Figure 1. Plenary speaker Shuji Nakamura described important research toward making solid-state lighting more efficient.

REPORT FROM CLEO/QELS 2005

Expanding the Horizons of Photonics Science and Technology

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The 2005 Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science (CLEO/QELS) and the Photonic Applications Systems and Technologies conference (*PhAST*) showcased more than 1,600 talks on the latest breakthroughs in optical research and applications. These meetings highlighted incremental and significant advances in LEDs, quantum-cascade and fiber lasers, photonic crystal devices, medical imaging, slow-light research and work towards integrated optical circuits.

Solid-state lighting

Shuji Nakamura's plenary talk, titled "Future Prospects for Solid-State Lighting," excited considerable comment among conference participants. Nakamura, a professor in the materials department at the University of California at Santa Barbara, made pioneering contributions to the LED industry, including introducing high-intensity blue GaN LEDs in 1993 while at Nichia.

According to session organizer Hong Choi at Kopin, "With the power efficiency of white LEDs reaching 100 lumen per watt, which is higher than that of fluorescent lamps, the use of LEDs for general lighting is getting closer to reality."

Nakamura described his recent work on the growth of GaN materials on non-polar substrates (Fig. 1). Unlike the c-plane sapphire substrates typically used in industry, non-polar substrates reduce the internal electric field in the GaN, which increases the efficiency of light generation. Nakamura accomplished the difficult task of growing quality GaN on non-polar substrates. He presented the surprising result that the LED light emanating from the film was partially polarized, thereby increasing the intensity along one direction up to 40 percent.

"Nakamura gave an outstanding talk at the plenary session," said Jeff Tsao of Sandia National Laboratories, who also gave a talk on solid-state lighting. Tsao described two drivers for new lighting technologies: reduced cost for lighting and increased control over the space, time, intensity and color temperature of lighting.

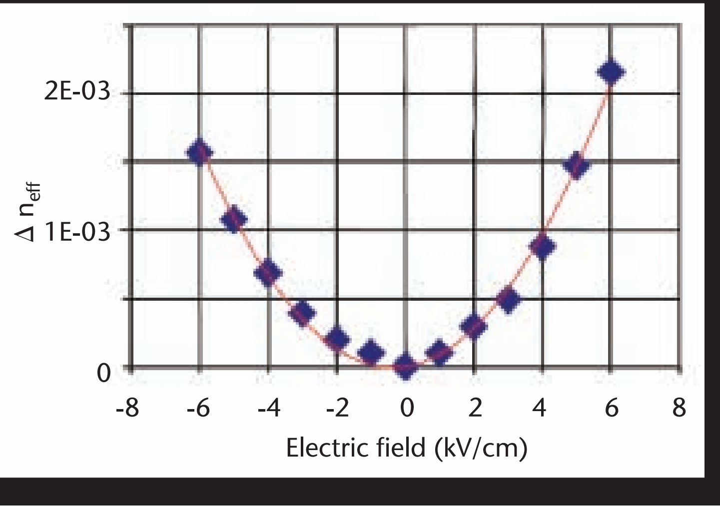

Figure 2. A large change in the effective refractive index of a vanadium-doped CdZeTe crystal results with different applied electric fields and a steady light intensity of 730 mW/cm^2. [Postdeadline paper CPDA4, Figure 1e.]

"The more we learn about the abilities of solid-state lighting, the more we get excited about it," said Fred Schubert, presider of a session on new materials for OLEDs and LEDs. "We recognize the smartness of the technology."

Another notable paper from that session described the use of photonic crystals to increase the efficiency of GaN LEDs. The work, done by Kent Choquette's group at the University of Illinois, showed a 30 percent increase in external quantum efficiency, although there are still questions about whether the photonic crystal improves the emission process within the material or enhances outcoupling.

Stressing crystals, cutting nerves

As usual, the three postdeadline paper sessions carried surprising reports. In particular, Mordechai Segev's group at Technion and elsewhere presented results on a nonlinear crystal with remarkable properties: Under illumination, the vanadium-doped CdZeTe crystals show a huge nonlinear index change—more than 0.008—which is larger than any other nonlinear index change measured in bulk semiconductors.

"The obtained index change is so remarkable that it cannot be explained in the framework of conventional mechanisms for electro-optic effect," the group reported. "The only way to explain such results is by postulating that the electro-optic coefficients themselves increase with light intensity." This implies that, in this crystal, light at relatively moderate intensities (about 1 W/cm^2) modifies the physical crystalline lattice.

The group presented experimental data showing that, after applying an electric field of 6 kV/cm and a light intensity

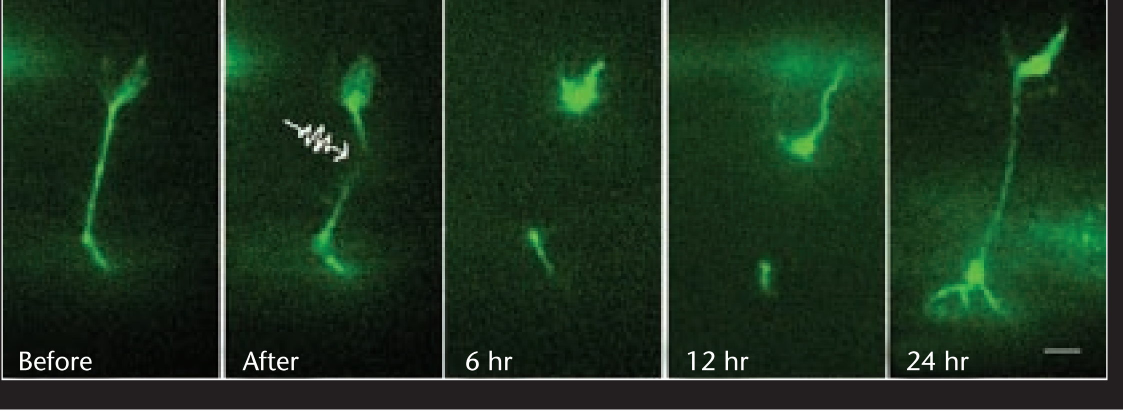

Figure 3. Femtosecond laser pulses sever nerves, but the nerves regenerate. [Postdeadline paper CPDA8, Figure 2.]

of 0.65 W/cm^2, they did indeed see the crystal show a huge strain (up to 0.15 percent) [Fig. 2].

The researchers suggest that the laser light breaks the cubic symmetry of the crystal, and therefore that all the quadratic nonlinearities will display a very large enhancement induced by light. If this proves true, and the crystal is otherwise suitable for industrial use, it could be useful for many nonlinear applications. For example, it could be used in frequency converters, THz generators, beam deflecters, optical limiters and all-optical interconnects, routers or switches.

Another postdeadline paper focuses on a very different area: using the femtosecond laser as a research tool for work on nerve regeneration. The researchers used the laser pulses to cut a few axons (the connections between neurons) in a living worm—which stopped it from being capable of moving backwards. Within 24 hours, however, about half the nerves repaired themselves and the worm regained the capacity to move backwards.

Biologists were at first unsure of what the laser pulse was actually doing, explains researcher Adela Ben-Yakar at the University of Texas at Austin. "Were we really cutting or just photobleaching?" By using near-infrared femtosecond pulses, she explained, you can use very small energies to ablate without substantial heating. "All the energy you put in the region ablates material at the focal point," said Ben-Yakar, allowing researchers to cut with much finer precision than a scalpel or other laser and do very little harm to the surrounding area.

"Dr. Ben-Yakar had to fight the skepticism of biologists regarding her achievements," said session presider Dan Botez. "After many experiments, she succeeded: It's clear now that nerves regenerate upon nano-surgery."

"People thought there might be nerve regeneration in *C. elegans*," added Ben-Yakar, but they couldn't demonstrate it because there were no techniques that could cut the nerves precisely in such a tiny organism with so little damage to the surrounding areas. The group's work allowed them to image the cuts (Fig. 3) as well as to observe the changes in the organism's functioning and behavior.

Next, Ben-Yakar wants to understand the laser's effect on regrowth, the mechanism and the reason why only some of the axons regrow. The group is also investigating the nerve regeneration process using two-photon imaging.

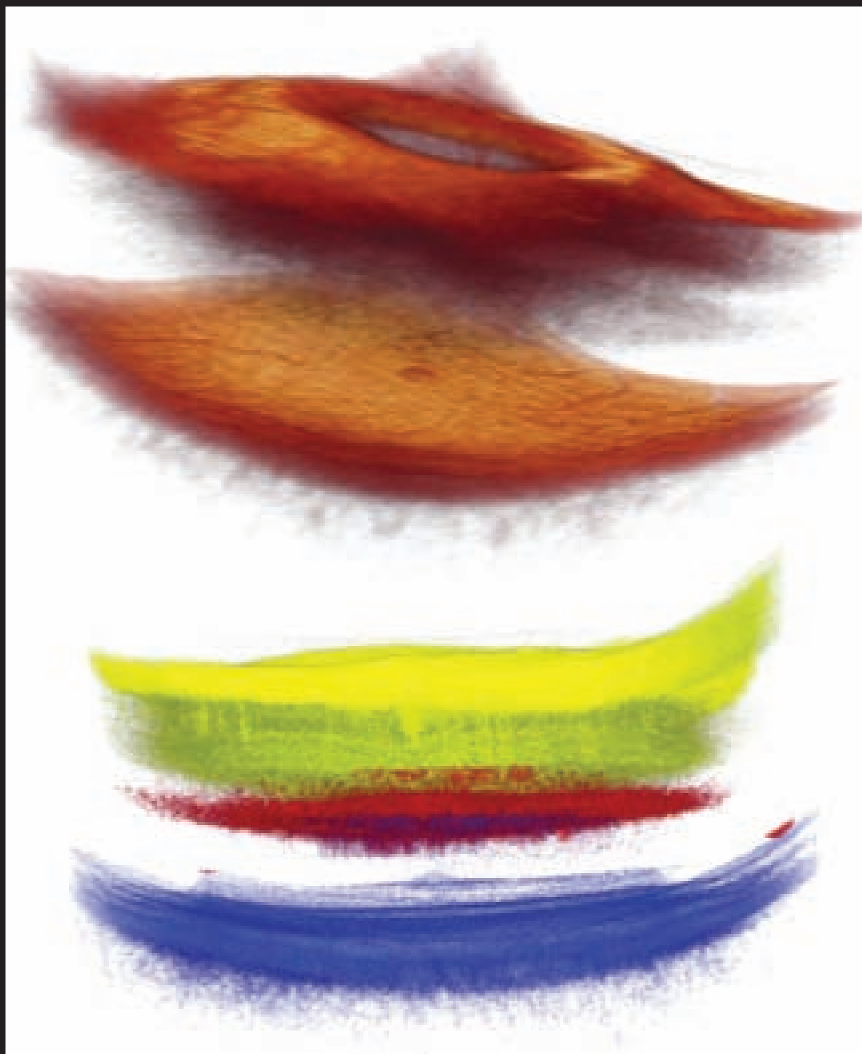

Figure 4. Fast optical coherence tomography provides three-dimensional data of tissue, allowing users to render an image of a normal human macula (*top*), or render segmented layers in the same subject (*bottom*). [Fujimoto Group, MIT.]

Medical imaging

A different sort of imaging was the subject of a lively session on optical coherence tomography (OCT). This imaging technique enables non-invasive micron-scale cross-sectional imaging of tissue microstructure *in situ* and in real time (sometimes called an "optical biopsy"). Session chair Guillermo Tearney of Massachusetts General Hospital said the session provided "a good cross-section of different areas where OCT is expanding and topics where OCT is becoming more advanced." Three papers focused on optical contrast agents, including two describing the use of nanosized particles.

Another talk, by James Fujimoto's group at the Massachusetts Institute of Technology (MIT), described high-speed, high-resolution retinal imaging using Fourier domain detection methods. The

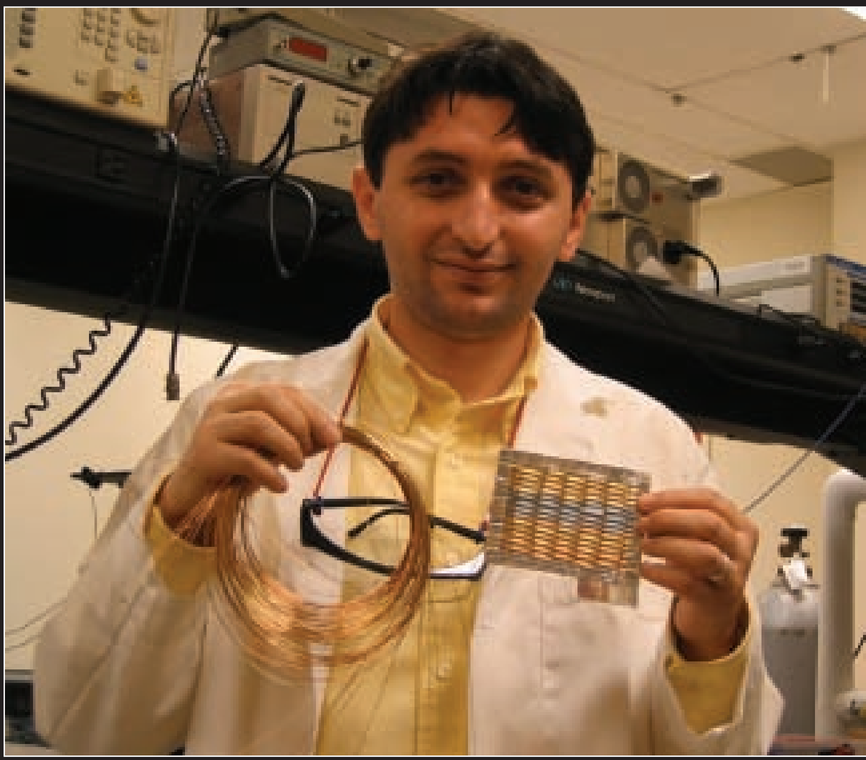

Figure 5. MIT postdoctoral student Mehmet Bayindir holds a woven spectrophotometer: Each fiber in the fabric is a functional photodetector, sensitive to a particular wavelength range along its entire length. [MIT.]

group reported a method that reduces axial resolutions to 2 μm in the lab and 3 μm in a clinical instrument, as well as providing very fast imaging—24,000 axial scans per second (Fig. 4). (By comparison, commercial ophthalmic OCT imaging systems have axial resolutions of 10-15 μm.) The higher resolutions can provide earlier detection of disease as well as perhaps leading to a better understanding of disease pathogenesis.

Xingde Li's group at the University of Washington described a different method to reduce the resolution to 2 to 3 μm. Typical OCT images put priority on the depth of the scans, but this typically results in slow scans without good transverse resolution. Instead of taking that approach, the Washington group performed real-time OCT imaging using a lateral-priority system that allowed them to maintain the transverse resolution throughout the entire imaging depth, and increase the speed with which images can be obtained.

As with other time-domain OCT systems, lateral-priority OCT imaging requires a Doppler frequency shift, which can be achieved using a pair of acousto-optic modulators. The group reported a method to optimize the optical spectral throughput for a pair of AOMs, resulting in the high-resolution scans.

A third group is focusing on another unusual method: common-path OCT. The common-path system, based on the design of a fiber Fizeau interferometer, is intended to eliminate some difficulties with the two-armed Michelson interferometer on which conventional OCT systems are based. This design has the potential to provide ultrahigh resolution, high speed and high sensitivity in a system that can be integrated into current endoscopes more easily than conventional OCT, explained Utkarsh Sharma at Johns Hopkins.

Slowing light

In a postdeadline paper, Phedon Palinginis at the University of California, Berkeley, described a quantum-well semiconductor structure that slows group-propagation velocities to less than 200 m/s. The delay can be controlled by varying the intensity of the control laser.

Slowed light could potentially be very useful as a data buffer for optical communication and computing systems. Another application is to store one photon (or a few) in order to make performing nonlinear operations on it (or them) easier. Light has been slowed in atomic vapor and solid-state materials in the laboratory, but the research is a long way from being translated into applications.

"All-optical switching would require storing hundreds of bits of information," said Jacob Khurgin of Johns Hopkins, the presider for the QELS session on electromagnetically induced transparency and slow-light. "But none of the talks at the conference reported even a single bit of storage—the research is still far from practical."

Robert Boyd at the University of Rochester presented a talk on the theoretical limits on how large a time-delay can be achieved. He concluded that there were no inherent limitations. For example, the potential limit to the time delay that is related to group velocity dispersion and spectral reshaping of the pulse can be negated if the transparency window is much wider than the pulse spectrum. Absorption effects could also impose limits, but those could be eliminated by using electromagnetically induced transparency (EIT) and related effects.

"EIT is the effect of reduced absorption in the vicinity of a strong atomic resonance in the presence of strong pump light," said Khurgin. The weak signal light close to the resonant frequency gets coupled in and out of the atom many times and thus gets delayed." A postdeadline paper from J.J. Longdell and others at National University (Australia) described using this effect in a crystal to stop, and store, light for more than a second.

Shorter accelerators

Two well-attended joint sessions focused on using lasers to accelerate electron beams. "Laser-driven acceleration is dear to the hearts of many advanced particle accelerator physicists and engineers," said presider Antonio C. Ting of the Naval Research Laboratory, because it offers the promise of accelerating high-energy electron beams over much shorter acceleration distances than conventional radio frequency acceleration. The idea is that electrons would be accelerated by the electric fields in waves of plasma, which are pushed along by pulses from powerful short-pulsed lasers. These sessions provided experimental verification that lasers can be used to accelerate particles.

Three groups from Lawrence Berkeley National Lab in the United States, the Blackett Lab in the United Kingdom and LOA (Laboratoire d'Optique Atmosphérique) in France reported their independent yet similar discovery that mono-energetic electron beams have been generated using the Laser Wakefield Acceleration technique. These results are all obtained with similar laser systems (multi-ten terawatt Ti:sapphire femtosecond lasers) and plasma conditions. "It is a breakthrough in this field because it demonstrated the possibility of generating usable high-energy electron beams with well-defined energies," said Ting.

Ting's group also reported staging a laser injection-laser acceleration experiment. In a proof-of-principle experiment, electrons created in one gas jet were injected and accelerated to 20 MeV in the plasma wakefield of a second gas jet. Injection and staging are the two most important aspects of a working laser-driven accelerator. This experiment demonstrated the possibility of synchronizing not only the laser pulses but also the slippage between the electron beam and the laser.

New and notable

One presentation that inspired many questions during CLEO was a novel fibers session based on work done by Yoel Fink's group at MIT. The group has been creating novel fibers that, in addition to conducting light, contain strands of materials that are electrically conducting, insulating and semiconducting. They announced at the meeting that they had created two functional optoelectronic devices: fiber photodetectors and dual electron-photon transport fibers (Fig. 5).

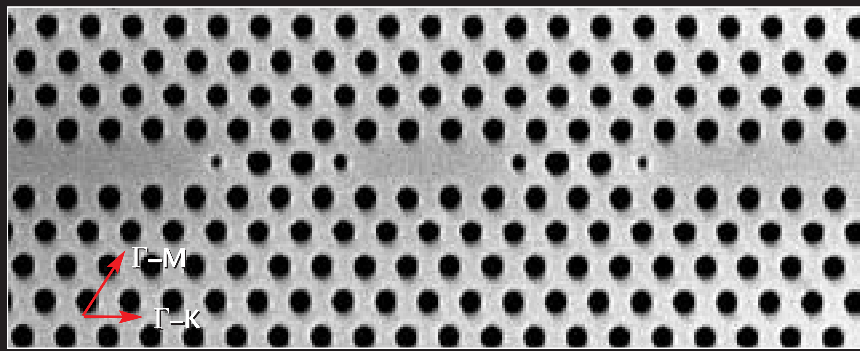

Figure 6. Three-point defect in a silicon photonic crystal forms a microcavity that catches resonant light. [Postdeadline paper QPDA5, Figure 1b.]

Also notable were two papers from Marty Fejer's group at Stanford University on a mid-infrared laser based on a quasi-phasematched GaAs and optical parametric down-conversion. Paulina Kuo's talk described an optical parametric generator that provides conversion efficiency greater than 10 percent, while Ofer Levi described a device that used difference frequency generation, also in GaAs, to offer longer infrared wavelengths.

All-optical switching with silicon

Michal Lipson's group at Cornell described an experimental device that allowed fast all-optical switching. Not only could the transmission be modulated by 94 percent in under 500 ps by a low-power beam, but the device was made out of silicon.

All-optical switches and modulators have been demonstrated with III-V compound materials, but making these devices in silicon is harder because the refractive index and absorption coefficients depend only weakly on the free-carrier concentration. Instead of increasing the control beam's power or the size of the device, Lipson's group made it more sensitive to small changes in the refractive index.

When the switch is blocking, the signal beam (the beam to be switched) is confined within a resonant ring cavity. When the control beam changes the refractive index slightly (through two-photon absorption, which creates charge carriers in the material), the ring is no longer resonant at the signal beam's wavelength, and the signal beam escapes the resonator into a nearby waveguide.

In theory, the device can switch within only a few tens of picoseconds. In order to speed up the device, the researchers embedded a P-I-N junction on top of the ring resonator to extract charge carriers quickly. The improved device works as a 10-GHz modulator.

In a postdeadline paper, Takasumi Tanabe and others at NTT reported a different approach that uses many of the same phenomena. This group also reported creating fast all-optical switches on silicon, but instead of confining light in a ring resonator, they used a photonic crystal microcavity. In a regular array of airholes drilled into the silicon, the places missing the holes provided the microcavities (Fig. 6). Tanabe's group measured optical switching in about 100 ps, with a 10-fJ switching beam energy.

The papers on LEDs and medical research, slowing the speed of light and speeding up electrons with light, and, of course, the reports of new nonlinear crystals, optoelectronic devices and lasers are just a small part of the many advances reported at CLEO/QELS this year. (For much more information, see the online program at www.cleoconference.org/about_cleo/2005.aspx or the proceedings.) Next year, CLEO/QELS will be held May 21 to 26 in Long Beach, Calif.

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