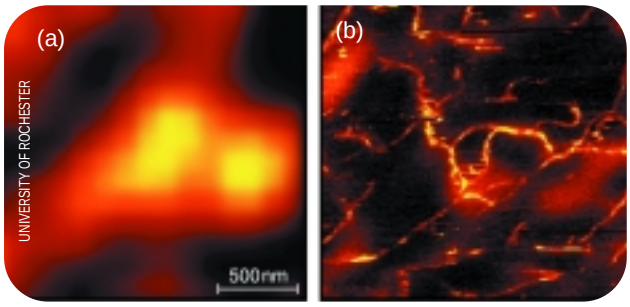
microscopy

near-field Raman microscopy images nanostructures

Constrained by fundamental limitations, light-imaging techniques have taken a backseat to scanning probe, optical tweezer, and electron microscope techniques for nanotechnology exploration—until now. In collaboration with Portland State University (Portland, OR) and Harvard University (Cambridge, MA), researchers at the University of Rochester (Rochester, NY) used a sharp silver tip as a probe to perform near-field Raman spectroscopy and imaging of single-walled carbon nanotubes (SWNTs) with 25-nm spatial resolution (see figure). Electrons at the probe tip are excited and interact with the vibrational atoms of the sample to produce a spectrum identifying the chemical composition of the material. "The method produces images with detailed chemical information of nanometer-sized objects," says Lukas Novotny of the research group.

The group produced the 10- to 15-nm radius silver tip by electrochemical etching and focused-ion-beam milling. Based on an inverted optical microscope, the optical setup consists of a 30- to 100-mW, 633-nm laser beam reflected by a dichroic beam splitter and focused by a 1.4 numerical aperture objective onto a transparent sample containing isolated SWNTs. The silver tip is positioned near the focus of the beam and about a nanometer away from the sample surface. Using a spectrograph and a thermoelectrically cooled CCD detector, or a narrow bandpass filter,



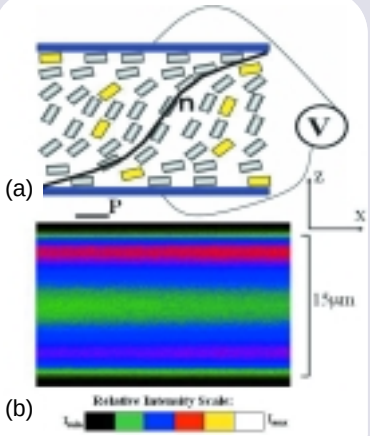
Images of carbon nanotubes on a glass substrate compare conventional microscope image (a) with near-field Raman technique (b).

instrumentation

liquid-crystal imaging goes 3-D

Typically, the molecular orientation of liquid crystals (LCs) is spatially complex and sensitive to external fields and molecular interactions. This sensitivity makes LCs ideally suited for applications such as sensors and low-power displays. However, until recently, indirect probing techniques could only obtain 2-D images of the average direction of molecular orientation (director field) in 3-D samples. Using a fluorescence confocal polarizing microscopy (FCPM) technique, researchers at Kent State University (Kent, OH) recently imaged edge dislocations in cholesteric LCs.

In order to make the instrument sensitive to orientational rather than concentration features in the test sample, the researchers supplemented the traditional fluorescence confocal microscopy method by probing the sample with linearly polarized light and by using a fluorescent dye composed of anisometric molecules that align in the LC host, preferably along the director field.



A vertical cross-section shows an LC cell undergoing the Frederiks transition under an applied electric field: the director field (*n*) describing the average orientation of LC molecules (a) and the FCPM texture visualizing this director field (b).

Determined by the angle between the transition dipole of the dye and the polarization of the probe beam, the measured fluorescence intensity pattern describes the director field's spatial configuration as the dye aligns to the LC. "A typical LC can be scanned up to the depth of 10 to 30 μm with a resolution of 1 μm or so," says Ivan Smalyukh of the research group.

The group is currently using the technique to probe director patterns in multi-component heterogeneous systems such as LC colloids, and plans on improving the image acquisition speed. The technique can be applied to a variety of orientationally ordered systems, and future applications will include high-tensile strength polymers, membranes, and colloids. —*Phillip Espinasse*

followed by a single-photon counting avalanche photodiode, the group raster-scanned the sample to record the Raman-scattered light and produce a near-field Raman image. "Instead of using a tip to locally scatter optical fields, our method uses the tips as nanolenses to concentrate the fields at the tip apex," says Novotny.

The group expects to boost the sensitivity of the technique by introducing clever tip geometries and materials. The end goal is to apply this technique to the identification of membrane proteins and other complex molecules of biological interest.

—Phillip Espinasse

medical imaging

fast fluorescence imaging achieves 100-nm resolution in 3-D

Fluorescence-based far-field microscopy has evolved into a powerful tool for studying structure and function at the cellular level. Researchers from the High Resolution Optical Microscopy Group at the Max Planck Institute for Biophysical Chemistry (Göttingen, Germany) are pushing the limits of the technology by producing 3-D images of living cells with both 100-nm axial resolution and greatly increased data-acquisition speeds.

The group has used the system to measure thickness and volume of living cells and to differentiate cell types. There is a lot still unknown about cellular metabolic states according to team member Stefan Jakobs. "This development was primarily about verification of the advanced microscope and imaging technique. The next steps will focus more on detailed biology and metabolic understanding," he says.

The instrument is a beam-scanning multifocal, multiphoton, confocal microscope that deflects an array of excitation foci across the specimen and images the resulting fluorescence on a CCD camera. This highly parallel scheme reduces the total imaging time to seconds without compromising the high resolving power. High-resolution and fast-data acquisition have been difficult to combine previously, but this work represents a 10- to 15-fold increase in detection speed and a three to fivefold finer optical sectioning capability. Nonlinear image restoration is applied to achieve the resulting 3-D imaging of the live cells at an equilateral resolution

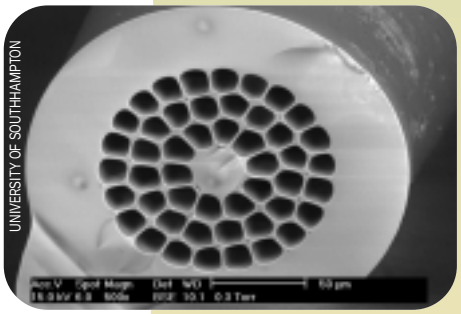
medical imaging *continued on page 8*

lasers

increased power puts fiber lasers on par with solid state

By doping fibers with neodymium (Nd), ytterbium (Yb), and other rare-earth materials, engineers can create extremely long-lasing cavities with very controlled optical properties for a wide variety of applications, including telecom, lighting, and laser marking. Although fiber lasers have not been known for their brightness, due in part to nonlinear effects created by the high length-to-width ratio of the lasing cavity, new fiber designs have boosted the output of these devices to a level that challenges that of traditional solid-state lasers for a fraction of the cost.

"Power scaling hasn't been a big part of fiber-laser research in the past," says Greg Quarles, director of research and development for VLOC Inc. (New Port Richey, FL) and technical program committee member for the Advanced Solid-State Photonics Topical Meeting (San Antonio, TX). "In the past, 50- to 100-W fiber lasers were out there, but there hadn't been a lot of reports about people who were starting to encroach on the half-kilowatt regime—and then boom, this paper comes out. The output power is very good, and there don't seem to be any real major restrictions."



A JAC fiber has a 10-μm core centered within a 28-μm Yb-ion-doped cladding layer, which is in turn surrounded by three layers of "holey" silica and then a silica outer shielding.

Researchers at the Institute of Applied Physics (Jena, Germany) demonstrated an ultra-high-brightness, continuous-wave (CW) fiber laser capable of delivering 500 W of output power from a single fiber co-doped with neodymium oxide and ytterbirum oxide, an achievement Quarles attributes to engineering and fiber core issues. Fiber-laser output has been limited in the past by inelastic processes such as stimulated Raman scattering in the forward direction and stimulated Brillouin scattering (SBS) in the reverse direction. Because of the high density of the optical pump power in the relatively small-diameter core (on the order of 10 μm) plus the long interaction length of the cavity (from meters to tens of meters), scattering leads to nonlinear interactions that limit

lasers *continued on page 8*

lasers *continued from page 7*

CW output power.

To reduce these effects, the Jena group chose a large-mode-aperture (LMA) fiber with a 30-µm core and 0.06 numerical aperture. The LMA core disperses the pump power over an area roughly nine times the size of a normal fiber. When combined with three multiplexed pump lasers (350 W at 976 nm, 175 W at 940 nm, and 175 W at 808 nm), the fiber produced 485 W of near-diffraction-limited output from 700 W of pump power for a conversion slope efficiency of 72%.

In a subsequent experiment, the group achieved 100 W of CW, narrow-linewidth, single-frequency output from a master-oscillator fiber power amplifier at 976 nm. Higher output powers were limited by SBS interactions that increased substantially at 108 W, although researchers estimate that the power could be boosted in excess of 200 W—far beyond the current record of 135 W from a 60-m Yb-doped fiber if the fiber length were reduced from 9.4 m to 5 m to limit SBS scattering.

In separate work from the University of Southampton's Optoelectronics Research Centre and Southampton Photonics (Southampton, UK), researchers used a jacketed-air-clad (JAC) fiber to generate 3.5-W CW single-mode output at 977 nm with a 0.2-nm linewidth, which is about 2.5 W more than the maximum output of single-mode diode lasers used today to pump Yb-amplifiers for telecom.

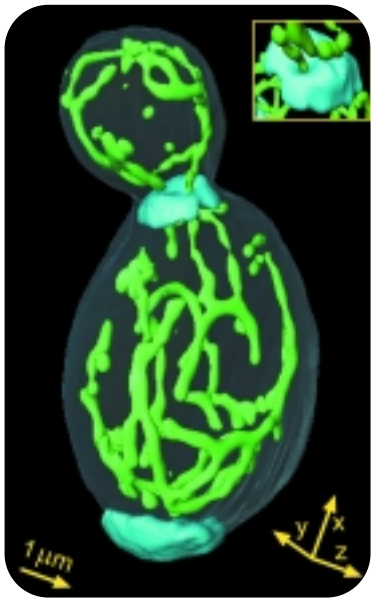
The Jena group used a neodymiu,-doped yttrium alumunim garnet nonplanar ring oscillator to create the narrow linewidth signal and then amplified that signal using an array of multimode 250-W diode-pump lasers on the double-clad Yb-doped LMA fiber, while the Southampton group's setup uses only 18 W of diode-pump power on a special JAC fiber. The JAC fiber is essentially a double-clad fiber with a 10-µm core centered in a 28-µm Yb-doped cladding (the pump layer), surrounded by layers of silica holes in the fiber (air cladding). A solid silica shell encapsulates the entire fiber (see figure on page 7). This structure helps to limit re-absorption of the 980-nm light by the Yb ions, which can lead to undesirable emissions around 1030 nm.

Like that of the Jena group, the extremely narrow linewidth of the Southampton fiber laser lends itself to frequency doubling in periodically poled materials for applications involving high-brightness blue lasers.

"What made people really take notice of these findings was that these sources are getting to a level where they can compete with solid-state lasers, which are significantly more expensive. So, you're looking at lower-cost, high-brightness alternatives," Quarles says.

—Winn Hardin

medical imaging *continued from page 7*



In the multifocal, multiphoton, 4Pi-confocal microscope, an array of 64 counterpropagating excitation foci are scanned through the living cell, and the induced fluorescence is simultaneously scanned across a CCD camera. Image processing is used to construct the 3-D image.

of 100 nm. The group used the microscope to assess the 3-D structure of mitochondrial compartments in the interior of yeast cells.

In the system, a mode-locked titanium-doped sapphire laser emitting at 800 nm or 890 nm is directed into an array of microlenses. The resulting array of beamlets is focused onto a pinhole array for spatial filtering. The scan mirror directs the array into the microscope head, where the beams are split and routed to the two microscope objectives. The objectives produce an array of counter-propagating excitation foci inside the specimen, which generates an array of fluorescence beamlets at 510 nm that are imaged back onto the spatial filter array. A dichroic filter spectrally separates the excitation and fluorescence wavelengths and sends the image information to the CCD camera. The rotating galvo mirror provides both the x-direction scanning across the specimen and the scanning image on the CCD camera. This dual-purpose galvo design locks the scanning of the excitation foci with the fluorescence foci. The y-direction scanning is

medical imaging *continued on page 11*

optical communications

innovative monolithic optical gate demultiplexes at 320 Gb/s

Ultrafast optical gates are key to high-bit-rate optical communications networks, but they have to be compact, offer stable operation, and feature a large bandwidth if they are to be practical. Currently, these requirements can be met only with electro-optic gates, despite the fact that the operating speeds of these gates can be adversely affected both by driver amplifier bandwidth and the electrical connections. Now Satoshi Kodama and a research team at NTT Photonics Laboratories (Atsugi, Japan) have developed an experimental monolithic optical gate that demultiplexes at data rates of up to 320 Gb/s.

The new gate consists of a unitraveling-carrier photodiode (UTC-PD) and a traveling-wave electro-absorption modulator (TW-EAM). The photodiode output signal directly drives the modulator without intervening electrical amplifiers; in other words, it is a monolithic photodiode-EAM (PD-EAM). "We successfully demonstrated that the PD-EAM has a very short gate opening of 2.3 ps," Kodama says. "We achieved a 160-Gb/s error-free demux operation and an optical RZ pulse gating corresponding to a 320-Gb/s data rate."

Specifically, the 1 mm × 0.4 mm monolithic PD-EAM has a back-illuminated indium phosphide/gallium arsenide UTC-PD, a TW-EAM with multiple quantum wells of indium aluminum gallium arsenide/indium aluminum arsenide, two bias capacitors, and a terminal resistor (R_γ); total junction area is 50 μm^2. A thin-film microstrip line (MSL) connects the PD anode to the signal line anode of the TW-EAM so that any optical input (photocurrent) generates a positive signal to the EAM, which becomes a transmission-type optical gate. The TW-EAM is also connected to the R_γ by an MSL.

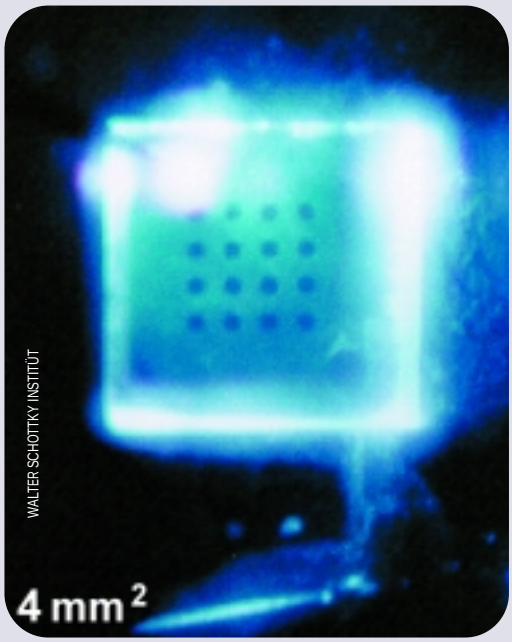
"Characteristically, the impedances of the EAM and TW-EAM are about 15 Ω," says Kodama, "so we set the impedance of the R_γ to match and eliminate electric signal reflections. In addition, we made the EAM ridge waveguide with a 200-μm active part and two 100-μm passive parts on either side of the active one."

The team improved the growth sequence of the TW-EAM, raising its static extinction ratio from 29 dB to 35 dB. They also set the UTC-PD absorber thickness at 80 nm for fast response.

"To test our PD-EAM optical gate, we set up a demultiplexer consisting of our optical gate, two erbium-doped fiber amplifiers, and a variable optical delay line," Kodama says. "We used a 1550-nm optical pulse stream from an actively mode-locked fiber laser as data and clock signals."

The team multiplexed an optical 10-Gb/s pseudo-random bit sequence with a pattern length of 2^7-1 into a 320-Gb/s data stream. "We also provided the same initial pulse stream to the PD-EAM from the laser as a 10 GHz clock signal," Kodama says. "Then we cross-correlated the optical input with the demultiplexed output signal waveforms to measure them."

The team achieved error-free 320-Gb/s demultiplexing at a receiver sensitivity of –18 dB and a bit error rate of 10^{-9}. "NTT Laboratories' results sound interesting," says Rainer



optoelectronics

AlN/diamond heterojunction shines the light

A 2 × 2 mm^2 aluminum nitride/diamond *p-n* heterojunction emits blue and UV light peaking at 442 nm (2.7 eV) under forward bias. Researchers at the Walter Schottky Institüt (Garching, Germany) fabricated the device by epitaxially growing aluminum nitride films on a (100) boron-doped (*p*-type) diamond substrate.

Hainberger of Photonic Systems Laboratory within Fujitsu Laboratories (Kawasaki, Japan). "However, the extinction ratio of adjacent channels of 14 dB might need further improvement. As for potential applications—apart from demultiplexing—this device might be a potential candidate for all-optical regeneration in ultra-high-speed systems [greater than 60 Gb/s]."

Kodama agrees. "Our PD-EAM optical gate shows excellent potential for use in future high-bit-rate optical communications systems," he says. *—Charles Whipple*

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medical imaging *continued from page 8*

accomplished by moving the microlens and pinhole arrays. Moving the specimen axially provides the z-direction scanning to complete the 3-D image.

The current setup produces an 8×8 array of beamlets and provides a 32 μm × 32 μm field. The number of foci in the scan field depends on the available laser power and is a primary factor in the speed of the instrument. The current average powers of 1.2 mW per spot correlate to peak intensities of about 80 GW/cm^2. This power per spot is sufficient for good imaging, although increasing the laser power would allow an increase in the number of foci and thus the parallelization and instrument speed. Damage to the specimens was not seen at these power levels. The group demonstrated that the foci could be brought as close as 2.8 μm without crosstalk-induced resolution degradation.

Equipped with the omni-directional resolution of 100 to 140 nm, the group studied the 3-D morphology of living mitochondria, which are known to be dynamic structures undergoing fusion and fission (see figure on page 8). The measurements on volumes and surfaces revealed information about protein biosynthesis and proved that the technique will be key in future studies. Further refinements will focus on raising the number of foci to 100 or above, and improved CCD detectors could enhance sensitivity by a factor of five, so the team anticipates a 20-fold increase in speed. The longer-term goal is to reach video data-acquisition rates, which will play an important role in exposing the relationship between structure and function in live cells. *—Michael Brownell*
