by Eric J. Lerner

Penetrating the fog

Free-space laser communication is an economically attractive way to get high-bandwidth signals the "last mile" to individual homes because it does not require laying millions of miles of fiber. However, laser signals cannot penetrate heavy rain or dense fog, and because the beams are scattered, multiple path lengths totally blur the signal modulation. Similar problems limit other laser-signal applications, such as range finding and laser-infrared-radar detection of pollutants.

One possibility for overcoming this scattering is to send signals through fog by using high-intensity ultrashort pulses. A research group at the Laboratory of Molecular and Ionic Spectroscopy (LASIM) at Université Claude Bernard (Lyon, France) has demonstrated that the stable light filaments generated by such pulses can maintain themselves and overcome heavy scattering through a substantial fog (*Appl. Phys. Lett.* 2003, *83*, 213).

The filaments are created because the light pulses, which have a power of more than 3 GW (7-mJ, 120-fs pulses), change the refractive index of the air though which they pass and create a strong focusing effect. This focusing further intensifies the light, breaking the beam up into filaments about 150 μm in diameter and hundreds of meters long. At a critical intensity, around 10^{14} W/cm^2, the filaments start to form ions from the air by multiple photon absorption. This phenomenon counters the decrease in refractive index and starts to defocus the filament. The balance between the focusing and defocusing maintains the stability of the filaments as they travel.

The French team studied the filaments as they interacted with an artificial fog of droplets from 30 to 100 μm in diameter, which is smaller than the filaments. They found that the filaments lost energy when scattered by the droplets but regained it almost immediately by drawing energy from the bath of unfilamented photons in the broader laser beam. As long as the surrounding beam had enough energy, the filament was almost unaffected by the fog and could carry a signal. The experiments showed that the filament could penetrate a cloud with an optical thickness of 1.2, typical of many real clouds; but in thicker ones, too much energy was lost to sustain the filaments.


Université Lyon 3/DAVM/Alexis Gratié

On a foggy night outside Lyon, France, when regular laser beams would be scattered, stable filaments of 400-mJ, 100-fs laser pulses are detected by a cloud chamber over a distance of 50 m.

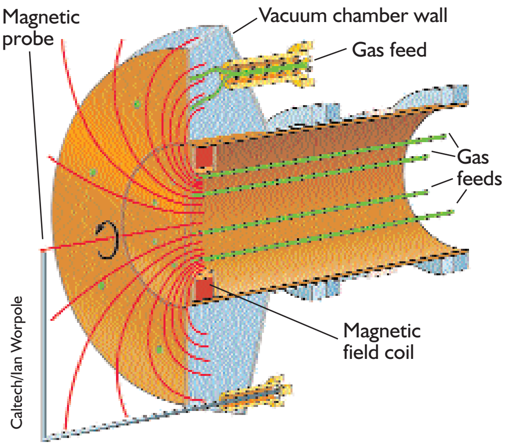
"We are not sure that the filaments could get through heavy rain because in this case, the droplets are larger than the filaments and might block them entirely," says Jean-Pierre Wolf, a leader of the research team. The next step is to test the approach using a more powerful system—the Teramobile, a joint French–German femtosecond–terawatt Ti:sapphire laser, which produces 400-mJ, 80-fs pulses. These experiments will be done with actual clouds.

Plasma self-organization

Researchers working on controlled thermonuclear fusion have tried for 30 years to confine hot plasmas with external magnetic fields, mostly using the tokamak device. The plasmas, however, tend to wriggle out of the confining fields before much fusion energy can be produced.

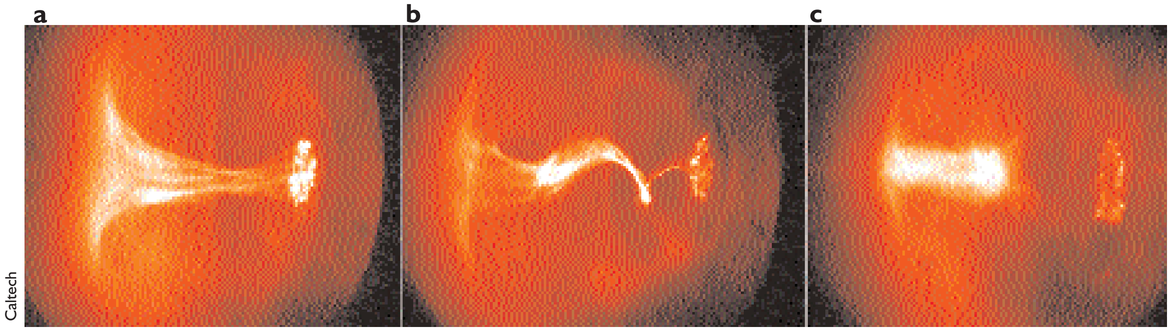
Another approach to fusion seeks to harness the plasma's own magnetic fields, produced by its currents, to confine it. This effort—which uses devices such as the reversed-field pinch, the spheromak, and the dense-plasma focus—attempts to induce the plasma to self-organize into structures called toroidal vortices, which resemble fat smoke rings. Because the Lorentz force on a charged particle depends on its motion perpendicular to the magnetic field, if the current and magnetic field are always parallel, there is no force on the particle. Thus, toroidal vortices (also called plasmoids or spheromaks) are force-free configurations in which the direction of the current flow and the magnetic field are everywhere identical. Physicists have long known that these structures have the least energy possible for the current carried, so they are intrinsically quite stable.

"Although we know how stable they are, and we know generally how to produce



Caltech/Ian Worpole

A high-speed multiple-frame CCD camera reveals images of the formation and helical instability of a collimated plasma injected into a vacuum chamber by this planar magnetized coaxial gun.



Caltech

Three images of plasma regimes (with the gun electrode on the right) show a stable column (a), a kinked column (b), and a detached plasma (c). Interframe time is 1.5 μs.

them, no one has known exactly how they form," points out Scott C. Hsu of Los Alamos National Laboratory. Somehow, filaments of intense current generate the vortices by an instability process. But without knowing the process, reliable production of the vortices is difficult, hindering alternative fusion approaches.

Now, Hsu and P. M. Bellan of Caltech have shown experimentally how the vortices form through the kinking of a column of current (*Phys. Rev. Lett.* 2003, *90*, 215002-1,2003). They used a pair of coaxial flat electrodes—an inner 20-cm-diameter disk as the cathode and a 32-cm inner-diameter ring as the anode. A pulse of current from a capacitor bank charged to 4 to 6 kV generated a plasma column along the central axis of the device in several microseconds. At the same time, an external magnetic coil added a controlled amount of poloidal (axial) magnetic-field strength. A charge-coupled device (CCD) camera took images every microsecond, and the team made detailed measurements of the magnetic field, also every microsecond.

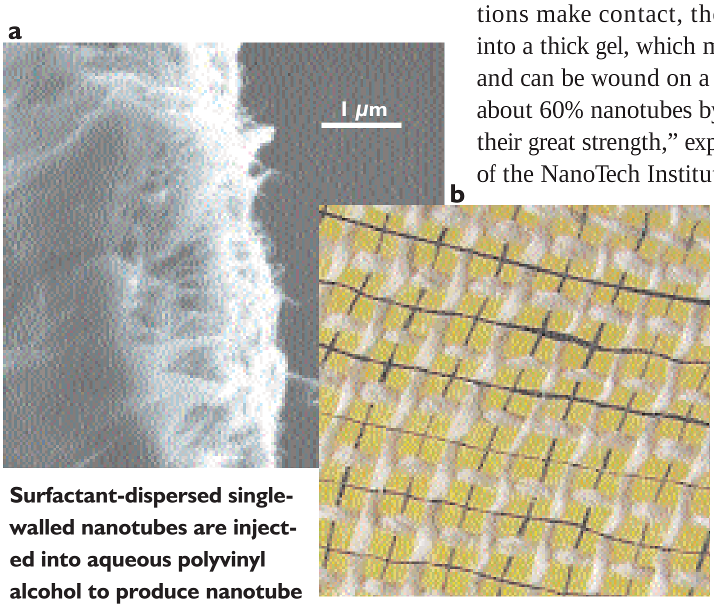
When the researchers adjusted the poloidal field to just balance the toroidal field created by the plasma currents, the plasma current kinked like an overtwisted spring. "Since the currents in adjacent loops of the kink attract each other, like all parallel currents do, the kink keeps growing tighter and tighter until the loops reconnect with their neighbors to form a separate toroidal vortex or spheromak," Hsu explains. The kinking mechanism is quite different from the symmetrical sausage instability that other researchers had speculated might lead to the toroidal vortices.

The kinking proved quite sensitive to the ratio of the axial magnetic field to the toroidal field. When the axial field was too weak, no kinks appeared, and when it was too strong, a detached plasma formed swiftly but not in the force-free toroidal-vortex configuration. Such a sensitivity, predicted by theoretical considerations, can aid researchers in establishing the conditions for reliable vortex production.

"We are not only studying these structures for their application in fusion work," says Hsu. "It is clear that these structures occur naturally in astrophysical phenomena such as the solar corona and in the production of astrophysical jets. Now that we know how the toroidal vortices are created, we can use laboratory plasma to better understand astrophysical ones, and vice versa."

Stronger than spider silk

Toughness is a measure of the energy per unit mass needed to break a fiber, and until recently, spider dragline silk was the toughest material known—5 times as tough as steel. However, no one has learned how to produce spider silk in fiber diameters that can be woven into a superstrong material. So Kevlar, with a toughness about that of steel, has remained the toughest commercial fiber for several decades.



NanoTech Institute, University of Texas at Dallas

Surfactant-dispersed single-walled nanotubes are injected into aqueous polyvinyl alcohol to produce nanotube gel fibers (a), which are pulled from the coagulation bath to form 100-m lengths of solid nanotube composite fiber (dark) that can be woven into textiles (light, in b).

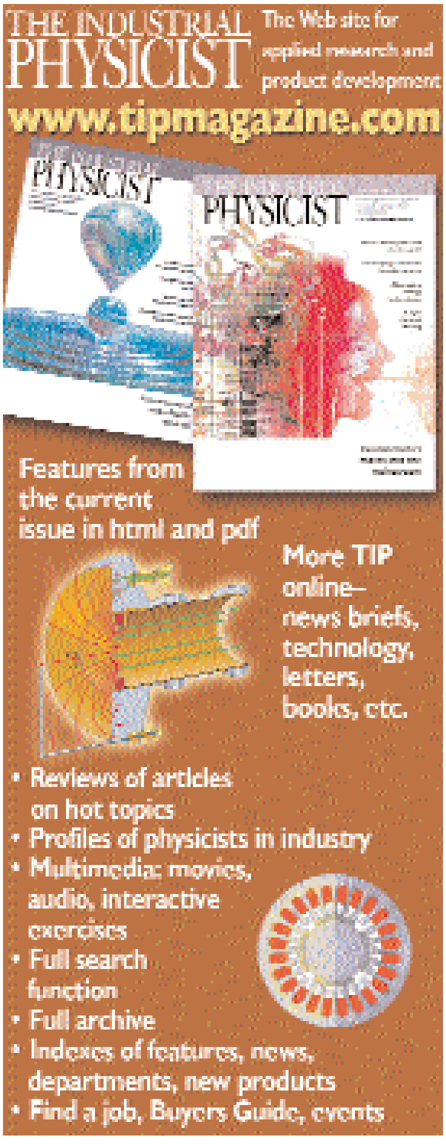
A collaboration between the department of chemistry and the NanoTech Institute at the University of Texas at Dallas (Richardson, TX) and the department of physics at Trinity College (Dublin, Ireland) has now yielded an artificial fiber made from single-walled carbon nanotubes (SWNTs) that tops the toughness of spider silk. The new fiber has a toughness of 570 J/g, 5 times that of silk and 25 times that of steel wire. With a diameter of 50 μm, the fibers are easily woven into fabrics (*Nature* 2003, *423*, 703).

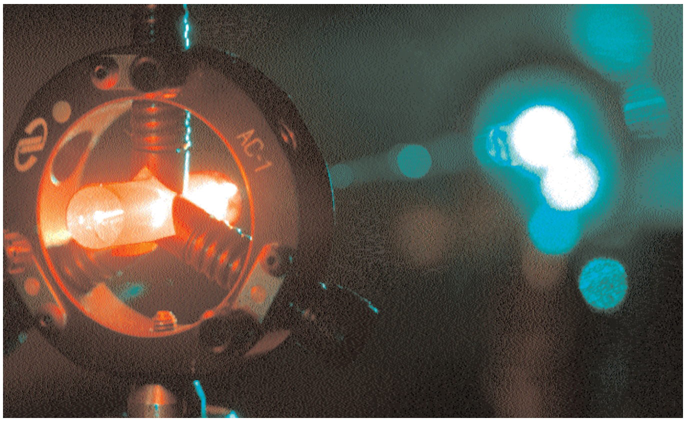
The fiber's toughness comes not just from its high strength of 1.8 GPa, equal to that of spider silk, but from an extremely high strain at failure—about 300%—which means the fibers can triple their length before breaking. Silk breaks at a strain of 30%.

To create the fibers, the research team uses detergents to put the SWNTs into solution, and then sends the liquid spinning into the center of a cylindrical pipe coated with flowing polyvinyl alcohol. When the two solutions make contact, the mixture collapses into a thick gel, which moves down the pipe and can be wound on a mandrel. "The gel is about 60% nanotubes by weight, so it shares their great strength," explains Alan B. Dalton of the NanoTech Institute. "But the polymer seems to act as a strong glue, both holding the nanotubes together and letting them slip past each other to allow for high strain." The part of the polymer in direct contact with the nanotubes is in a pseudocrystalline state, but the polymer farther from the nanotubes is amorphous, which seems to allow for strength and flexibility.

The fibers also have remarkable electrical properties, such as extremely high capacitance per unit mass—as much as 60 F/g for a single fiber. Even at low voltage, such high capacitance allows for storing considerable amounts of electrical energy, comparable to a battery on a mass-for-mass basis. In addition, when charge is injected into the fibers, they contract slightly, with a force per unit mass that is at least twice that of muscle fibers.

"Right now, we are concentrating on the mechanical properties because the electrical characteristics are limited by the low conductivity of the fibers," says Dalton. Large-scale applications will also have to wait until SWNTs become less expensive. They currently cost $500 a gram, and prices will not drop dramatically for three or more years, when new production facilities come on-line.




University of Rochester

Light has been observed to travel at only 91 m/s in a crystal of alexandrite at room temperature in an experiment at the Institute of Optics, which has also slowed light in this ruby crystal.

Slow light

Since the discovery a few years ago of ways to slow light pulses to very low velocities, researchers have looked for ways to use this phenomenon for practical purposes. Last year, a U.S.–Korean group took a major step in this direction when it achieved slow light in a solid (see *The Industrial Physicist*, April/May 2002, pp. 10–11). However, that effort required cooling the material to 5 K. Now Matthew Bigelow, Nick N. Lepeshkin, and Robert Boyd of the Institute of Optics at the University of Rochester (NY) have taken the next step by demonstrating light at 91 m/s in a solid at room temperature (*Science* 2003, *301*, 200). The new work utilized a different quantum effect to achieve the result.

Extremely high refractive indices, and corresponding extremely low group velocities for light waves, occur when the absorptivity of a medium varies rapidly with wavelength. Because the material must be transparent enough to transmit a useful signal, the trick is to create a very narrow spectral band of increased transparency within a broader region of absorption.

The Rochester experimenters used a crystal of alexandrine ($BeAl_2O_4$) to generate an extremely narrow band of transparency through the phenomenon of coherent population oscillations. To set up these oscillations, in which the entire population of electrons oscillates between the ground state and a higher-energy metastable state, they used an argon-ion laser to pump the electrons up to a broad absorption band. The electrons decayed in picoseconds from this band to a metastable state and returned to the ground state in a few milliseconds. A second laser beam—the probe beam, which had a slightly different frequency—caused the electrons to oscillate between the ground and metastable state at the beat frequency (the difference in frequency between the two laser beams). Only when the difference in frequency between the pump beam and the probe beams is so small that the oscillation is slower than the decay time can a large oscillation occur. In practice, this occurs over a bandwidth of 8 Hz.

Within this narrow bandwidth, the pump beam can send energy through the oscillating electrons to the probe beam, thus dramatically decreasing the absorption of the probe beam over the 8-Hz spectral band. This extremely rapid variation of absorption sets up the high refractive index and slow light transmission.

By a similar trick involving a narrow band of absorption, rather than transmission, the researchers created a negative refractive index condition, in which the peak of the light pulse emerges from the material before the peak enters—a negative group velocity. This is less impressive than it sounds, because the heavily absorbed emerging peak lies wholly within the leading edge of the entering peak. Thus, no individual photons actually travel faster than the speed of light in a vacuum.

One possible practical application of slow-light materials is for delay lines to hold up signals for telecommunications or quantum computing. A 1-cm-thick sample of alexandrite can delay a light signal for 100 μs, as much as a fiber delay line 30 km long. "However, for telecommunications, you need huge bandwidths, not the very narrow ones we are working with," Bigelow acknowledges. "We think we have ways to address this problem, and that is what we will be working on next."