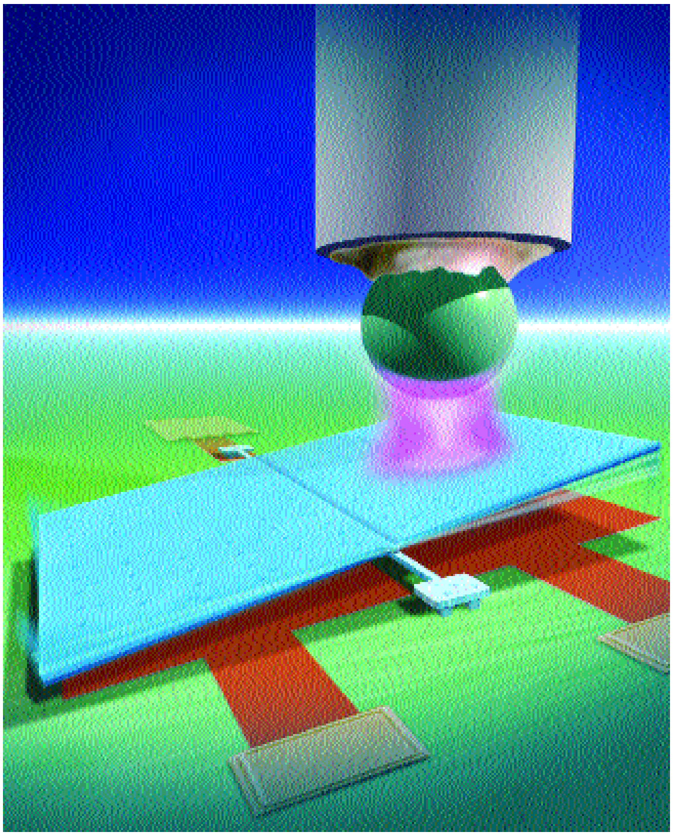
by Eric J. Lerner

Quantum stickiness put to use

As researchers shrink electronic and mechanical devices to the scale of nanometers, they are encountering quantum phenomena that are negligible at larger scales. One of these is the Casimir force, an effect due to quantum fluctuations of the electromagnetic field in a vacuum. At Lucent Technologies' Bell Laboratories (Murray Hill, NJ), Federico Cappasso and colleagues have developed a microelectromechanical device that both demonstrates and accurately measures the Casimir force (*Science* 2001, *291*, 1941). The force, which causes conducting plates to attract each other at very short distances, could be put to work in nanoscale motion sensors, among other possible applications.



K. D. Drake, Lucent Technologies' Bell Labs

The Casimir force, due to quantum fluctuations of the electromagnetic field in a vacuum, is negligible at 1/3 µm but creates a pressure of 1 atm at a distance of 10 nm.

H. B. G. Casimir first predicted the effect in 1948, and E. M. Lifshitz generalized it in 1956 to the case of two dielectrics. The quantum fluctuations that cause the Casimir effect occur everywhere, even in a vacuum in the absence of a radiation field. Between two parallel conductors, there are fewer possible ways (modes) that the fluctuation can occur and, therefore, there is somewhat less energy in the fluctuations than outside the conductors. The difference creates a pressure that decreases as the fourth power of the distance between the plates. At distances of even one-third of a micrometer, the Casimir force is negligible. However, at 10 nm, the pressure applied by the force is equal to 1 atm.

"The difference between the Casimir force and the van der Waals force, which causes molecules to stick to each other, is that the Casimir force applies to objects that, although tiny, are much larger than a molecule," explains Cappasso. "This is also a topological force—it depends on the shape of the objects. For example, although the Casimir force between two plates or a relatively large sphere and a plate is attractive, that between two concave spherical surfaces is repulsive."

The Bell Labs device consists of a polysilicon plate suspended on thin torsion rods. On the underside of the plate are two electrodes, each one-half the size of the plate. Corresponding electrodes are embedded in the substrate below the plate with a 2-µm gap between them. A circuit measures the capacitance of each set of electrodes, which is a direct function of the distance between the plate and the substrate. Thus, the difference between the two capacitances is a sensitive measure of the rotation of the plate.

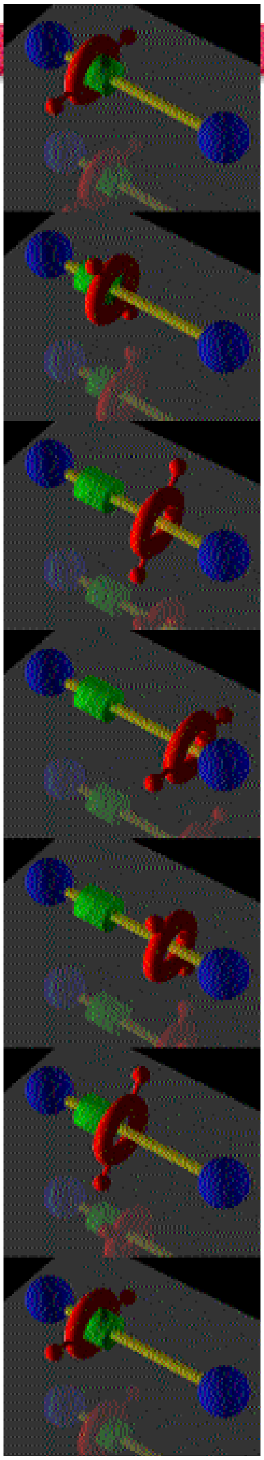
To create the Casimir force, one side of the plate is brought close to a relatively large (100-µm radius) polystyrene sphere, which is covered with a thin conducting layer of gold. A piezoelectric motor brings the sphere close to the plate, causing the plate to tilt toward the sphere. As the sphere is moved from 300 nm to 75 nm from the plate, the force on the plate increases sharply, in exactly the way predicted for the Casimir force.

Because the Casimir force increases so rapidly at small distances, and because it becomes quite sizable, Cappasso thinks that devices based on it can be used as extremely sensitive position and distance sensors. In addition, because Casimir forces exist wherever two conductors come into close proximity, future nanodevice design will have to take these forces into account, no matter what a device's purpose.

Molecular piston

The Casimir force cannot generate net energy because exactly as much energy is absorbed separating two surfaces as is gained in letting them move together. So the force cannot power nanomachines. However, an international research team has devised a way to convert energy from a laser to mechanical work at the molecular level. It has invented a light-powered molecular piston (*Science* 2001, *291*, 2124).

"Molecular pistons can carry out a variety of useful tasks," explains David Leigh of the Centre for Supramolecular and Macromolecular Chemistry at the University of Warwick (Coventry, England). "For one thing, they can rearrange the structure of surfaces and switch catalytic sites on or off. In addition, they could pump ions across membranes—something cells manage to do very well but that is difficult to do artificially." Conceivably, such pistons also could be used to construct other



This animation (with its reflection) represents the pistonlike cycling of a molecular cluster on a thin atomic thread, where input of laser energy causes the shuttle to change stations and, after charge recombination, return.

Aden Murphy, Leigh Group, The University of Warwick

nanomolecular machines and devices.

The molecular piston was developed in collaboration among researchers at the University of Warwick, University of Amsterdam, and University of Bologna. It uses a type of rotaxane, a family of molecules that have attracted increasing interest for their ability to switch back and forth between different configurations. The molecule consists of a large cluster of atoms, called the shuttle, which is locked onto a thin thread of atoms. The shuttle portion of the molecule can bind to the thread at one of two binding sites located at either end of the thread.

When the rotaxane absorbs an ultraviolet (UV) photon from the exciting laser, the molecule rapidly takes up an electron from a donor in the surrounding solution. The charged shuttle is then attracted to the other bonding site, which has a slight positive charge. After the molecule gives up the electron again, the shuttle returns to its original position. The initial position shift, which delivers the mechanical power, takes about 1 ms, while the recovery stroke takes about 100 ms. The researchers detected the change in configuration by measuring changes in the molecules' spectra and their response to nuclear magnetic resonance instruments, which detect changes in the electronic environments of nuclei.

The pistons are quite efficient. About 20% of all photon energy absorbed is converted to mechanical energy through the movement of the shuttle. On a weight-for-weight basis, the molecules are extremely powerful, converting about 500 MW/kg of mass if they stroke at their maximum rate of 10 kHz. By comparison, kinesin, the protein that makes muscle tissue contract, can generate at most 20 kW/kg. In part, this difference is because the kinesin molecule is 100 times larger than the rotaxane used for the shuttle. An even bigger factor, however, is that the energy for muscle contraction is supplied chemically by adenosine triphosphate, or ATP, whereas the shuttle gets its energy from a laser pulse. In practice, the amount of mechanical work produced is limited by the ability of the system to dissipate the excess heat generated, but for tiny systems, heat dissipation can be efficient.

The researchers are now trying to take the next step and attach the shuttle to some other molecule to make it perform useful work. "We also hope to find other systems that can use visible light rather than UV—possibly even sunlight," says Leigh.

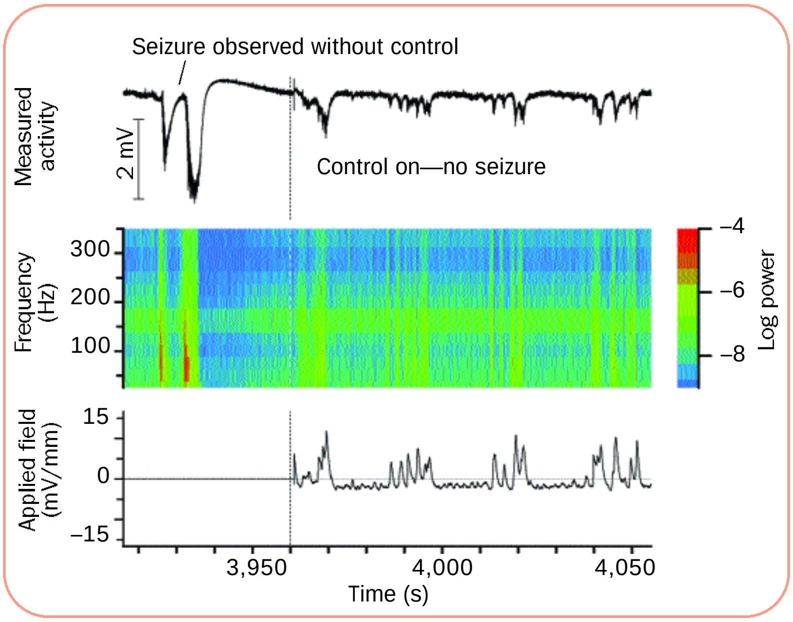
Fighting epilepsy

Models used to explain brain function have increasingly shifted away during the past decade from seeing the brain as a computer. Instead of emphasizing the discrete, pulselike functioning of individual neurons, the new models envision brain functioning as the cooperative actions of millions of neurons, linked not only by electrical spikes but also by continuously varying electric fields. With this shift, the physics tools developed to study chaotic systems have been brought to bear on the mysteries of brain behavior (see *The Industrial Physicist*, August 2000, pp. 18–21).

One researcher investigating nonlinear systems and control, Bruce Gluckman of George Mason University (GMU) in Fairfax, Virginia, wondered if feedback mechanisms could be used to control epilepsy by regulating electric fields in the brain. In epileptic seizures, sections of the brain go into uncontrolled electrical oscillations at high frequency, which cause convulsions and often the loss of consciousness. Gluckman, GMU colleagues Hanh Nguyen and Steven J. Schiff, and Steven L. Weinstein of George Washington University School of Medicine have taken the first step by showing that such electric control can suppress epileptic-like activity in brain slices of rats (*J. Neuroscience* 2001, *21*, 590).

"Attempts at controlling epilepsy by putting sharp, discrete spikes of current into brain tissue have had poor results in the past," explains Gluckman, "Instead, we are using continuously varying electric fields that are imposed over a relatively large area—about a square millimeter." Previous research has shown that electric fields aligned along the axis of certain types of neurons can slightly raise the electrical threshold for firing pulses, which makes firing less likely and potentially suppresses seizures. But the neurons adapt to steady fields, so Gluckman's team tried a feedback mechanism. They applied the suppressing electric field only when it was needed to stop the onset of seizures.

To use a feedback field, the researchers had to reliably distinguish the field that they imposed from the brain-produced field that they wanted to measure. Both fields are of comparable strength, about 1 to 3 V/cm. First, the team measured the brain-produced field in a direction perpendicular to that imposed by an electrode placed atop the brain slice. In addition, the



George Mason University, Department of Physics and Astronomy

An electrical field applied over a small area of a brain slice can be effective in suppressing seizures when it is fed back from measured brain activity.

power of the electric field generated by the brain slice was measured at a frequency band of 100 to 500 Hz, but the imposed field varied much more slowly, mostly at frequencies below 3 Hz.

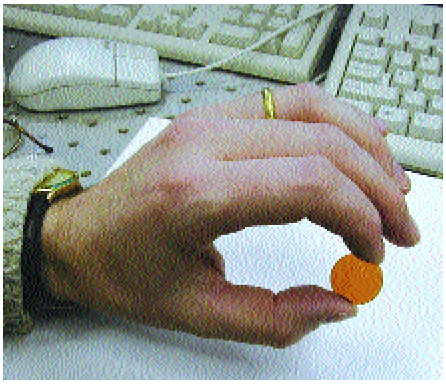
The feedback method was intended to increase the suppression field in proportion to the power that the brain slice produced at high frequency. The suppression field was activated when the brain slice produced energy above a certain threshold. A frequency filter was used to ensure that the suppression field varied only slowly. The field imposed by the researchers functioned to suppress neuronal firing and, thus, the production of a high-frequency electrical field when the brain's electrical activity went above the threshold.

Using living slices of tissue cut from a rat's brain, a common laboratory system, the researchers showed that the feedback method cut high-frequency brain oscillations by 75% and stretched the interval between seizurelike activity from 40 s to as long as 16 min. Neither a constant field nor a randomly varying field succeeded by itself in suppressing the seizurelike activity. So the feedback mechanism was the key.

"The next step is to move onto experiments with live rats, which have had epilepsy induced by drugs or surgery," says Gluckman. In the rats, and eventually in human epilepsy patients, electrodes will have to be surgically inserted under the skull because its bone effectively blocks outside electric fields. Electrodes would be located near the source regions of epileptic activity, which can be accurately mapped in the brain. If these experiments are successful in controlling epileptic seizures, the technique may prove successful in other brain diseases, such as Parkinson's, Gluckman believes.

Holographic data storage

Since the invention of holography 40 years ago, researchers have tried to use it for digital data storage. Holography seemed ideal because data can be stored in the volume of holographic materials, not just on the surface, allowing huge data



This plastic embedded in glass has all the characteristics needed for holographic recording, paving the way for data densities millions of times greater than that of optical disks.

Optenia, Inc.

density. In addition, many holograms can be stored in the same volume by varying the angle at which they are recorded and the wavelength of the light used. In theory, data densities millions of times greater than that of current optical disks could be achieved. At the same time, read–write rates could increase thousands of times.

But practical holographic data storage has always foundered on one very real obstacle—the lack of a suitable recording medium. Any holographic medium must change its refractive index in response to the intensity of light impinging on it, so as to preserve the interference patterns created by the hologram. (The hologram is generated by interfering a laser beam carrying an image with a reference beam. Another beam can then regenerate the image by shining through the recorded hologram.) Simple inorganic compounds, such as lithium niobate, tend to have their interference patterns partially erased every time read-out occurs. Highly sophisticated spectral-hole burning techniques allow recording and read-out at many different wavelengths, but require cooling materials to 2 K. Photorefractive polymers are stable against erasure, but they tend to shrink as they change their refractive index, making read-out difficult and preventing the use of anything but thin films.

Pavel Cheben of Optenia, Inc. (Ottawa, Canada), has proposed a way that seems to solve the shrinkage problem and, thus, deliver a stable, high-density, bulk holographic medium for the first time. “Why not put the photosensitive polymer into a glass so it can’t shrink?” he asked.

Using the sol–gel low-temperature technique for forming glass, which was first developed in the mid-19th century, Cheben and his colleagues at the National Institute for Aerospace Technology of the Spanish Ministry of Defense in Madrid, where he then worked, and at other Madrid institutions, created a series of materials consisting of plastics embedded in glass. The most recent such material, reported in *Applied Physics Letters* (2001, *78*, 1490) achieves all of the characteristics needed for holographic recording in bulk materials.

The biggest advantage of the new material is that it produces large changes in index of refraction in response to exposure to light and can be fabricated as a thick slab of high optical quality. With the help of an initiator chemical that captures the light energy, the monomer is linked to a polymer with a dramatic change in refractive index. This change means that the image can be reconstituted with nearly perfect efficiency and little noise, which allows the recording of thousands of images, each carrying millions of bits, in a single block of material. In addition, there is no erasure on reading because the hologram is written with 514-nm light and read out, at a lower intensity, with 632-nm light. The hologram is stable for six months, and the material can be made to any thickness, which increases the number of images stored.

This particular material can be used only for permanent, nonerasable memories, but Cheben hopes that similar organically modified glasses can be developed that are fully erasable and rewritable.