughput	<3 s align time per device
Repeatability	<0.3 dB

as important since modeling is a design engineering activity.

Wafer acceptance applications seek to verify performance of the chip design, examining device functionality, repeatability, and performance of multiple devices across the substrate. In this case, a balance between precision and throughput is important so that the fabrication process can be proven over samples of many devices.

Inline process monitoring applications seek to continuously verify the wafer manufacturing process, watching for any failures in the production flow. Since process monitoring is a high-volume application, measurements tend to be optimized for speed while checking a minimum number of metrics.

Prober use cases

Due to the industry demand for a wide range of applications, flexible probing platforms are needed that can be quickly optimized for the needs of the application. Numerous parameters need to be considered when configuring a prober for one of the applications previously described, along with typical alignment performance requirements in terms of accuracy, throughput, and power coupling repeatability (see table).

Each prober configuration is driven by the specific needs of the application. One example of an optical-to-electrical (O-E) probing system configuration setup measures photodiode responsivity, insertion loss, and power coupling efficiency as a function of laser wavelength and state of input polarization (see Fig. 1).

In another configuration, an optical-to-electrical-to-optical (O-E-O) positioner setup is highly directional: optical positioners in the east/west for optical I/O, DC in the south for biasing, and RF in the north for modulation (see Fig. 2). All probes are mounted on motorized positioners for automated indexing between subdie locations with different probing layouts.

Alignment methods

Engineering probe systems expose a programmer's interface to the end user's Test Executive program, which implements the master control logic for the measurement. The prober's programming interface enables the master workflow to be tailored to the specific needs of the application. In general, the workflow for a SiPh measurement application consists of the following logic at the master level:

For each wafer
- *Load/swap wafer from FOUP onto chuck*
- *Align wafer with vision system*
- *For each die*
  - *For each subdie structure*
    - *Step wafer chuck to subdie*
    - *Move positioners to subdie I/O*
    - *Move chuck into contact with electrical probes*
    - *Align optical probes to device*
    - *Perform device measurement*
  - *Next subdie*
- *Next die*

Next wafer

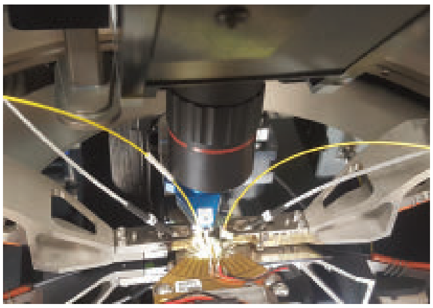

FIGURE 2. Silicon photonic components are positioned and probed in real time.

All the steps in the sequence above are typical and standard to the probing industry, except for the key step *Align optical probes to device*, which is new. In the optical alignment step, a high-precision alignment with six degrees of freedom (for both translations and rotations) is required to optimize optical power coupling with a given device.

Noncontact optical coupling optimization is critical to minimize insertion loss that will result due to the sensitivity of the alignment error. This contribution to insertion loss is not only a property of the device being tested, but rather involves characteristics of the entire measurement setup, including the probe station and positioning hardware. One key to minimizing loss and performing successful, highly repeatable measurements is to implement a set of calibration functions that compensate for aligning the motion axes of the optical positioners to the motion axes and coordinates of probe station.

To accomplish the optical alignment within performance targets, a specialized 3D piezoelectric actuator and proprietary control algorithms are used. For vertical grating coupler applications, these algorithms include automated move-and-measure control sequences for fiber height control in *z*, high-speed optical scans in *xy*, rotation scans in qz, incident angle alignments in qy, gradient searches in *xy*, and first light search. Similar algorithms are also available for edge coupling applications where the optical signal propagates nominally in the *x* direction and alignment scans are performed in the *yz* plane.

Using an optical scan alignment algorithm, the piezo actuator performs a

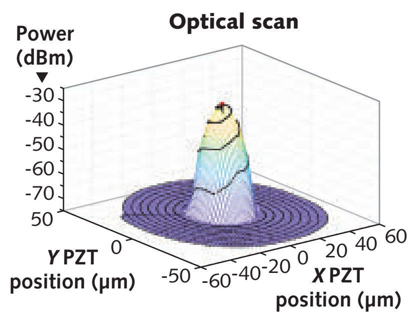

FIGURE 3. Among the probing requirements, optical scans are used to measure power coupling vs. the *xy* or *yz* position of the fiber.

spiral scan motion about the nominal coupling position on the device while synchronously capturing transmitted power through the device in real time (see Fig. 3). Once the scanning motion completes, the power vs. position data is analyzed in firmware and the fiber is moved to the identified peak. This operation can be accomplished on a two-sided optical-to-optical (O-O) setup within a typical <300 nm accuracy and <3 s alignment time performance target.

Once the alignment is complete, the probing system is in a state to take device measurements. Because of the many and varied needs of the application, typically the Test Executive software triggers a measurement routine with the instrumentation such as a wavelength sweep, polarization sweep, *s*-polarization-parameter measurement, and other user-specific tests. Data is captured on a per-subdie basis and used as appropriate for the application.

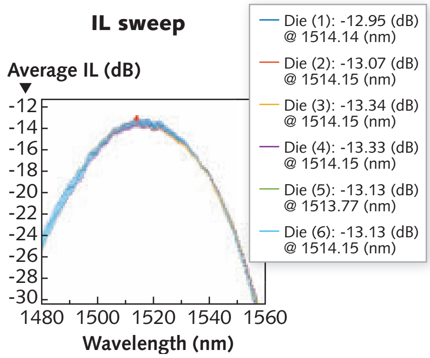

FIGURE 4. Wavelength sweeps measure power coupling efficiency as a function of wavelength.

Power coupling can be measured as a function of tunable laser wavelength through a series of insertion loss (IL) wavelength sweep measurements over several devices (see Fig. 4). It is important to note that while the system level calibrations ensure stable measurement repeatability, optical optimization is performed on each device to ensure maximum power transfer.

Putting it all together

FormFactor's wafer probing system, the Cascade CM300xi-SiPh, is engineered as a fully integrated turnkey solution for wafer-level SiPh probing. A wide array of optional hardware, along with industry-exclusive automated system level calibration and alignment routines, both expedite and eliminate the challenge of getting light into and/or out of photonic devices with high precision and application flexibility. Most of the probing parameters discussed previously are supported by our solution, with a long-term roadmap to keep pace with a rapidly evolving industry.

Joe Frankel, **Kazuki Negishi**, and **Mike Simmons** are systems engineers in the probe systems division, **Dan Rishavy** is the market segment director for silicon photonics, and **Eric Christenson** is the hardware engineering manager of the probe systems division, all at FormFactor, Livermore, CA; e-mail: eric.christenson@formfactor.com; www.formfactor.com.

SWIR cameras cut through haze for surveillance and security

JOHN WALLACE, Senior Editor

Covert operations commonly use thermal imaging and/or night vision, but the shortwave-infrared (SWIR) band has its own advantages, such as seeing through atmospheric haze.

The use of imaging systems for security, defense, and surveillance depends greatly on taking advantage of the infrared (IR) spectrum, which can be divided into near-, shortwave-, midwave-, and longwave-infrared (NIR, SWIR, MWIR, and LWIR, respectively). NIR cameras for security and surveillance are typically low-light (night vision) devices, while MWIR and LWIR cameras accomplish their tasks via thermal imaging. However, SWIR cameras are useful security and surveillance devices in their own right—sometimes by themselves, and often in combination with other imagers.

The spectral border between NIR and SWIR is commonly stated to be around 1.4 μm, although for this article, an exact figure is not important. The boundary between SWIR and MWIR is generally stated to be 3 μm.

Imaging through haze

Sensors Unlimited (Princeton, NJ), a part of Collins Aerospace, produces a wide variety of SWIR imagers, including handheld SWIR scope systems, area cameras, line-scan cameras, and linear photodiode arrays. The sensor technology, based on indium gallium arsenide (InGaAs), was brought to market in 1991 by Sensors Unlimited.

Applications for these SWIR devices include facility, port, and border security and surveillance, as well as other covert operations; low-light-level imaging; military driver vision enhancement; and military IR laser spotting and tracking. As an example, the GA1280JSX SWIR camera has a high-definition (1280 × 1024 pixel) sensor that images at 60 frames per second (fps) at full resolution with high sensitivity in the 0.9–1.7 μm spectrum and covers NIR/SWIR from 0.7 to 1.7 μm or, optionally, visible/SWIR from 0.5 to 1.7 μm.

“One of the most compelling security and surveillance uses of the GA1280JSX high-definition SWIR camera involves imaging through atmospheric haze,” says Curt Dvonch, an applications engineer at Sensors Unlimited. “These two images [see Fig. 1] were captured simultaneously and clearly demonstrate how SWIR cameras outperform visible cameras in polluted, hazy environments. The

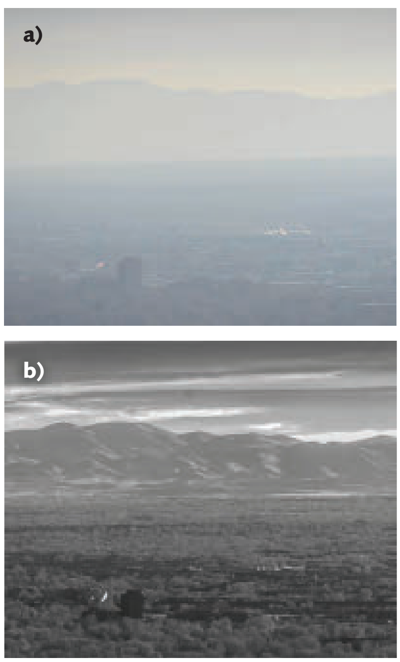

FIGURE 1. Utah’s Salt Lake Valley occasionally experiences an atmospheric phenomenon that traps air pollution for days or weeks at a time. During these atmospheric inversion events, ground-level visibility is severely reduced. These images taken from a video show visible imagery (a) and shortwave-infrared (SWIR) imagery (b) during a period of very low ground-level visibility on December 7, 2017 at approximately 3:30 pm MST (to see the video, visit https://youtu.be/3cBkfQb8vxQ). The SWIR imagery was captured at 60 fps with the Sensors Unlimited GA1280JSX mini-SWIR area camera and a 200 mm SWIR-optimized *f*/1.6 lens. The visible imagery was captured with a Nikon D5100 DSLR camera in video mode and a 55–200 mm *f*/4.5-5.6 lens. Both sets of imagery are cropped, but are otherwise unchanged. *(Courtesy of Sensors Unlimited)*

SWIR camera outperforms the visible camera primarily because SWIR photons are able to penetrate through atmospheric haze and smog, while visible-wavelength photons are scattered in air that is heavy with particulate matter."

Multiple target tracking

FLIR Systems (Wilsonville, OR) makes InGaAs SWIR cameras based on its focal-plane array (FPA), which the company also sells separately. These FPAs have a capacitive transimpedance amplifier circuit design that is optimized for applications ranging from security imaging to high-speed scientific laser testing (which requires multiple outputs and dynamic windowing).

One of FLIR's SWIR cameras, the Boson, is optimized for size, weight, and power plus cost (SwaP+C). With a 21 × 21 × 28 mm size, 15.5 g lensless weight, and power consumption of <1.6 W, the camera is military-qualified—it has no thermoelectric cooler (TEC), which helps it achieve its SwaP+C optimization. The Boson's slightly larger cousin, the Tau, does have a TEC, which gives it the temperature stability needed for precision use in the field. The camera is 38 × 38 × 36 mm in size and consumes 3.2 W or less of power. Both cameras come in SWIR (0.9 to 1.7 μm) and visible/SWIR (0.6 to 1.7 μm) versions.

In addition to cameras, FLIR produces an entire all-terrain reconnaissance and surveillance vehicle called the LTV-X (see Fig. 2), which carries swappable mounted sensors and imagers of various types, including NIR, SWIR, thermal, laser rangefinding, and radar. The vehicle can be transported in a V-22 Osprey

FIGURE 2. This light tactical reconnaissance and surveillance vehicle by FLIR, the LTV-X, carries a complementary sensor array that can include NIR, SWIR, thermal, laser rangefinding, and radar devices. *(Courtesy of FLIR)*

tilt-rotor military aircraft and, with its camera control system, can track up to 500 threats simultaneously.

OEM variants

Raptor Photonics (Larne, Northern Ireland), which has been making InGaAs-based cameras for 13 years, has built up a range of both SWIR and visible/SWIR cameras with various resolutions and pixel sizes from 320 × 256 to 640 × 512 and, most recently, a new high-definition camera with 1280 × 1024 pixel resolution. Using InGaAs sensors from several suppliers, both off-the-shelf and custom-designed, the company designs low-noise core modules. As described by Mark Donaghy, the company's vice president of sales and marketing, Raptor can then offer custom variants including mechanical layout, interface, cooling, optical design (see Fig. 3), and so on to meet the exact needs of its surveillance and security customers. "In fact, 90% of what Raptor ships each year are OEM variants," Donaghy says. "For example, there are now 16 different OEM variations of the OWL 640 camera, each one designed to the specific needs of individual customers."

FIGURE 3. This OWL 1280 visible/SWIR camera by Raptor Photonics was produced with a custom lens setup. *(Courtesy of Raptor Photonics)*

With a 1280 × 1024 InGaAs sensor, the OWL 1280 camera has a spectral range that extends all the way across the visible spectrum, resulting in a total range of 0.4 to 1.7 μm at high sensitivity. The 10 × 10 μm pixel pitch enables high-resolution imaging with less than 40 electrons (e-) readout noise and with a large intra-scene dynamic range of 69 dB, enabling simultaneous capture of bright and dark portions of a scene, Donaghy says.

The camera runs from 10 up to 60 Hz and has onboard automated gain control (AGC) to enable optimal contrast images from low light to bright light. The camera is temperature stabilized with no fan. Donaghy notes that it is well suited for low-light and nighttime imaging for land and airborne applications.

"The OWL 1280 has been adopted into several gimbal programs by OEMs and prime contractors," he explains. The HD format offers much better resolution for the operator and the VIS-SWIR range enables imaging through smoke, haze, sea fog, as well as other low-visibility conditions. It is also critical for seeing key laser lines—for example, 1550 nm. Being housed in a gimbal, the OWL 1280 is designed to offer optimum SWaP performance and the camera can handle extreme environmental conditions such as temperature (-40°C to +75°C) and moisture (conformally coated electronics). Each camera is built to ISO9001:2015 standards, meaning the camera's quality and reliability is exceptional, crucial for mission-critical applications.

Donaghy notes that for one specific customer, the camera is being provided in a board format laid out with flexible cables in a configuration designed so that the assembly can be "concertinaed" (compressed) into a tight space envelope.

High-speed imaging

First Light Imaging (Meyreuil, France) has unveiled an uncooled SWIR camera, the C-RED 3, which is optimized for low SwaP+C. The camera is based on a TECless InGaAs sensor sensitive from 0.9 to 1.7 μm and has a more than 70% quantum efficiency (QE), says Jean-Luc Gach, the company's founder and scientific advisor. The camera has a refresh rate of up to 600 fps with a readout noise below 50 e-.

The C-RED 3 includes an embedded electronic shutter with an opening width lower than 5 μs. While the camera is intended primarily for industrial use, it is also well suited for surveillance via fixed mounting or on mobile platforms such as unmanned aerial vehicles (UAVs).

The camera supports a high-dynamic-range mode (HDR) providing 93 dB dynamic range and a true 16-bit linear response, having at the same time a low noise below 50 e- and a full well capacity of more than 10^6 e-. The C-RED 3 can work also in AGC mode at standard dynamic range. It is especially well suited for short exposure times in applications where very high speed is needed.

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Innovations in OCT

RICHARD GAUGHAN, Contributing Writer, *BioOptics World*, and
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Optical coherence tomography (OCT) continues to develop, leveraging advances in computing power, innovation in system design, and application of artificial intelligence.

Given the dramatic contributions of optical coherence tomography (OCT) to biomedicine, it is fitting that the first plenary session at SPIE Photonics West 2019 opened by honoring work in OCT by one of its pioneering developers. The BiOS Hot Topics plenary kicked off with presentation of the 2019 Biophotonics Technology Innovator Award to Stephen Boppart, director of the Center for Optical Molecular Imaging and leader of the Biophotonics Imaging Laboratory at the University of Illinois at Urbana-Champaign. The award particularly recognizes Boppart's work in developing novel technology for computational OCT and applying it to basic and clinical sciences.

Computational OCT is an evolutionary progression from the original OCT, akin to the development of magnetic resonance imaging (MRI) from nuclear magnetic resonance.[1] Computational OCT leverages advances in computing power to address results-degrading limitations of traditional OCT, including the inherent tradeoff between depth-of-field and transverse resolution, the dispersion mismatch of sample and reference paths, and aberrations imposed by optics. Taken together, computational techniques not only improve the quality of OCT imaging, but also boost imaging speed and enable OCT data to provide greater insight. And because they manipulate data, they allow for simpler, lower-cost setups, greater flexibility, and require much less time to produce images. And while many recent developments in OCT have involved computational approaches (including one from Boppart's group that achieves wavefront correction by combining computational and hardware methods[2]; see Fig. 1), a number of advances have emerged—even just in the past year—from other types of innovation.

Conditioning monochromatic light for OCT

At SPIE Photonics West 2018, Prof. Dalip Singh Mehta of the Indian Institute of Technology Delhi (India) described a way to improve spatial coherence of a light source while simultaneously maintaining other characteristics necessary for optimal performance.[3] OCT performance depends in large part on coherence properties of the system's light source. Interferometers measure intensity patterns that result from recombining separated parts of an optical beam (sample and reference paths). A path difference of an integral number of wavelengths provides an intensity maximum, while half a wavelength longer or shorter gives an intensity minimum. Two beams will interfere only if they have a well-defined phase difference—that is, if their phases are correlated. The measure of correlation as a function of distance is the coherence length. The intensity variation of two recombined beams—or, equivalently, the fringe contrast—vanishes if the difference between the two path lengths is greater than the coherence length.

OCT uniquely identifies the distance to different surfaces in the object path. For ophthalmological applications, those structures are layers within and beneath the retina. There's an intensity maximum if the distance to a particular layer, say the retinal pigment epithelium, exactly matches the reference distance. If, however, the surface of the choroid membrane is, say, exactly 30

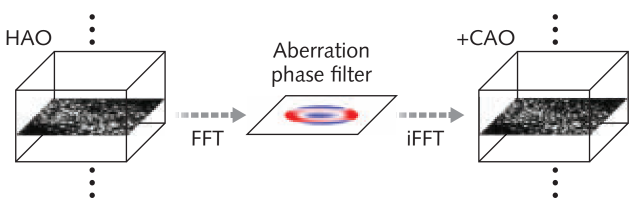

FIGURE 1. Aberrations remaining in OCT data produced with hardware adaptive optics (HAO) can be corrected with post-processing using computational adaptive optics (CAO).

wavelengths away, then that surface will also provide an intensity maximum—that is, if the coherence length of the source is greater than 30 wavelengths.

To eliminate degeneracy, the traditional practice in OCT is to use a broadband light source. But a broadband source is inherently subject to birefringence effects in the sample. Also, the relatively low power output demands that the source be scanned across the sample point-by-point. It would be far more convenient to acquire a full 2D image in a single shot. Both of those problems could be overcome if the broadband source were replaced by a laser source, but lasers intrinsically have long coherence lengths, which degrades the axial (depth) resolution from the few microns of broadband OCT to several millimeters.

Mehta's team devised a beam conditioning method that reduces spatial coherence while retaining the monochromaticity and intensity necessary for an ideal OCT source (see Fig. 2). The multistage process starts by expanding the source beam, splitting it in three, and combining those beams on a diffuser at angles of 30°, 0°, and -30°. A condenser lens couples the diffuser light into a vibrating multimode fiber bundle and the output of that fiber bundle is collimated to become the OCT source.

The conditioning introduces spatial, angular, and temporal diversity into the monochromatic beam. Axial resolution is then a function of longitudinal spatial coherence rather than temporal coherence. "With our system," Mehta says, "we can solve two problems simultaneously: we significantly reduce the speckle effect, leading to uniform illumination,

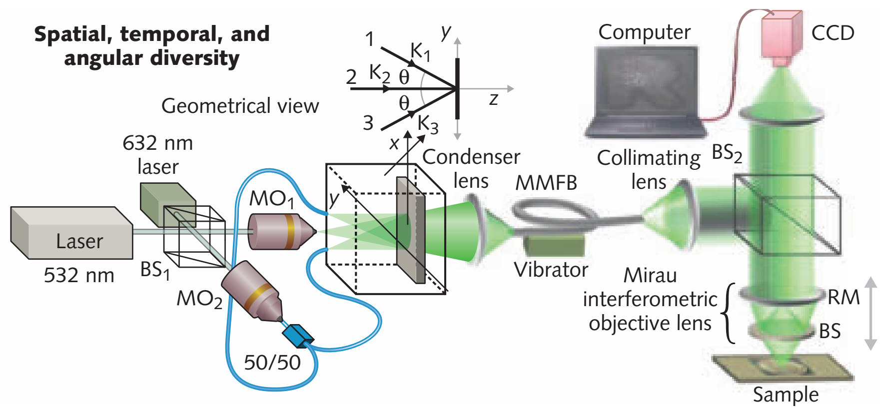

FIGURE 2. Longitudinal spatial coherence gated high-resolution full-field OCT using laser light source.

and also decrease the sample interactions using our broad angular frequency spectrum light source."

Prior work, Mehta says, implicitly assumed that short temporal coherence was necessary for good axial resolution. Then, he says, "our group and some others thought to play with the spatial coherence properties of a monochromatic light source." The different approach is paying off: Mehta's group has demonstrated axial resolution of ~4 μm and lateral resolution of ~2 μm.

Learning and quantification

Mehta's team has since gone on to apply machine learning to OCT tissue analysis and also to leverage machine learning to quantitatively classify damage to human skin inflicted by burns.[4] While other groups have worked on quantitative assessment of such damage using OCT, Mehta's team seems to be the first to report fully automated detection of burn injuries *in vivo* in humans. The researchers' objective was to assess surgical margins automatically based on OCT imaging. Working to extract quantitative features from OCT images depicting normal and burned tissues, they created a classifier for machine learning and then applied it to train a linear classification model. Testing of the model revealed 90% specificity and 91.6% sensitivity. Further, the team has developed a deep learning architecture called LightOCT to classify OCT images into diagnostically relevant classes.

Other applications of deep learning have also begun to address OCT imaging as well. For instance, researchers at Shanghai Jiao Tong University (Shanghai, China) have applied this type of artificial intelligence to 3D endoscopic OCT, with a goal of faster procedures.[5]

Current methods use a data-intensive process to create 3D OCT images by assembling series of 2D images taken sequentially at equal distances. The Shanghai Jiao Tong team used "sparse sampling" to acquire dramatically fewer 2D images (for example, 120 frames vs. 200 in standard OCT), and then applied compressive sensing algorithms to supply missing data to create the 3D depictions. The researchers' tests confirmed that effective 3D OCT imaging can be done with 40% less experimental data. "After we perform enough experiments to demonstrate that our probe and imaging method are useful for observing malignant features, our technique will be ready for clinical trials," says team leader Jigang Wu.

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Spatial coherence engineering of lasers enhances use for illumination

HUI CAO

Spatial-coherence tailoring extracts more image information from laser-illuminated microscopes and other optical systems.

Lasers have enabled major scientific and technological advances due to their high brightness, high coherence, high efficiency, and good spectral control. However, high spatial coherence can cause deleterious effects such as speckle noise, limiting laser application in full-field imaging, parallel projection and display, materials processing, optical trapping, holography, and lithography.

To avoid speckle, lamps and LEDs of low coherence are often used as illumination sources. These sources have low power per mode, which is insufficient for imaging through a scattering medium or for high-speed imaging with short recording time. Alternatively, lasers can be used in a raster-scanning mode—however, scanning is time-consuming and not suitable for imaging of moving objects or transient processes. Parallel imaging is desirable because of high speed, but it requires an illumination source with high power and low coherence.

A common way of reducing the spatial coherence of a laser is to generate many speckle patterns with a time-varying scattering system and then sum the intensities. Even though each speckle pattern has a contrast of unity, an incoherent sum of N uncorrelated speckle patterns reduces the speckle contrast by a factor of $N^{1/2}$. Lowering the speckle contrast to below the level of human perception (<3%) requires summing about 1000 different speckle patterns. The imaging speed is then limited by the time it takes to sequentially generate these speckle patterns.

Instead of first making a highly coherent laser only to then reduce the spatial coherence of its emission with a spinning diffuser, why not just insert the diffuser into the laser cavity to reduce spatial coherence directly? Since the diffuser scatters light, the question is whether lasing can still be achieved with scatterers inside the cavity. The answer is yes. In fact, the more scatterers, the lower the lasing threshold.

Random lasing

When a gain medium consists of many scatterers, the spontaneously emitted photons will be scattered multiple times and undergo a "random walk." The increase in the path length of photons in the gain medium enhances light amplification via stimulated emission of photons (see Fig. 1a). Furthermore, the scattered waves may return to spatial positions that they have visited before, providing feedback for lasing oscillation. Thus, lasing can occur without a conventional cavity; such a laser is called a random laser.[1]

Random lasers can operate in a highly multimode regime. Individual lasing modes, formed by interference of

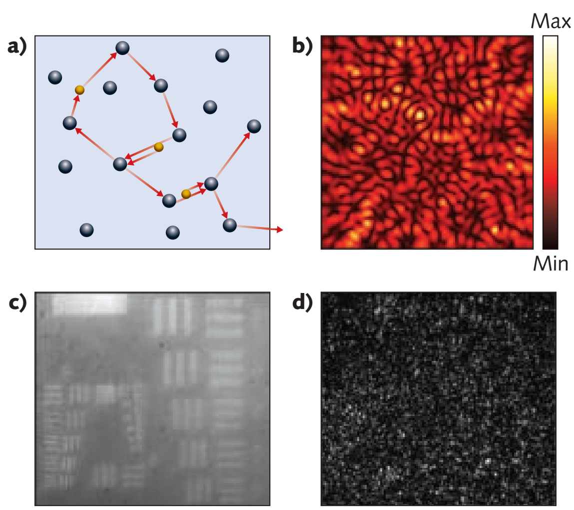

FIGURE 1. A schematic (a) illustrates the principle of a random laser with low spatial coherence; optical scattering in a random medium enhances stimulated emission of photons. The black circles denote scattering centers and the orange dots are excited atoms. The calculated spatial intensity distribution (b) of a lasing mode in a 2D disordered structure is shown. A resolution chart is imaged under illumination by a random laser (c) and a standard helium-neon (HeNe) laser (d). The random laser has low spatial coherence and suppresses speckle noise. (*Adapted from B. Redding, M. A. Choma, and H. Cao*[4])

scattered waves, have distinct frequencies and spatial structures (see Fig. 1b). When a large number of modes lase simultaneously with uncorrelated phases, their distinctly speckled wavefronts combine incoherently to produce emission with low spatial coherence.[2,3] Because the reduction of spatial coherence does not rely on the motion of scatterers inside the cavity but on multimode lasing, the scatterers may be static. The time it takes for spatial coherence reduction is given by the spectral linewidth and frequency spacing of individual modes. Speckle-free full-field imaging is demonstrated with random laser illumination in the setting of intense optical scattering (see Figs. 1c and d).[4]

Compared to lamps and LEDs, the random laser emission is much stronger and allows much shorter exposure time and much higher speed for full-field imaging of transient processes.[5,6] For example, a random laser can be triggered to produce a short illumination flash at a well-defined delay time, enabling time-resolved speckle-free wide-field microscopy with an exposure time as short as 10 ns.

Studies of random lasers reveal how to design a laser with low spatial coherence. First, the laser cavity must support numerous low-loss modes of similar quality (Q) factor, so that they have a similar lasing threshold. Secondly, mode competition for gain must be minimized so that many modes can lase simultaneously. Finally, these modes should have distinct emission patterns so that, when they lase independently, an incoherent sum of their emission intensities lowers the spatial coherence. Of course, combining mutually incoherent emission from many uncoupled lasers, such as a vertical-cavity surface-emitting laser (VCSEL) array, can lower the spatial coherence. However, incorporating all lasers to a single cavity will reduce the system size and fabrication cost, as demonstrated by the wave-chaotic microcavity laser.

Wave-chaotic cavities feature chaotic ray dynamics, in contrast to regular ray dynamics in conventional laser cavities. One example is the D-shaped cavity: a two-dimensional (2D) circular cavity with a section removed along a straight cut (see Fig. 2a). This cut eliminates the whispering-gallery modes that have extremely high Q factors. The remaining modes have a pseudorandom structure (see Fig. 2b). They have similar Q factors and, hence, lase with almost identical thresholds. Because their spatial profiles are spread over the entire cavity, their competition for gain is reduced as compared to whispering gallery modes that are concentrated near the boundary of a circular cavity. Consequently, more than 1000 modes lase simultaneously and independently in a D-shaped gallium arsenide (GaAs) disk with a radius R of 500 μm, producing emission of low spatial coherence.[7] The disk is fabricated on a commercial GaAs quantum-well wafer via standard photolithography and wet chemical etching. Lasing is achieved at room temperature with electric current injection. The spectral radiance of the D-cavity laser, measured by photon degeneracy number δ (the number of photons per coherence volume), is 4–5 orders of magnitude higher than that of a thermal source or of a bright LED. For speckle-free imaging, the D-cavity laser is the brightest illumination source available, with a compact size and low cost.

Spatial coherence gating for microscopy

In addition to high-speed, speckle-free full-field imaging, a source with low spatial coherence and high power per mode enables massively parallel phase-sensitive interferometric confocal microscopy. It was shown that spatial coherence gating provides 18,000 continuous virtual pinholes for imaging the entire *en face* plane in a snapshot.[8] The integration time is as short as 100 μs and the 2D frame rates exceed 1 kHz. The interferometric detection retrieves both amplitude and phase of optical signals. An ultrahigh-speed, phase-sensitive, full-field reflection interferometric confocal microscope (FFICM) was developed for *in vivo* quantitative microscale physiology—for example, visualization and quantification of cilia-driven surface flows and cilia beat frequency in tadpoles.[9]

The lateral resolution is 2 μm and the axial gating depth is 8 μm.

Although speckle poses a serious issue for imaging the structure of an object, its temporal fluctuation caries useful information about the motion of the object. Laser-speckle contrast imaging relies on time-varying speckle created by moving blood cells to map blood flow in living tissue. To obtain both anatomical and functional information on living tissue, speckle-free and speckled images are recorded with two separate illumination sources: a laser and a LED. However, a single illumination source with tunable spatial coherence but constant power will eliminate additional optical alignment and potential power change. To this end, an efficient method of tuning the spatial coherence of a degenerate laser was developed.[10]

A degenerate cavity is a self-imaging system, as exemplified in Figure 3a, that shows two lenses in a $2f_1$-$2f_2$ telescope arrangement between two flat mirrors. Because an arbitrary field distribution at any plane in the cavity is imaged onto itself after one round trip, any field distribution is an eigenmode of the cavity. All eigenmodes are degenerate, having identical lasing threshold. In a degenerate solid-state laser, more than 10^5 transverse modes lase simultaneously and independently, producing emission with extremely low spatial coherence.[10]

To tune the degree of spatial coherence, the number of transverse lasing modes is varied by inserting a variable circular aperture to the mutual focal plane of the two lenses, as shown in Fig. 3b. The aperture serves as a spatial filter that introduces loss to high-order transverse modes. When the aperture is sufficiently small, only the lowest-order transverse mode lases. Because the spatial overlap between the lasing mode and the gain medium remains the same, the total power extracted from the gain medium is unchanged.

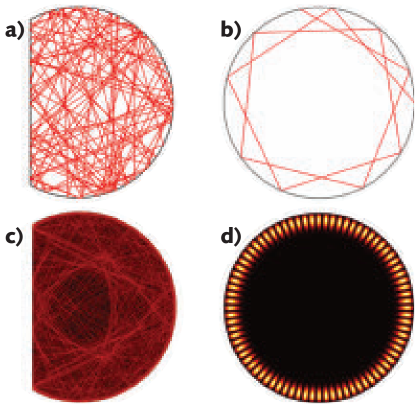

FIGURE 2. Two-dimensional microcavities can have regular or chaotic ray dynamics. A typical ray trajectory in a D-shaped cavity (a) spreads over the entire cavity due to chaotic ray dynamics. A whispering gallery trajectory in a circular cavity (b) keeps close to the cavity boundary. The spatial intensity distribution of a resonance in a D-shaped dielectric disk (c) displays a pseudorandom structure. The spatial intensity distribution of a whispering gallery mode in a circular dielectric disk (d) is confined to the disk boundary. (*Adapted from B. Redding et al.*[7])

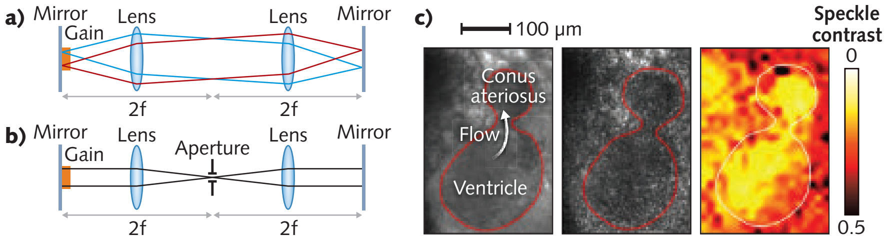

FIGURE 3. Switching of spatial coherence of a degenerate laser is depicted. In a schematic of a degenerate laser cavity in the self-imaging configuration (a), light emitted from any point in the gain medium will be imaged back to itself after one round trip. A large number of transverse modes lase simultaneously and independently to produce low spatial coherence. Inserting an aperture to the mutual focal plane of the two lenses (b) yields a single transverse lasing mode that emits with high spatial coherence. Coherence switching of a degenerate laser is used for imaging embryo heart function in *Xenopus* embryo (c): low-coherence illumination achieves high-speed (100 frames per second) speckle-free imaging of dynamic heart structure (left); high-coherence illumination generates a speckled image (middle); and the speckle contrast (right) reveals blood flow. (*Adapted from S. Knitter et al.*[12])

Experimentally, decreasing the diameter of a circular aperture in a solid-state degenerate cavity changes the number of transverse lasing modes from 10^5 to 1, while the output power reduces by less than 50%. The spatial-coherence properties can be further engineered by resorting to more sophisticated intracavity spatial masks. For example, a variable slit enables independent control of the degree of spatial coherence in one coordinate axis without affecting that in the orthogonal axis.[11]

Both structural and functional information are obtained

The spatial coherence of an electrically-pumped semiconductor-based degenerate vertical external-cavity surface-emitting laser (VECSEL) was switched for imaging the embryo heart function in *Xenopus*, an important animal model of heart disease (see Fig. 3c).[12] The low-spatial-coherence illumination was used for high-speed (100 frames per second) speckle-free imaging of the dynamic heart structure, and the high spatial-coherence illumination for laser speckle contrast imaging of the blood flow. Therefore, a single source can be employed for two microscopy modalities to obtain both structural and functional information.

Spatial-coherence control of lasers not only provides an efficient means for eliminating coherent artifacts, but also enables new applications. These schemes for reducing and switching the spatial coherence are applicable to a variety of lasers that operate at different wavelengths and with different gain materials. Each scheme has its own advantages and is suitable for different applications.

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Engineered metaoptics forge new nonlinear devices

YURI KIVSHAR

Recent progress in metaoptics driven by Mie resonances of high-index dielectric nanoparticles provides a novel platform for subwavelength localization of light in supercavities and opens new possibilities for nonlinear nanophotonics.

Nanophotonics describes the subwavelength localization of light, and it is usually associated with plasmonics. However, the emerging field of optically resonant dielectric nanophotonics provides novel research directions for nanoscale optics.[1] All-dielectric resonant nanophotonics use subwavelength Mie-resonant (or particle morphology-dependent) dielectric nanoparticles as elementary units (or "meta-atoms") for creating highly efficient optical metadevices.

Whether called metamaterial-based optics or metaoptics, the unique optical resonances of these engineered nanoscale structures are accompanied by strong localization of both electric and magnetic fields, and they are expected to replace different plasmonic components in a range of potential applications. Importantly, resonant dielectric structures can lead to many novel effects originating from interference of several modes.

Optical cavities and Mie resonances

One of the key targets for making a successful laser is to confine light in an optical cavity. A conventional optical cavity traps light by using real or effective mirrors and using the physics of total internal reflection or scattering from periodic microstructures such as photonic crystals. Trapping in all such systems is characterized by the quality factor (Q factor)—a measure of the efficiency of the reflecting boundaries—being weakly dependent on the cavity geometry.

But recent advances in metaoptics based on Mie resonances on high-index dielectric structures suggest an alternative way to confine light by using nonradiating optical states such as anapoles or bound states in the continuum that can induce large subwavelength field enhancements at the nanoscale that are crucially dependent on system geometry (see Fig. 1).[2,3]

Of primary importance is that these isolated dielectric nanoparticles with simple geometries can support both electric- and magnetic-type resonances of comparable strengths. A strong magnetic dipole resonance occurs due to a coupling of incoming light to the circular displacement currents of the electric field, owing to the field penetration and phase retardation inside the particle. This occurs when the wavelength inside the high-index material of the particle becomes comparable to the particle's spatial dimension—namely, $2R$ is approximately λ/n, where n is the refractive index of the particle's material, R is the nanoparticle's radius, and λ is the wavelength of light.

This is a type of geometric resonance that requires the nanoparticle to have a large refractive index to support strong magnetic-dipole resonances in the subwavelength regime. Similarly, a dielectric nanoparticle can support resonances dominated by the electric dipole and other high-order multipoles such as electric quadrupole and magnetic quadrupole resonances. The Mie resonances are usually associated with localization of the incident electromagnetic

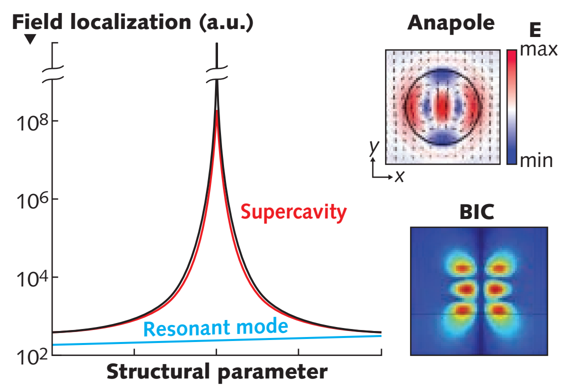

FIGURE 1. Conventional lasers use an optical cavity that traps light at certain resonances, so the field localization and quality factor depend weakly on the geometry; by contrast, the field localization of anapoles and bound states in the continuum (BICs) of metamaterial optics depends on the geometry.

field inside the particles, suggesting at least two-orders-of-magnitude enhancement of many optical effects observed with high-index dielectric nanoparticles compared to nonresonant cases.[1]

Supercavities: Anapoles and bound states in the continuum

The term anapole means "without poles" and was originally proposed in the late 1950s by Yakov Zeldovich to model elementary particles that do not interact with the electromagnetic fields.[4] Anapole states have been investigated in astrophysics, as they could explain the origin and composition of dark matter in the universe within the parameters of classical physics.

In the context of nonradiating sources, the theory developed during the 1990s demonstrated that different types of nonradiating states could be generated by combining classical electric and magnetic dipole modes with electromagnetic toroidal multipoles in configurations where the angular distribution of the energy density has the same and opposite parities. The simplest of these configurations is created by a toroidal dipole mode oscillating out of phase with respect to a single electric dipole.[2]

It was noted that such a particular interfering state—the superposition of an electric dipole and toroidal dipole modes—forms a simple but nontrivial nonradiating point source, later recognized as an elementary dynamic anapole state (see Fig. 2). A special feature of these two dipoles is that their far-field distribution is identical. For a particular set of parameters, these two dipoles can completely cancel each other by destructive interference in the far-field region when oscillating out of phase, hence creating a (weakly radiating) anapole.

Bound states in the continuum (BICs) originate from strong coupling between the modes in dielectric structures such as photonic crystals, metasurfaces, and isolated resonators. These BIC solutions were introduced in quantum mechanics 90 years ago by J. von Neuman and P. Wigner,[5] while in photonics they were rediscovered only a few years ago.

A true BIC is a mathematical object with an infinite value of the Q factor and vanishing resonance width, and it can exist only in ideal lossless infinite structures or for extreme values of parameters. In practice, a quasi-BIC can be realized as a supercavity mode when both the Q factor and resonance width remain finite and approach the mathematical condition of a BIC asymptotically.

Recent discoveries[6] reveal that even a single subwavelength resonator made of a high-index dielectric can be tuned into the regime of a supercavity mode supporting quasi-BICs (see Fig 2). This can be achieved by varying the geometrical parameters of a nanoparticle when the radiative losses are almost suppressed due to destructive interference of leaky modes.

A new era of nonlinear nanophotonics

A large enhancement of the Q factor of high-index dielectric nanoscale resonators, with the parameters tuned to the supercavity conditions, offers a paradigm shift in nonlinear optics through the development of nonlinear metadevices.

The reason is that nonlinear optics at the nanoscale are governed by strong field confinement and resonant response not limited by phase matching. As a result, the processes of high-order harmonic generation can be boosted dramatically since they scale as $(Q/V)^n$, where n is the process order and V is the mode volume.

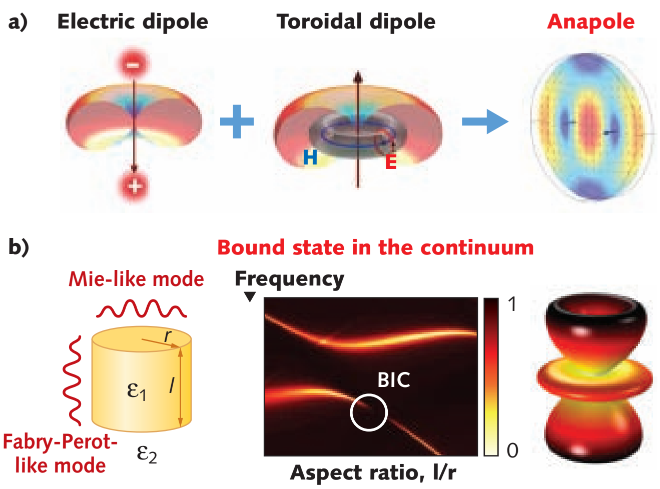

FIGURE 2. A (weakly radiating) anapole optical state (a) appears through interference of simultaneously excited dipole and toroidal optical modes that can be supported by a single Mie-resonant dielectric nanoparticle; emergence of bound states in the continuum (BICs) for a single nanoparticle (b) occurs due to a variation of the aspect ratio and strong coupling of the Mie- and Fabry-Perot-type optical modes.

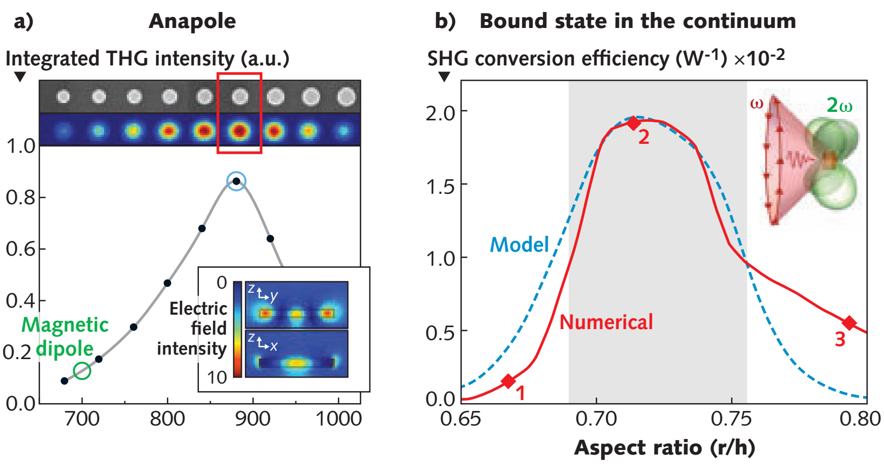

FIGURE 3. Enhanced nonlinear third-harmonic generation (THG) is observed (a) in germanium (Ge) nanodisks near the anapole conditions; the inset shows the numerically simulated field structure of the anapole. A predicted giant second-harmonic generation (SHG) effect is shown for BIC conditions in an aluminum gallium arsenide (AlGaAs) nanorod (b); the inset shows the multipolar field structure.

Therefore, a giant increase of the generation efficiency is expected in isolated subwavelength nanoparticles, as was recently predicted for second-harmonic generation (SHG) in aluminum gallium arsenide (AlGaAs) nanodisks.[7]

The first approach exploiting the anapole state to enhance nonlinear harmonic generation was demonstrated for germanium nanodisks (of 100 nm of thickness and radii ranging from 250 to 500 nm) by Grinblat and colleagues (see Fig. 3).[8] When excited in the vicinity of the anapole resonance and taking advantage of a high field confinement, this structure performed a third-harmonic conversion from incident infrared light (1650 nm) into green light (550 nm) with an efficiency that is orders of magnitude higher than a flat structure.

Recently, a team at the Australian National University predicted and demonstrated the enhancement of the SHG efficiency for individual dielectric nanodisks in the quasi-BIC regime.

In the team's experiments, the resonator is excited by an azimuthally polarized Gaussian beam providing perfect mode matching with the high-Q resonance, whose electric field is uniform with respect to the azimuthal direction, assuming a diffraction-limited beam waist and the value of the second-order nonlinear susceptibility of 290 pm/V. Both theoretical proposals[7] and experimental observations on quasi-BIC nonlinear nanoparticles demonstrate breakthrough conversion efficiencies[9] on the order of 10^{-3} W^{-1} (see table).

In the recent past, nonlinear nanophotonics was dominated by metallic nanoparticles. Metals were an attractive choice due to their extremely high intrinsic nonlinearities. In addition, the support of plasmon resonances allowed for light confinement and local intensity enhancement near electric-field hot spots. However, the overall efficiency of the nonlinear frequency conversion in plasmonic nanostructures remained very small—on the order of 10^{-10} W^{-1}.

Platform	Resonance	SHG efficiency
Au	Plasmonic	5×10^{-10}
GaAs-on-AlO_x	Magnetic dipole	1.5×10^{-8}
AlGaAs-in-insulator	Magnetic dipole	6.4×10^{-6}
AlGaAs-on-glass	Supercavity	10^{-2} to 10^{-3}

A comparison of the second-harmonic generation (SHG) conversion efficiencies in plasmonic and all-dielectric nanoparticles driven by the supercavity modes is shown.[7-10]

Conversion efficiencies in nanophotonics are usually limited by losses, small mode volumes confined to metal surfaces, and low laser damage thresholds. But all-dielectric nanostructures with Mie resonances provide an important pathway to enhance the nonlinear efficiency beyond the limits associated with plasmonics—approaching 10^{-6} W^{-1}. These values can be pushed much higher to almost 10^{-2} W^{-1} with the concept of supercavities (see table).

In summary, resonant dielectric nanostructures provide an alternative solution to enhance the performance of many nanophotonic devices that used metallic elements and plasmonic effects in the past. The study of resonant dielectric metaoptics has become a new research direction in metamaterials and nanophotonics, and it is expected to complement or substitute some of the plasmonic components in a range of potential applications.

The unique low-loss resonant behavior of engineered metaoptics makes it possible to reproduce many subwavelength resonant effects already demonstrated in nanoscale plasmonics without essential energy dissipation and, in addition, brings many novel concepts to practical applications. We anticipate that the novel physics of nonradiating optical states originating from the 90-year-old concept of BICs and enhanced by the recent discovery of optical anapoles will provide a new twist for both active and nonlinear nanophotonics.

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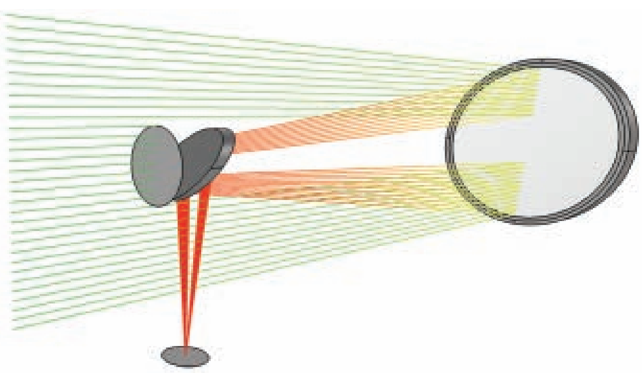

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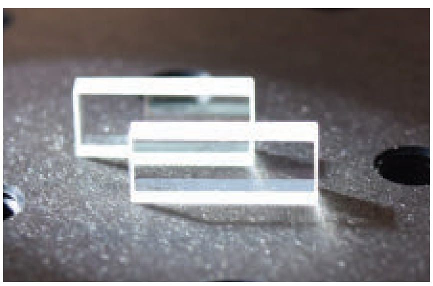

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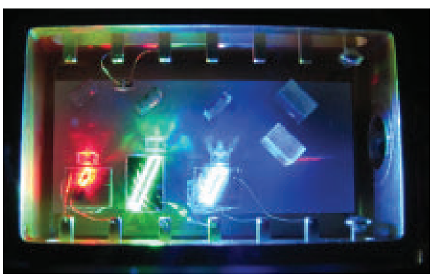

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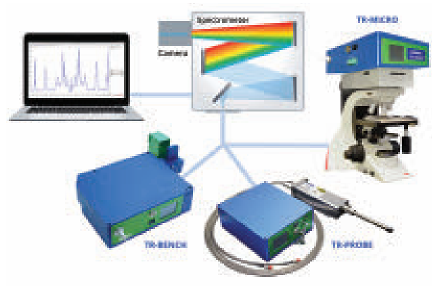

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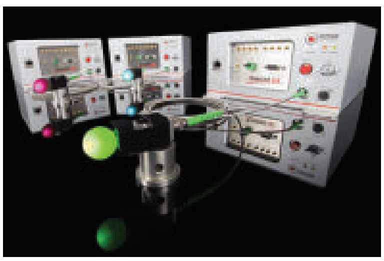

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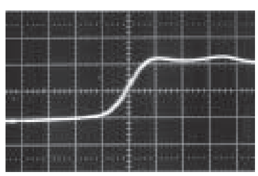

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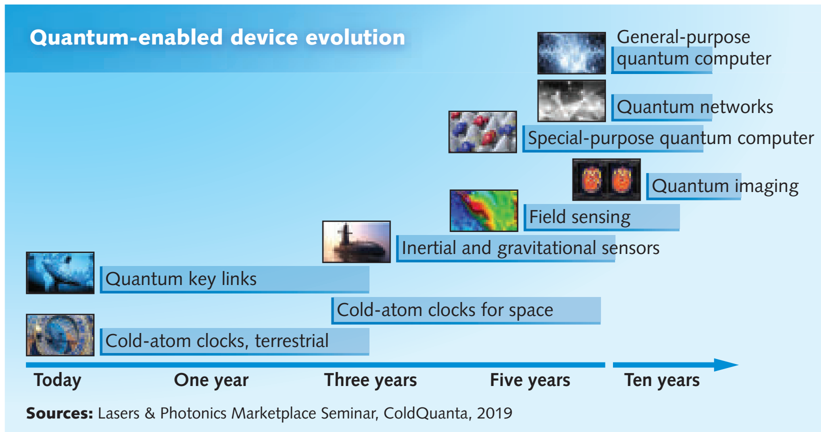
Mastering a changing laser market

CONARD HOLTON, Editor at Large

As I prepared to chair the 31st annual Lasers & Photonics Marketplace Seminar in February 2019, I considered what I should say in my opening remarks. It struck me that "change" was the best theme for the meeting. Of course, it's a trite observation—everything changes all the time, especially in photonics. But some things seem fundamentally different now and I could see it in the way the Seminar agenda came together.

It started with our keynote talk by Ralf Kimmel, general manager of TRUMPF Laser Technology. Here was a senior executive of one of the largest makers of lasers in the world and he didn't talk about laser diodes, fiber lasers, or disk lasers. Instead, he talked about solutions and holistic approaches, and IoT and digitization—that was different. And it all reflected a deep commitment by the company to a new vision of industrial manufacturing processes that acknowledges the fact that, in many cases, the laser itself has become something of a commodity.

Next, Allen Nogee, our laser analyst from Laser Markets Research, painted a picture of 2018 laser markets that looked much different from 2017, which had been a banner year for sales of high-power lasers (year-over-year growth of 48.6% in this one segment). Instead, the overall growth rate for all segments in 2018 was closer to a typical rate of about 6% growth, reaching a total revenue of approximately $13.5 billion. Sensors, especially those based on VCSELs, and medical lasers were the star segments in 2018 and look to be the same in 2019. The 2019 Worldwide Market for Lasers report is now available from Strategies Unlimited.



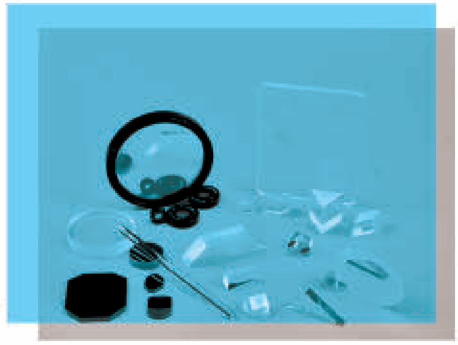
The timeline for quantum-enabled device evolution is shown. *(Courtesy of ColdQuanta)*

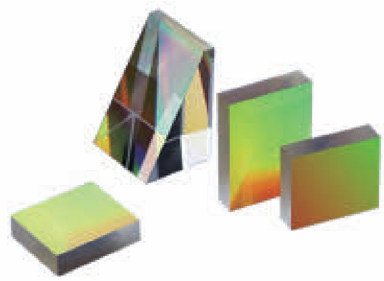
The Chinese laser markets are also clearly changing and having a major impact on global markets since China buys roughly 40% of the world's lasers. According to Bo Gu from Bos Photonics, more conservative government funding policies and significant trade uncertainties have fostered new caution about investment in China. Still, the overall market for industrial lasers and systems grew a very healthy 20% in 2018.

There were several more talks, interviews, and panels that explored the changes in markets for precision optics, the global mergers and acquisitions scene, and lasers used in flow cytometry. But the final panel of the day turned out to be the one that everyone in the audience stayed to hear long after the scheduled end of the Seminar. It was titled: Scaling quantum information systems—Photonics holds the keys. The full implications of what moderator John Dexheimer called "a land rush of global investments" will unfold over several decades, but it's becoming clear that photonics components and systems will play a major role (see figure).

As panelist Tim Day, executive chairman of ColdQuanta, said, quantum computers and other quantum devices have many common photonics-related needs, including highly precise light sources, ultrasensitive detectors, optical interfaces, and photonics packaging. Together with panelists from IonQ, M Squared Lasers, and Vector Atomic, they addressed these needs and the emerging market opportunities. You can read a much more complete description of the full Seminar in our special Summary Report (http://bit.ly/2019summary), and by viewing upcoming video webcasts from the Seminar.

CONARD HOLTON is Editor-at-Large for *Laser Focus World* and Chair of the Lasers & Photonics Marketplace Seminar; he previously served as Editor-in-Chief of *Laser Focus World*.





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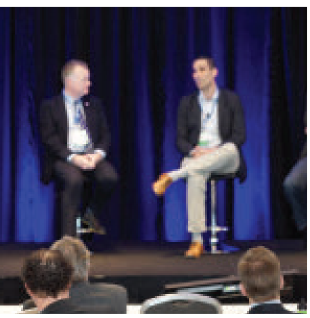



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Riding the winds of change: Photonics in 2019

Conard Holton
Editor at Large
cholton@pennwell.com

As you will read in this Report on the 31st annual Lasers & Photonics Marketplace Seminar (held February 4, 2019), the revenue numbers remain good for lasers and across many photonics markets—but the ground is shifting. Macroeconomic factors, trade disputes, and political tensions have created uncertainty. And new technologies, along with new ways of delivering products and services, reveal that even more changes are afoot.

This year, the Seminar format contained a mix of presentations, interviews, and panel discussions so that the audience could hear direct answers to questions and not rely so much on PowerPoint presentations. For example, I interviewed laser market analyst Allen Nogee after his presentation on global laser markets. And after lunch, I was on stage talking to Matthijs Glastra, CEO of Novanta.

Two panels engaged the audience in different ways on very different topics: precision optics and quantum technologies. The precision optics panel featured participants from Heraeus, Optimax Systems, the University of Rochester, and Synopsys, while emerging market opportunities for photonics in quantum information systems were discussed by panelists from Atomic Vector, IonQ, ColdQuanta, and M Squared Lasers.

We also heard talks from a scientist at the National Cancer Institute on the future of lasers in flow cytometry, a consultant on the tumult in Chinese laser markets, and two talks on changing global trends in mergers and acquisitions from Ceres Technology Advisors and Renevo Capital. To lead off, the general manager of TRUMPF Lasers described the new solutions-oriented thinking necessary to support the changing demands of industrial manufacturing customers.

I hope this Report gives you a sense of the Seminar and the information presented. The Lasers & Photonics Marketplace Seminar, I believe, remains the leading event where you can network with colleagues as you hear about developments in our markets and consider the implications for your business.

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The day began at 7:00 a.m. with breakfast and networking before the sessions, which started at 8:00 a.m. with a welcome from Seminar Chair Conard Holton.

The 2019 Lasers & Photonics Marketplace Seminar—Mastering the changes

ANDREAS THOSS, Contributing Editor, Germany

A look at the current photonics markets reveals numerous upheavals underway: Many lasers are becoming commodities, integrated solutions that take account of industrial digitization offer a way forward, and new technologies are arising. And on a regional basis, the Chinese market still demands the most attention, along with evolving global merger and acquisition trends. Meanwhile, when will quantum technologies really hit the market? All these changes and much more were discussed with the largest audience ever at the 31st annual Lasers & Photonics Marketplace Seminar.

Keynote Talk: Solution-oriented integration as key for sustainable success in the laser business

RALF KIMMEL, TRUMPF Laser Technology

Back in 2013, TRUMPF vice chairman Peter Leibinger drew a lot of attention when he called the laser a commodity. In 2019, this has become the common wisdom regarding most laser sources. So, what is the solution in a market with a growing sales volume and decaying margins? Ralf Kimmel, the general manager of TRUMPF Laser Technology, presented his company's approach: "Solution-oriented integration as a key for sustainable success in the laser business."

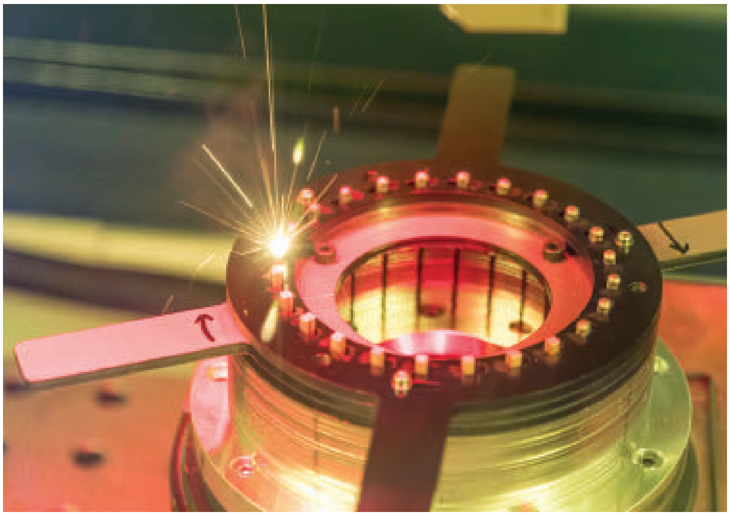

FIGURE 1. Laser welding of copper hairpins is a typical application in e-mobility. *(Courtesy of the TRUMPF Group)*

Privately owned TRUMPF relies on a sustainable development philosophy that starts with substantial investments in technology and applications development. But machines and manufacturing processes are just parts in a complex solution that reaches from financing (the company founded its own bank) to cloud-based solutions that make use of data collected during production.

The driver for this holistic approach is the technological problems that customers must solve. Kimmel first explained this using the example of hairpin welding in e-mobility, where new materials such as copper must be processed (see Fig. 1). In a three-step approach, they started with a modified laser source, developed the welding process technology, and, finally, established a global network to exchange best practices. This way, they were able to offer much more than just a machine.

In a second example, he went much further: He explained how TRUMPF responded to the growing demand for adaptable, but ever-more efficient production lines. Without naming it, he referred to the solutions that are known in the framework of Industry 4.0. For such vertically integrated production processes, TRUMPF offers sensors and data on every tiny step in production. They also bought a whole company to include safe IT gateways into their portfolio. This allows for the safe, remote processing of production data from various machines or places around the world.

Predictive maintenance on laser machines or the rapid adaption of lasing processes to varying material parameters are just first steps to make use of such data. In the future, production structures could become vertically and horizontally integrated and offer production time as a service on demand. In the end, customers probably just buy a volume of parts produced on those machines, and the machining service provider guarantees a specific availability.

This is the way TRUMPF thinks beyond the "laser as a commodity" challenge. Technological advances go together with new thinking about production structures and models, where the term "solution" is applied toward a new and holistic service proposal.

In the subsequent Q&A session, it turned out that handling the data from production is currently the biggest challenge in this process. Safety and standardization are also major issues.

Global laser markets: Insights and forecasts

ALLEN NOGEE, Laser Analyst for Strategies Unlimited

Market numbers and their interpretation are at the heart of the annual Laser & Photonics Marketplace Seminar. While 2017 had been a year of unprecedented growth for many fields of laser technology, 2018 meant a return to a more typical growth rate.

Looking at the macroeconomic numbers, Nogee stated that 2018 was quite a good year for the U.S. economy with a GDP growth of 2.9% (2017: 2.3%). Europe's GDP growth stood at 2.2% (2017: 2.3%), and industrial production growth slowed down from 3.8% in 2017 to 1.1% in 2018. The Asia-Pacific rim showed solid 5.5% GDP growth, with China's pace slowing from 6.6% in 2017 toward 6.5% in 2018.

Tariff conflicts between China and the U.S. have raised a lot of interest in recent months. Talking to a number of laser companies, Nogee found that the direct impact was low or even negligible. Indirectly, the tariff discussion led to uncertainties in the market that may have caused recession fears. Probably more important was a downturn in Chinese infrastructure investments, which had a negative impact on investment decisions. China consumes about 40% of the world's lasers—and a more cautious investment policy there, plus fewer smartphones or cars produced, have had an immediate and severe impact on laser sales.

Comparing quarterly financial numbers from big laser companies such as Coherent, IPG Photonics, and TRUMPF, Nogee found that 2018 started strong, but then the revenues went down for all of them. Accordingly, stock prices were falling in the second half of 2018 for most laser companies. Interestingly, China's Han's Laser stock price went down in a similar fashion, so the downturn was not limited to U.S. companies.

How were the separate laser markets faring in 2018? The medical sector grew strongly, with dental and cosmetic systems growing at 13%, while ophthalmic lasers showed only 2% growth. The flat panel business and particularly OLED displays grew well in 2018. When Apple used an OLED screen for iPhone X, many other companies jumped in and used OLEDs as well. But at $110 for an OLED screen, they are still expensive and slowing sales of iPhones means new laser orders have been canceled.

According to Nogee, sensing is the laser market segment currently seeing the biggest growth. Vertical-cavity surface-emitting lasers (VCSELs) have caused a lot of excitement in this segment. Again, Apple had a big influence by pushing VCSEL production in 2017. Several mergers and acquisitions followed: II-VI bought Finisar for $3.2 billion, Lumentum acquired Oclaro for

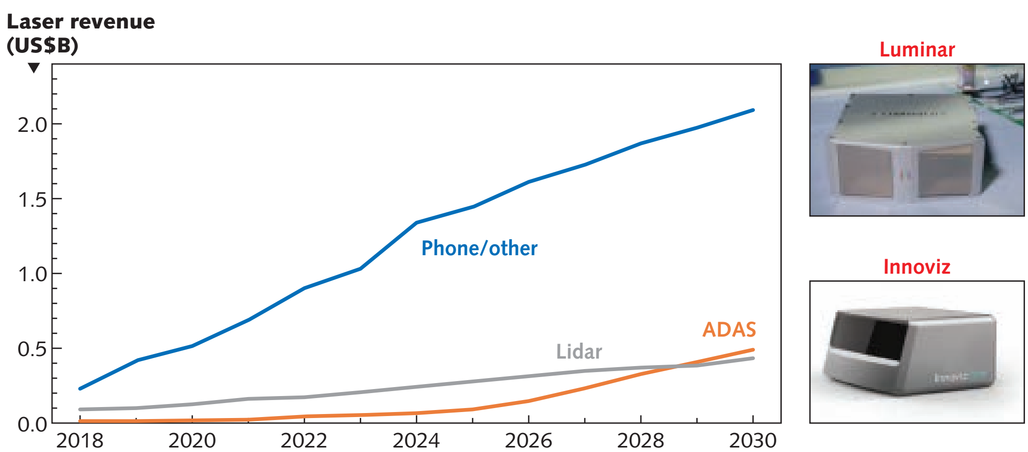

FIGURE 2. Driven by smartphone sales, the market for VCSELs will prosper in the coming years; advanced driver assistance systems (ADAS) and lidar are gaining market share. *(Courtesy of Strategies Unlimited)*


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$1.8 billion, and last—but certainly not least—TRUMPF bought Philips Photonics. VCSELs can be used for infrared (IR) illumination in face recognition, 3D shape measurements, and proximity sensing. Therefore, they have potential for smartphones, autonomous driving (lidar), and industrial applications (see Fig. 2).

In the material processing market segment, Nogee saw a substantial saturation in 2018. In particular, macroapplications (that is, 1 kW+ power for cutting and welding) grew only 3.7% after an incredible leap of 48.6% in 2017.

The entire laser market is estimated (by Nogee) to be approximately $13.5 billion in 2018. This would be a 5.3% growth over the excellent results from 2017, and includes a moderate +4.8% for kilowatt materials processing lasers, as well as an excellent +28.9% for sensors.

For 2019, Nogee expects strong growth of 12% for photolithography lasers, another +4.2% in macro, and -2.4% in micromaterials processing. Nogee counts in the micro segment all lasers for material processing with <1 kW power, including excimer, but excludes marking lasers.

Medical lasers will also prosper: After approximately 14% growth in 2018, another 9% is expected for 2019. The segment with the strongest growth (almost 25.8%) will be sensors and instrumentation. For all these numbers, it should be noted that Nogee counts the numbers of lasers, but not systems such as those used in material processing.

A final version of the data will be published in a separate report titled *The Worldwide Market for Lasers: Review and Forecast, March 2019,* by Strategies Unlimited.

Trade, tariffs, and tumult: New challenges for lasers in China

BO GU, Ph.D., Bos Photonics

In 2018, the Chinese GDP grew to RMB 90 trillion ($13.45 trillion). In doing so, it overtook the Eurozone, which came in at $12.8 trillion. With 3X stronger growth, it will remain ahead for the foreseeable future. The U.S. economy grew to a GDP of $20.5 trillion or 24.2% of the world's GDP. With China's share at 15.8%, the two countries represent about 40% of the world economy. This is one more reason why it is so important that the two countries learn how to deal with each other.

The Chinese economic growth is slowing from 6.8% in Q1 to 6.4% in Q4 of 2018. In total, China's economy grew 6.6% in 2018, which is still within the range of 6% to 7% required for a soft landing. The reasons for the slowdown are plenty, as Gu said. One reason is a transition from a steel and concrete economy toward high-tech production. Another reason is a decreasing level of business confidence and tightening finances. Gu noted that, together with U.S. President Trump's unpredictable policies, this causes uncertainty and leads to fewer investments—people will need to just wait and see.

From another vantage point, the high-tech industry is still growing in China: 11.7% in total, with 40% growth in electric cars and 183% in high-speed trains. Most of these high-tech industries make use of lasers—for example, batteries and cars, smart TVs, ICs, lidar, and 5G wireless technology. 5G is predicted to add $5 trillion to the global market, which helps explains why the U.S. and China fight for this market.

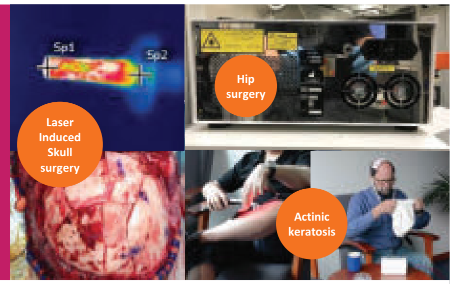
The Chinese market for lasers and laser systems has evolved positively in 2018. After the unique 2017 with almost 30% growth, Gu expects more than 20% for 2018 to RMB 60 billion ($9 billion) in revenue. Among the different types of laser sources, fiber lasers are still conquering more shares, from 51% in 2016 to 55% in 2017, and 60% in 2018. This goes mostly on

DISCOVERY & INNOVATION

- Optical pacing / Optogenetics
- Nerve stimulation / Ischemic stroke – accelerated FDA track
- Light activated drug release liposomes
- Example: Stanford pediatric cardiac project

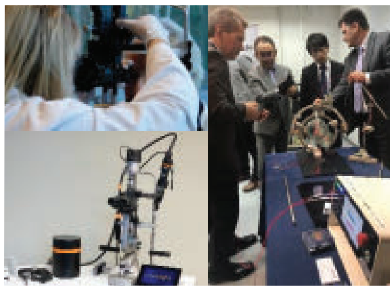
PROTOTYPING

- Novel opthalmictreatment
- MRSA / Hip surgery (UCL)
- Light activated skull pin fixation
- In-vivo illumination kits
- Actinic keratosis
- Surgical lasers
- Non-invasive glucose monitoring,



TESTING / CONCEPT VALIDATION

- Validate business idea / product / clinical trial / efficacy
- Product improvement
- Example: Uveal melanoma case Aura
- Data collection & analysis
- GDPR / HIPAA: Often yes

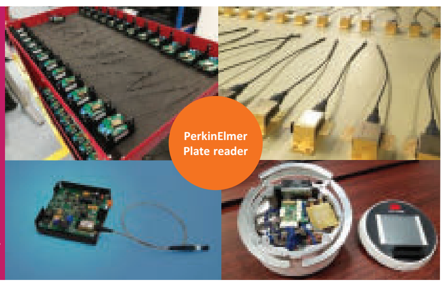


PRODUCTIZATION

- Design for manufacturing
- Example: Glioblastoma
- Data collection, Cloud monitoring of clinical trials, future sell-out monitoring, Efficacy improvement & analytics, pre-emptive maintenance
- Phase 3 simultaneously or after
- GDPR / HIPAA: Yes
- Modulight as production partner

PRODUCTION

- Small / medium (10s/100s / 1000s) + High volume partnerships
- Regulatory support / FDA visits / 3rd party customer audits support + Vigilance reporting
- Sell-out reporting & customer intimacy analytics
- Example: PerkinElmer plate reader
- GDPR / HIPAA: Yes



LIFE CYCLE MGMT

- Post market support
- Vigilance reporting
- Warranty & service
- Calibrations
- EXAMPLE: Visudyne/Photofrin/ PerkinElmer Envision
- Online / cloud materials and user support

modulight

Take a tour in Modulight cleanroom: youtu.be/XWzLpgnUFeo the expense of CO_2 lasers, which are expected to decline 7% in 2018 (see Fig. 3).

Additive manufacturing—or 3D printing, as Gu called it—is growing rapidly in China. In 2015, 2016, and 2017, the growth was more than 50% and reached $2 billion in 2017. The technology is widely employed and only cost issues prevent even more applications. The same holds for ultrafast laser technology.

One important question is the relation between imported and domestic systems, which becomes particularly interesting for fiber lasers.

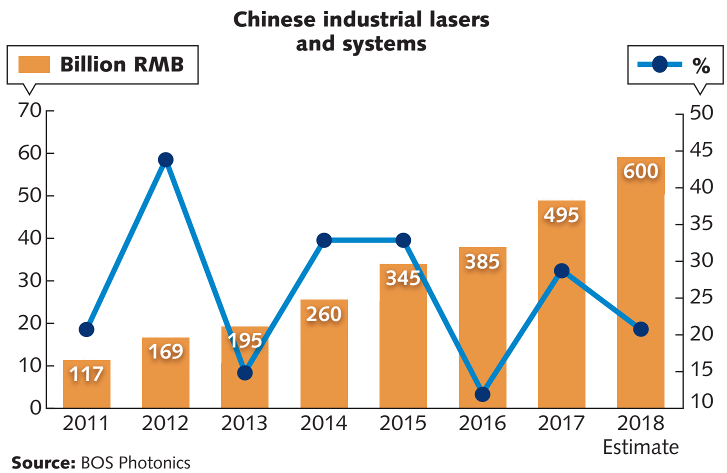


FIGURE 3. Given that China has the world's largest laser market, a 20% growth is still very good news. *(Courtesy of Bos Photonics)*

For low-power fiber lasers with <100 W, domestic laser manufacturers have taken over the market. For mid-power lasers of <1.5 kW, the share of domestic systems is at about 43% in 2017 and 2018. Only within the high-power segments of over 2 kW power do imported systems dominate the market with about 81% (estimate for 2018). But the number of domestic systems in this market has more than doubled every year within the last three years. A Chinese 10 kW prototype has been tested at the customer site, and a 20 kW system has been announced.

The picture is slightly different if we look at laser components. In 2017, components for about $2 billion have been imported and exports were at about $609 million. The imports grew much faster than the exports. In other words, foreign companies still dominate the market for core laser components.

Any forecast for the Chinese laser market strongly depends on relations between China and the U.S. Gu compared the two economies and had a look at the first consequences of their recent trade conflicts. While the trade dropped in 2016, it grew in 2017, and the trade deficit between both countries reached an all-time high of $375 billion. The most adverse effect became visible in the number of Chinese investments in the U.S.—from the first half of 2016 to the first half of 2018, it dropped more than 90%.

The actual issues to be solved between the two nations are plenty: Some are relatively easy to solve (such as protection of IP rights), while others are more difficult to deal with (for example, subsidies and state-owned enterprises). Although Gu listed eight major trade talk issues, he expressed his optimism that most of them will be solved.

His optimism is partly based on major strategic plans in China. One is "Made in China 2025," in which China details its steps from a low-value adding manufacturing house toward a high-tech nation. This initiative refers to 10 key areas such as next-generation IT, new energy automobiles, bioengineering, and medical devices, all of which require lasers. Current tariffs hinder the development in these fields. On the other hand, as Gu showed, about 75% of U.S. companies plan for investments in China. So, there is currently a lot of uncertainty, which hopefully will be diminished by a new trade agreement in March.

In his conclusion, Gu drew a mixed picture: After a good year in 2018, the Chinese laser industry may face headwinds in 2019, depending on Sino-American relations. Personally, he expects "that China very soon is going to sign the deal with the U.S. and then just outplay everybody else, including the European Union."

The laser business in China will grow substantially with applications such as welding, micro- and nanofabrication, cleaning, additive manufacturing, face recognition, displays, and more. For mature applications fields such as cutting and marking, the price erosion will continue.

Technology and Markets Panel: How advances in precision optics are driving new applications

MODERATOR **TOM HAUSKEN,** Ph.D., Senior Industry Advisor, OIDA/OSA

PANELISTS **TODD JAEGER,** Ph.D., Global Sales Director, Heraeus Quartz Commercial Optics

JANNICK ROLLAND, Ph.D., Brian J. Thompson Professor of Optical Engineering, University of Rochester

GROOT GREGORY, Technical Marketing Director, Optical Solutions Group, Synopsys

JESSICA DEGROOTE NELSON, Ph.D., Director of Technology & Strategy, Optimax Systems

Within this discussion, Tom Hausken guided the panelists through major questions of the promising technology of freeform optics (see Fig. 4). It started with the question, what are freeform optics (FO)? By definition, FO is an optical design that involves at least one freeform surface that has no translational or rotational symmetry about axes normal to the mean plane.

Freeform design has been around for a while in illumination systems and now it creates new opportunities in imaging optics. Eyewear for augmented and virtual reality greatly benefited from FO. One freeform element may replace several conventional (that is, rotationally symmetric) elements. The challenge is in the manufacturing and metrology of such surfaces.

Todd Jaeger emphasized that while FO may reduce the total number of optical elements, it challenges the maker of optical materials to come up with new materials for shorter or longer wavelengths, lower thermal expansion coefficients, etc. Closer partnerships with customers are what he sees as the path to success for the glass maker of the future.

A close partnership along the entire value chain is also something that Jessica Nelson wished for: "all the way from the materials to the end tubes and finding creative solutions that may not be something that exist today." This is the way the optics industry must go to speed up development processes.

This speedup will be required since new technological challenges such as EUV lithography or even nano- (or meta-) optics, as presented by Federico Capasso at SPIE Photonics West, demand

FIGURE 4. The Optics Panel (left to right: Moderator Tom Hausken, Todd Jaeger, Jannick Rolland, Groot Gregory, and Jessica DeGroote Nelson) started with a question probing the importance of freeform optics.

a new thinking from materials research, metrology, and optical design, to name a few of the involved partners.

Besides the technical trends, the panel also discussed one regional development: China. The technical trends are similar there. While the general quality of production processes is catching up and partially exceeding North American standards, wages are catching up as well. While the level of precision manufacturing is constantly growing, China is no longer considered extremely inexpensive.

Keynote Discussion: A conversation with Matthijs Glastra, CEO, Novanta

Sustainable growth is the task of every CEO, but it is a rare chance to have one of them talking about how to get there. Seminar Chair Conard Holton did exactly that with Matthijs Glastra, the CEO of Novanta (see Fig. 5). The company was formerly known as GSI Group—in 2016, the name was changed to better serve a strategic vision. Novanta is a medium-sized company with approximately 2000 employees and more than $600 million revenue in 2018. Adjusted revenues for the past five years have been growing at a compound annual growth rate of about 18%.

Behind these numbers, there is a remarkable success story, as Glastra shared in the conversation. Novanta now has a three-segment structure: Photonics (about 40%), vision (another 40%), and precision motion (about 20%). It is a technology provider that sells to many original equipment manufacturers in the medical and advanced industrial domains.

Seven years ago, more than 40% of the company's revenue came from cyclical semiconductor markets. Through a tough divestment and investment policy, this was reduced to approximately 10% today, and the company has developed a strong medical portfolio that makes more than half of the revenue. That was a long journey with difficult decisions: "We got out of businesses where we couldn't really lead, or they were not part of growth markets," Glastra says.

The vision was to move from cyclical markets to more sustainable businesses such as medical. One field that Novanta focused on was precision robotics—now, it provides the core motion of many surgical robots, with more than a million robotic surgery procedures executed every year.

As a medium-sized player that is active in very different fields of technology, Novanta must focus on individual technical innovations developed with their customers. "More than 90% of what we sell is not standard," Glastra says. The key is an elevated investment in R&D over the last six years. In some fields, it is 5%, while in other fields it is more

FIGURE 5. Seminar Chair Conard Holton (left) and Novanta CEO Matthijs Glastra (right) discussed sustainable growth and finding new markets during a discussion after lunch.

than 10% of revenue. This goes together with a well-balanced policy of organic growth and acquisitions. The organic growth over the last three years has been approximately 8%, as Glastra estimated, so the inorganic part was slightly larger.

Another recipe for their sustainable success might be a structure in which separate brands and different operating businesses such as Cambridge Technologies, Synrad, or Laser Quantum are retained with separate R&D and even general administration.

Financial perspectives on the photonics industry

Linda Smith, President, Ceres Technology Advisors, started the first of two presentations with an investor's view on the photonics business. She looked at the markets and their current behavior. In addition, she provided some insights on the valuation of photonics companies and recent merger and acquisition (M&A) activity (see Fig. 6).

From her perspective, photonics companies serve many vertical markets. In general, serving vertical markets means to provide several products or services along the value chain to some specialized customers. Such a tight relation between providers and customers in a small niche usually warrants higher profits. From biophotonics through defense to advanced manufacturing, this is mostly true for photonics companies.

But markets and business models are changing rapidly, as Smith showed in a number of examples. A radical transformation of consumer and end-user companies is currently happening through "a collision of industries." When Amazon moves from being a book retailer to a provider of IT services and consumer goods, she sees good growth opportunities for

FIGURE 6. Linda Smith described a rapidly changing world of end-users and markets that require new thinking by the photonics component and subsystem companies serving them.

photonics companies, too. Within the current societal transformation, traditional sectoral lines blur and industries converge. Smith discussed lidar and AR/VR as technologies that create value across such lines, and she showed how 15 corporate venture firms are investing in photonics. The top five investors (Intel Capital, Baidu Ventures, Google GV, Airbus Ventures, and Boeing HorizonX) have a variety of approaches.

As far as the valuation of photonics companies, Smith brought some good news: The last year saw a record number of M&As, probably up 20% from 2017. One highly interesting slide showed how the M&A Implied Enterprise Value (IEV) multiples depend on the companies' sector. For hard engineering businesses such as robotics or materials processing, you might only get a multiple factor of 1 or 2 on your revenue, but life science companies make an average of 28.53 (median 11.10) in a M&A process. IEV multiples outside biophotonics were between 1 and 6X annual revenues, on average.

The IEV multiples for EBITDA were much higher, but varying considerably. In general, she remarked, this evaluation on photonics companies is somewhat bipolar. While more traditional companies sell for a multiple of 5 to 9X, some more innovative companies may "enjoy much healthier evaluations."

The second presenter in this session was Mike Powell, Managing Director and Partner, Renevo Capital Limited. Both Linda Smith and Mike Powell spoke about their experience with current American legislation. The Committee on Foreign Investment in the United States (CFIUS) has of late greatly increased its importance. Even deals that do not involve American partners are currently submitted to CFIUS, just to avoid any potential issues.

The Foreign Investment Risk Review Modernization Act (FIRRMA), effective November 10, 2018, has expanded CFIUS jurisdiction to non-controlling foreign investment into U.S. businesses in possession of "critical technologies." It has the authority to block involvement by foreign buyers in critical technology markets on the basis of national security concerns. It was instrumental in blocking the Broadcom/Qualcomm transaction.

Mike Powell introduced the Chinese formalities for M&A activities. He went through two examples and explained Chinese formalities such as the outbound direct investment (ODI) review process. This involves the State-owned Asset Supervision and Administration (SASAC) approval, National Development and Reform Commission (NDRC) application, and the State Administration of Foreign Exchange (SAFE) and Ministry of Commerce (MOFCOM) declarations.

Powell still sees an appetite for M&A from Chinese companies. For 2018-2022, he expects increasing Chinese acquisitions in Europe, even if CFIUS or slow Chinese approval processes may delay some activities.

Lasers and flow cytometry

BILL TELFORD, Ph.D., National Cancer Institute, National Institutes of Health (NIH)

Flow cytometry was first patented in 1953, but it became an effective method for the analysis of large numbers of biological cells with the introduction of lasers. Simple flow cytometers shine the beam of a single laser onto a rapidly flowing jet of particles. By the fluorescence (or scattered) radiation, the machine can recognize certain spectral features and thus distinguish or even actively sort single cells.

As described by Bill Telford, a scientist at the Flow Cytometry Research Laboratory of the National Cancer Institute, from genetics to pathology, flow cytometry has proved to be an efficient technology throughout almost all fields of medicine and life sciences. With hundreds of different fluorescent markers available, one can label almost every protein in or on a cell. Detecting receptors, pumps, or nuclear proteins allows researchers to identify and trace every part of a cell.

Modern flow cytometers use several lasers and can track many labels simultaneously. Small systems with one or two lasers follow 2–4 fluorescent parameters for simple analytical tasks like cell viability. Clinical flow cytometers can analyze 4–10 fluorescent parameters, and research systems analyze up to 30 fluorescent parameters simultaneously.

Telford said that in the future, more wavelengths in the UV and IR are expected. New imaging techniques will be added to next-generation flow cytometers and full-spectrum analysis will become viable. Microfluidic-based cell sorters are now available, although they are still slower than their electrostatic ancestors.

Scaling quantum information systems—Photonics holds the keys

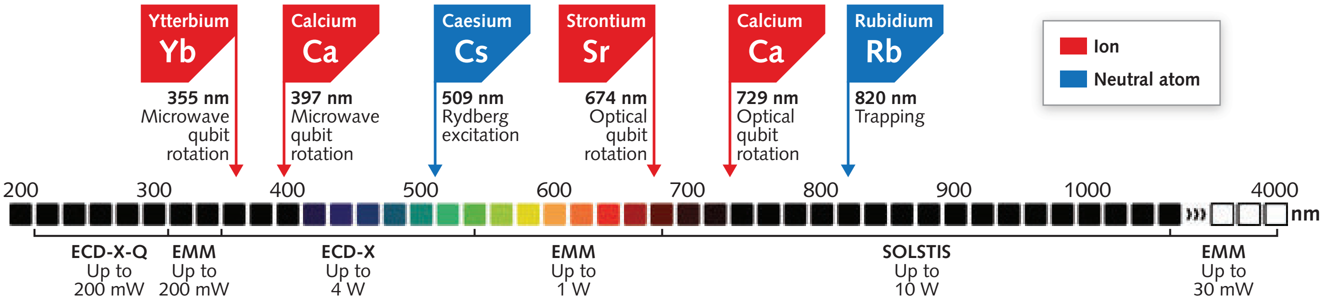
MODERATOR **JOHN DEXHEIMER,** President, LightWave Advisors

PANELISTS **TIM DAY,** Ph.D., Executive Chairman, ColdQuanta
CHRIS MONROE, Ph.D., CEO, IonQ
JAMIL ABO-SHAEER, Ph.D., CEO, Vector Atomic
GRAEME MALCOLM, Ph.D., CEO, M Squared Lasers

The commercialization of quantum technology is a much-discussed topic and panel moderator John Dexheimer took the current level of interest as his headline: "Quantum information has entered a land rush of global investments." Governments in China, Europe, and North America are devoting multi-billion-dollar programs to quantum technologies, and commercial investment is flowing as well. Leading venture and private equity funds as well as major corporations compete for rapid investments of considerable size.

Why? Dexheimer cited the Boston Consulting Group's 2018 report that estimates a quantum computing market of nearing $60 billion in 2035,

FIGURE 7. The Quantum Technologies Panel (left to right: Moderator John Dexheimer, Graeme Malcolm, Jamil Abo-Shaeer, Chris Monroe, and Tim Day) tried to answer questions such as the types of systems that vendors need from the photonics sector in terms of component specs/technologies.



which would grow further to $295 billion in 2050. So, there are plenty of opportunities for photonics companies to innovate and expand in this field. Therefore, Dexheimer presented his panelists with three major questions (see Fig. 7):

1. What do systems vendors need from the photonics sector in terms of component specs/technologies?
2. Are we at the stage where it is "just engineering," or is there still science to do?
3. Where do you see the applications in terms of volumes in three and seven years?

The first presenter, Tim Day from ColdQuanta, gave more details on recent investments and the plentiful potential applications and markets. With a short case study on quantum computer photonic subsystems, he also addressed the first of Dexheimer's questions.

Second panelist Chris Monroe was introduced as the de-facto speaker of the U.S. National Quantum Initiative and founder of IonQ, where he brought in investment from Google Ventures and Amazon. But he is also a hardware guy: He gave a short introduction of basic building blocks needed for quantum computing, such as miniature vacuum packages to store atoms, or lasers that are stable to nine or 10 digits of accuracy. For scaling up quantum technology, he sees a strong need for an engineering phase. That is one reason to start a company in which physicists, engineers, and software staff work together on quantum technology.

The third panelist was Jamil Abo-Shaeer from Vector Atomic. This one-year-old startup focuses on commercializing quantum technologies for navigation, telecommunications, and oil and mineral exploration. His role was to give an overview of opportunities and requirements for quantum sensors. These sensors are not only the most precise measurement devices on the planet, they also have the shortest time horizon to market. The technology for atomic clocks exists, and can be used to build inertial sensors, magnetometers, and field sensors that are all best-in-class.

But, as Shaeer said, "What industry needs to focus on is integration, operability in real-world environments, and reliability." And the photonics industry has to reduce prices for lasers if they want to compete with established sensor technology. The same holds for electronics.

The last panelist was Graeme Malcolm from M Squared Lasers, a 100-person photonic and quantum technologies company. Citing Bill Gates, he noted the limits of current technology: If the sheer volume of mankind's data grows steadily, we will run out of appropriate computing capacity.

Quantum computing may help, but that's challenging. For example, M Squared built a laser with extreme phase stability for qubits with 99.99% fidelity. Still, more qubits are needed and so are more laser systems (see Fig. 8). Based on market research from Tractica, Malcolm expects the market for lasers in quantum systems to go beyond $1 billion within the next five years.

Not unexpectedly, this panel commanded a lot of attention and discussion from a full audience, which is quite unusual for the last event of the day. The discussion went from expectations of laser features to the need for new thinking about quantum computing. It won't be perfect for all problems, but it may open up entirely different solutions. One important point was made before the cocktail hour: Further standardization of laser technology will be a key issue for the development of very small, inexpensive lasers for quantum computing.

FIGURE 8. Current quantum experiments are either based on ions (red) or neutral atoms (blue) and highly stabilized lasers to manipulate the quantum system. *(Courtesy of M Squared Lasers)*