tum in each of the spin states. As seen in figure 1c, atoms in the bare spin-up state $|\uparrow\rangle$ are found predominantly near the predicted minimum at $q/k = -1$, with a few spin-up atoms, arising from the dressed spin-down state, found near the degenerate minimum at $q/k = +1$. Likewise, the atoms with spin down were found predominantly at $q/k = +1$, with a small number of them at $q/k = -1$. At higher coupling strength, when the two minima have merged into a single minimum, both bare spin states are centered at a value of quasimomentum $q = 0$.

Spatially separated spins

The up and down pseudospin states of ^{87}Rb atoms examined in the NIST experiment are normally well mixed in a BEC, absent SOC. However, Spielman and his colleagues found that as they increased the laser coupling strength above a critical value, the two pseudospin states segregated themselves spatially. The new repulsion between the spin states results from a laser-induced interaction between the two dressed spin states. Figure 2 shows the atoms in a homogeneous phase and in spin-separated phases.

Jason Ho notes that SOC should also give rise to a periodic variation in density in the BEC that is caused by the interference between the two dressed spin states. (The spatially separated spin states constitute indirect evidence of that.) If so, he says, such a spatially varying BEC might be used to simulate the crystalline lattice in a condensed-matter system without having to create one with interfering laser beams. That's yet another of the myriad possibilities for this new addition to the ultracold atom toolbox. **Barbara Goss Levi**

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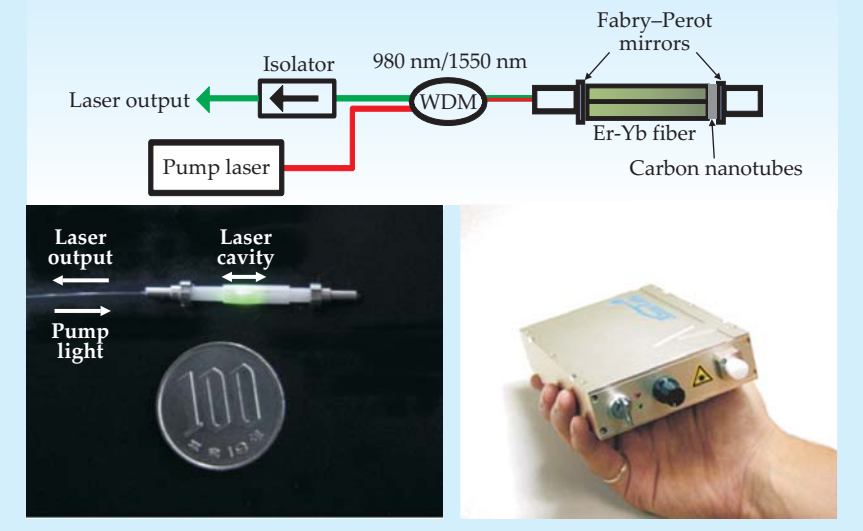
New fiber lasers deliver pulses at tens of gigahertz

Ultrafast charge-carrier dynamics and broadband tunability make carbon nanotubes and graphene appealing materials for phase-locking cavity modes.

Time and frequency are the most accurately measured physical quantities, largely thanks to the precision available from ultrafast lasers. A train of femtosecond laser pulses can generate a coherent broadband spectrum that with suitable optics is resolvable into a comb of equally spaced reference frequencies. Indeed, optical clocks based on such frequency combs can be more precise than the best atomic clocks.

The titanium:sapphire laser is the standard among femtosecond lasers, able to produce a spectrum spanning more than an octave of frequency. But the fiber laser, whose cavity is a length of fiber-optic glass, has its own natural appeal: It's durable and robust, far less expensive, and exceedingly compact—about the size of a paperback novel—and it produces superb-quality subpicosecond pulses. What's more, when composed of glass doped with erbium ions, fiber lasers emit at telecommunication frequencies. Those advantages make them ideal for portable metrology, optical signal processing, and communications applications, particularly if the pulse rate can be driven into the tens of gigahertz, the data-transmission rate that fiber optics currently handle.

A fiber laser is usually pumped by a laser diode that excites a superposition of many cavity modes. Because the relative phases of those modes rapidly change, any steady-state emission is more or less a continuous wave. The presence of an intensity-dependent component known as a saturable absorber in the cavity, however, can lock the phases of those modes together. The absorber, typically composed of semiconducting quantum wells, enforces that locking by being opaque to light below some threshold intensity but increasingly transparent above it. The result is a cavity door, in essence, that transmits a stream of high-intensity pulses at a repetition rate f_{rep} set by the length L of the cavity: $f_{rep} = c/2nL$, where c is the speed of light in vacuum and n the fiber's index of refraction.



The mode-locked 20-GHz fiber laser consists of a 5-mm-long erbium- and ytterbium-doped glass fiber bounded by two highly reflective mirrors, one of which is coated with a thin film of carbon nanotubes that enforce pulsed lasing by passing only light above some threshold intensity. A 980-nm-wavelength laser diode pumps the fiber, which lases at 1550 nm. A wavelength division multiplexer (WDM) couples the pump light to the cavity, and the optical isolator ensures unidirectional light propagation. The complete device, including optical components, the pump laser, and associated electronics, fits in the palm of a hand. (Courtesy of Amos Martinez.)

Typically, the lasers operate at tens of megahertz due to the long lengths—on the scale of meters—needed for sufficient gain in Er-doped fiber. To raise that into the gigahertz regime, one could tap into a higher harmonic of the fundamental repetition rate. But that approach relies on having more than one pulse in the cavity at a time and leads to pulse jitter and noise. Instead, several engineers have opted to steadily push the fundamental rate higher by simply shortening

the cavity while keeping its losses below the accumulated gain.

Amos Martinez and Shinji Yamashita, both at the University of Tokyo, report the latest milestone in that effort: a pulse rate of 20 GHz from a fiber laser just 5 mm long.[1] Key to that achievement is the incorporation of semiconducting single-wall carbon nanotubes as the saturable absorber, which abuts one of two highly reflective Fabry–Perot mirrors used to form the laser cavity, as shown in the figure on page 15. Yamashita's group introduced nanotubes into a fiber-laser cavity six years ago and have been refining the approach ever since by optimizing the system's parameters and efficiency.

Pulse shaping

Researchers have long known that the gain from silicate fiber rises dramatically when the fiber is doped not just with Er, which has a low absorption cross section and tends to cluster at high concentration, but also with ytterbium, which doesn't cluster and whose absorption cross section is two orders of magnitude higher. Martinez and Yamashita exploit those properties by loading their fiber with Yb^{3+} ions, which allows them to shorten the fiber's length.

But although the gain can be made great enough to beat losses, the removal of silicate fiber reduces the material's nonlinear interactions with light, interactions that keep the pulses from stretching out in the cavity. Moreover, as the cavity shortens, the energy per pulse drops proportionately; on average, the net fiber nonlinearity decreases as the square of the drop.

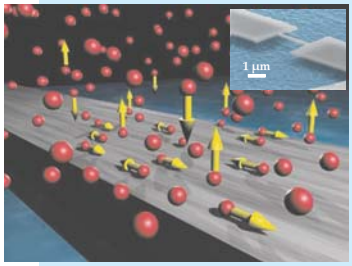
That loss of intensity and of the fiber's pulse-shaping nonlinearity places a greater burden on the saturable absorber, explains MIT's Erich Ippen. "You want this door to be stiff enough to quickly close behind the pulse as the intensity drops, but as it's made stiffer, it can be harder to open." Carbon nanotubes seem ideal in that respect; so fast are their charge-carrier dynamics that once the nanotubes absorb light, electrons relax from excited states in less than a picosecond. And yet, as Martinez and Yamashita's demonstration confirms, the absorption can begin to saturate even at the lower light intensities of a short fiber.

The nanotubes also exhibit low losses and consume essentially no space. The researchers just spray them directly onto one of the mirrors after ultrasonically dispersing the nanotubes to break up bundles formed by van der Waals forces. The film is kept thin (about 100 nm) to reduce light scatter-

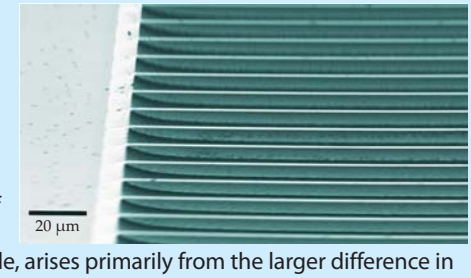
physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

Tracking atoms on and off a nanoscale mass sensor. An electromechanical system capable of sensing the mass of a single molecule or a few atoms typically consists of a nanometer-thick beam whose resonant frequency measurably shifts in response to the loaded mass. Naturally, such devices are sensitive to the adsorption and desorption of individual analytes or their diffusion along the beam's surface; both processes, shown in the schematic, cause the resonator's frequency to fluctuate. Now, Michael Roukes and colleagues at Caltech's Kavli Nanoscience Institute have determined the contribution of those processes to frequency noise for a nanoscale resonator vibrating at 190.5 MHz. The experiment, which was conducted in a temperature-controlled vacuum cryostat, relied on a nozzle that delivered a steady stream of xenon atoms to a silicon carbide resonator, shown in the inset. As the resonator was cooled, the average number of adsorbed xenon atoms increased; subsequently, so did the magnitude of the frequency shift. By measuring the fluctuation of surface adsorbates, the researchers found that sliding off after lateral diffusion—rather than simple desorption—was the favored route for atoms leaving the resonator and contributed the most to frequency noise in excess of the resonator's inherent thermal fluctuations. The combination of experimental data and analytical models also revealed previously unknown power-law dependence in the system's noise spectrum, a finding that could be used to probe the sensitivity limits of wide classes of nanoscale frequency-shift sensors. (Y. T. Yang et al., *Nano Lett.*, in press, doi:10.1021/nl2003158.) —JNAM



Microresonators as temperature sensors. In yet another application for micro- and nanostructures, recent experiments have demonstrated the potential for microresonators to serve as ultrasensitive temperature sensors. Last year, Ashok Pandey, Oded Gottlieb, and Eyal Buks of the Technion–Israel Institute of Technology showed that the resonant frequency of a suspended, microfabricated gold–palladium beam, hundreds of microns long but just a micron wide and a fraction of a micron high and supported at each end, was a strong function of temperature. The dominant contribution came from the temperature dependence of the tension in the beam, which is due to the difference between the thermal expansion coefficients of the beam and of the silicon substrate below it. The researchers could measure temperature changes by monitoring the relative frequency shift; as a temperature sensor, the beam's sensitivity was about a third that of commonly used, macroscopic platinum sensors. More recently, a team led by Anja Boisen of the Technical University of Denmark has reported aluminum microresonators, such as the ones seen here, whose resonant frequencies are even more sensitive to temperature. The improvement, of more than an order of magnitude, arises primarily from the larger difference in thermal expansion coefficients and from the Al beam's smaller initial tension compared with that of the Au–Pd beam. With their high quality factors, microresonator-based sensors would potentially have exceptional temperature resolution as well. (A. K. Pandey et al., *Appl. Phys. Lett.* **96**, 203105, 2010; T. Larsen et al., *Appl. Phys. Lett.* **98**, 121901, 2011.) —RJF



An ancient meteorite recorded its changing environment. In the past decade or so, planetary scientists have significantly changed their view of the protoplanetary disk from which Earth condensed. Once described as having well-defined concentric zones, the disk is increasingly seen as a dynamic place whose materials could travel huge distances away from or toward the Sun. Now former University of California postdoc Justin Simon (currently a research scientist at NASA's Johnson Space Center) and colleagues have used oxygen-isotope analysis to document what appears to be the wild ride of a meteorite fragment that

ing and minimize the output pulse width. In addition, the nanotubes' high thermal conductivity, Martinez speculates, may help sink the heat that builds when the pump laser drives the fiber at higher powers.

Tuning the absorption

The researchers' nanotubes were produced with diameters such that the fiber-laser frequency roughly matches that of the tubes' absorption. The quest to precisely tune those diameters and control whether the nanotubes are semiconducting or metallic remains a significant challenge, though. Having nanotubes out of resonance adds to cavity losses.

Nevertheless, even a wide distribution of tube diameters can prove advantageous. Three years ago Cambridge University's Andrea Ferrari and his colleagues designed a nanotube mode-locked laser tunable over a much broader range of wavelengths than other systems.[2] Although the nonsaturable losses are greater and degrade the mode locking, Ferrari argues, they're tolerable in fiber lasers with relatively large gain coefficients. And the mixture of semiconducting and metallic nanotubes in the Tokyo team's system lowers the absorption recovery time, as excited-state electrons can relax more quickly by tunneling to a nearby metallic nanotube.

More recently three independent groups—Ferrari's,[3] Yamashita's,[4] and Dingyuan Tang's[5] at Nanyang Technological University in Singapore—each developed ultrafast lasers mode locked using graphene. Thanks to the linear dispersion of graphene's Dirac electrons (see PHYSICS TODAY, January 2006, page 21), there always exist electron–hole pairs in resonance with light of any frequency, a property that makes the material ideal for a tunable system. Unlike semiconductor quantum wells and nanotubes, graphene requires none of the bandgap engineering or diameter control to optimize performance.[6]

Even so, nonsaturable losses remain on par with those from nanotubes. To overcome those losses, the challenge will be to improve graphene's synthesis.

Mark Wilson

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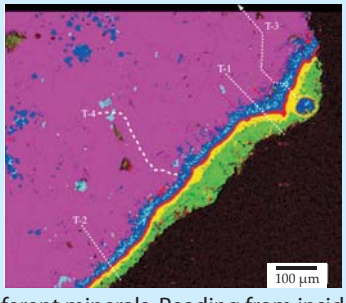
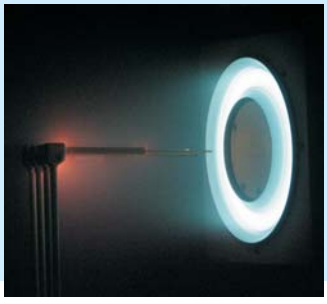
formed early in the solar system's history. The relative abundance of oxygen-16 and oxygen-17 indicates the radius at which the primitive material incorporated oxygen. That's because solar radiation able to liberate ^{17}O from carbon monoxide ($C^{17}O$) is less attenuated as it travels through the disk than is the radiation that encounters the more prevalent $C^{16}O$. Regions of the disk far from the Sun thus have an extra bit of ^{17}O that can be integrated into meteorites. With exquisite precision, the Simon team determined relative oxygen isotope abundances along four transects through a pea-sized piece of the Allende meteorite. In the figure, colors represent different minerals. Reading from inside to outside, the group found regions that were ^{16}O rich, poor, then rich again. Conceivably the fragment remained stationary in a part of the protoplanetary disk with a dramatically changing environment. But a more natural interpretation is that the isotope signature represents a stamped, roundtrip ticket of a journey that began within the orbit of Mercury and extended beyond that of Mars. (J. I. Simon et al., *Science* **331**, 1175, 2011.) —SKB



Unexpected wear may yield new plasma rockets. A Hall-effect thruster (HET) is a type of electric propulsion system that produces thrust by the formation of an electron current around a circular channel that interacts with a radial applied magnetic field to create a strong axial electric field. That electric field then accelerates propellant ions to very high speeds. (For an introduction to HETs, see the Quick Study by Mark Cappelli, PHYSICS TODAY, April 2009, page 76.) HETs have been used on many near-Earth missions, but most deep-space travel requires extended thruster operation, typically for years, which raises a major challenge: Some of the ions smash into the ceramic channel and erode it over time, leaving critical thruster components exposed to high-energy ions. Such erosion is known to limit a thruster's lifetime. However, during recent testing of the commercial HET design shown here, the erosion surprisingly stopped after about 5600 hours of operation, and remained suppressed until the test ended after more than 10 000 hours. Now a team of scientists at NASA's Jet Propulsion Laboratory has developed a new simulation code for HETs that exposed the physics behind those test results. As the channel eroded, the magnetic field topology changed and induced an effective shield against ion bombardment. The scientists suggest that carefully designing the magnetic field in future HETs can reduce channel erosion by several orders of magnitude. (I. G. Mikellides et al., *Phys. Plasmas* **18**, 033501, 2011.) —SGB



Convection homogenizes magma intrusions. Plutons are mountain-sized formations of igneous rock that poke through Earth's surface. Their origin as solidified eruptions of magma is straightforward to explain. What's puzzling is why plutons are so homogeneous on large scales, despite their immense size and despite being inhomogeneous in their mineral composition on small scales. Alain Burgisser of the Institute of Earth Sciences in Orléans, France, and George Bergantz of the University of Washington in Seattle have proposed an answer. In their model, a mass of viscous, semisolid magma—"mush" is the technical term—lies beneath the surface, hemmed in by walls of more solid rock. Pluton formation begins when the slow churning of the mantle below happens to bring a body of hot magma into contact with the bottom surface of the cooler mush. Over the ensuing decades, the heat rises slowly via conduction, making the mush less viscous and—crucially—less dense. In a process that Burgisser and Bergantz call unzipping, the gradually growing layer of hot, light mush abruptly undergoes a Rayleigh–Taylor instability, which sends convective plumes of hot mush upward through the nascent pluton. Within a few months, the first plumes reach the top of the nascent pluton, cool, then sink. Only a few successive cycles of overturning suffice to homogenize the mush on plutonic scales. Burgisser and Bergantz's model can plausibly account for the speed with which three real plutons formed, including the one left by the 1991 eruption of Mount Pinatubo in the Philippines. (A. Burgisser, G. W. Bergantz, *Nature* **471**, 212, 2011.) —CD