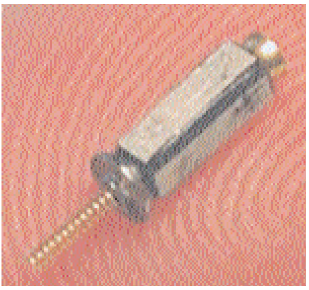
A rice-grain-sized motor

Microminiaturized machines require microminiaturized motors to drive them. But conventional electromagnetic motors do not scale well as they get smaller because the finer the wire the current must run through, the more energy is wasted in resistance. These motors have more than 90% efficiency at 1 kW power but work with 30% efficiency at 30 W, and the smallest practical micromotors, which have 0.2 W input and are about 7 mm in diameter, have 2% efficiency.


Pennsylvania State University

A rotor is activated when an alternating current is applied to one of two piezoelectric plates at right angles to a tiny metal tube.

An alternative to the electromagnetic motor is one driven by ultrasonic vibrations set up in a piezoelectric material by an alternating current. Researchers at Pennsylvania State University's Materials Research Institute in University Park have recently developed a piezoelectric motor that is only 1.5 mm in diameter and 4 mm long, about the size of a grain of rice (*IEEE Ultrasonic, Ferroelectric, Frequency Control Trans*., in print). The motor works with 30% efficiency and delivers enough power to propel tiny instruments through the internal tracts of the human body.

"We had originally developed a motor based on a tube of PZT, a piezoelectric material," explains Kenji Uchino, professor of electrical engineering at Penn State. "We attached four electrodes, and by adjusting the alternating current to the electrodes, we got the tube to bend and wobble. This then conveyed rotary motion to a shaft." But the power delivered was limited by the relatively low strength of the piezoelectric ceramic. So the team developed a smaller and simpler device.

This new motor consists of a tiny metal tube with two PZT plates attached to it at a 90° angle. When one PZT plate is excited with an alternating electrical current, the bending movement combines with the off-axis weight of the other plate to create a wobbling elliptical rotation, which is conveyed to a rotor. When current is applied to the other plate, the direction of rotation reverses. The tiny motor produces a torque of 1.0 mN•m at 1,800 rpm. This is 5 times the output power supplied by the smallest electromagnetic motor, which is 60 times larger in volume and uses 10 times as much input power as the Penn State motor does.

"Using a metal tube greatly decreases the cost of these motors as well," Uchino points out. "Metal tubes of this size are a mass-produced item, and the cost of materials for each motor is less than a penny. We expect that the whole motor could be produced for 40 cents."

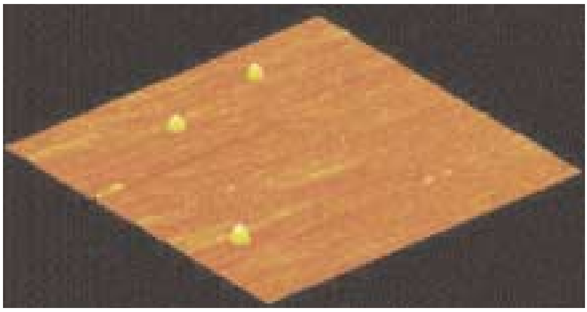
At 1.5 mm in diameter, the motor is small enough to probe the inside of the human body. For example, it could drive propellers on miniature cameras to survey a patient's digestive tract. Such a motor also could reduce the size of urinary catheters that are used to break up kidney stones, reducing the discomfort of the procedure, and the motor has sufficient power to disrupt the kidney stones. In addition, because the piezoelectric motor needs no magnetic materials and uses no magnetic fields, it can be used while the patient is viewed with magnetic resonance imaging, as is sometimes found necessary during microsurgery. Ω

Single-photon source

Sources that emit one photon at a time in a controllable fashion are essential for some types of quantum computing and for quantum-secured communications. If information is encoded by individual photons—for example by the polarization of the photon—no one could intercept or copy a message without the recipient noticing one or more missing photons. By their nature, single-photon-based messages can only be received by one recipient. Thus, a single-photon source could be used, for example, to distribute keys to conventional encryption schemes.

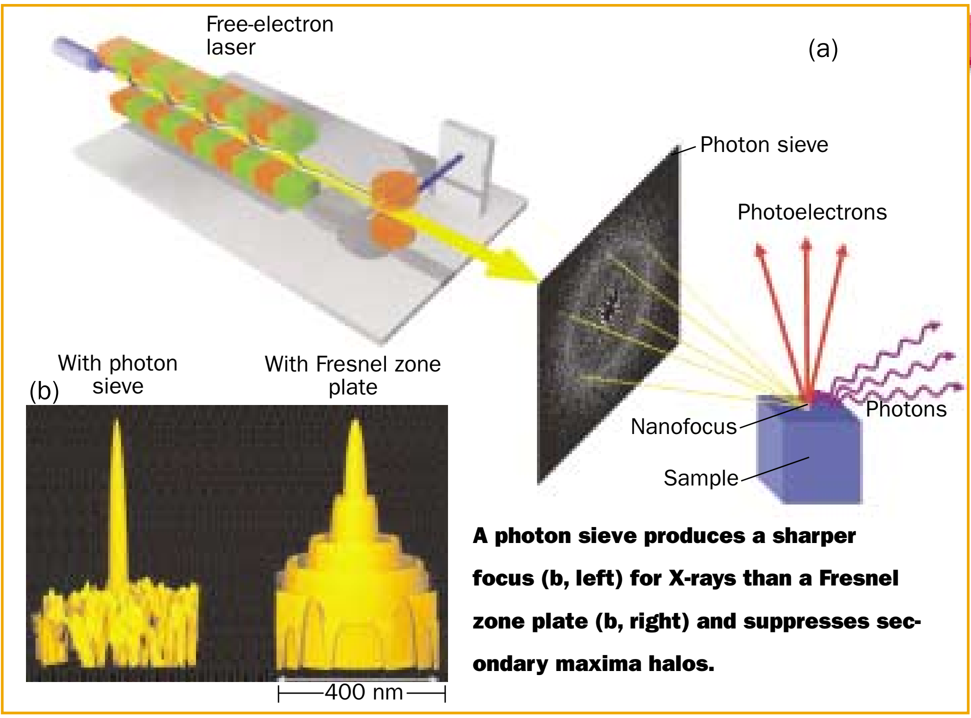
Just reducing the intensity of a laser will not produce single photons because lasers intrinsically produce a randomly distributed array of photons. Researchers showed that they could produce single photons by using a laser to excite individual molecules and cause them to fluoresce. But a practical device has been needed to convert electrical signals directly into single photons. A collaboration between researchers at Toshiba's Cambridge Research Laboratory and the University of Cambridge's Cavendish Laboratory in England has now produced such an electrically driven, single-photon source (*Science* **2002**, *295*, 102).

The device uses a layer of quantum dots in a light-emitting diode. A quantum dot is a tiny volume of a lower-bandgap semiconductor that traps pairs of electrons and holes. The quantum dots in this device are just 5 × 15 nm, so they contain only two electrons and two holes. When a tiny electrical pulse applies an electric field, the holes and electrons combine, emitting two photons at different wavelengths. A simple filter then selects the desired single photon.


Toshiba Research Europe Ltd.

When a tiny electric pulse is applied to a quantum dot 5 nm high and 15 nm in diameter separated from its neighbor dots, one of two emitted photons can be filtered out.

Such small dots cannot be produced by conventional lithography, but other researchers had already developed a method that allowed the dots to form by self-orga-



A photon sieve produces a sharper focus (b, left) for X-rays than a Fresnel zone plate (b, right) and suppresses secondary maxima halos.

Universität Kiel, Germany

nization at a density of $5 \times 10^8/\text{cm}^2$. Because each dot is separated from its neighbor by more than 500 nm, it is easy, with conventional lithography, to create an aperture that exposes only one of the quantum dots.

Although the team demonstrated that only single photons are emitted with each subnanosecond electrical pulse, “there is still some way to go to produce a useful device,” says Andrew Shields of Toshiba, one of the researchers. “First, we need to increase the temperature of operation, which is currently 5 K. We think we can do this by using dots with deeper confining potentials.” Deepening the dots’ potentials will also change the emitting wavelength to the 1.3-μm wavelength used in optical communications so that the photons can be fed through conventional fibers. Ω

Photon sieve for X-rays

Focusing X-rays for lithography, microscopy, and spectroscopy is not easy, especially for soft X-rays with an energy of around 1 keV, which are strongly absorbed by nearly all materials. X-ray mirrors, which use glancing reflection to focus the radiation, are difficult to fabricate. Thus, one popular technique has been to use Fresnel zone plates, which consist of alternating transparent and opaque rings. The interference effects generated between the rings create constructive interference only on the axis, focusing the X-rays. However, the size of the focal spot, around 20 to 40 nm, is limited by the minimum width of the rings, and that width, in turn, is dictated by the finest lines that can be drawn with current lithographic techniques.

Researchers at the University of Kiel and the University of Hamburg had another idea (*Nature* **2001**, *414*, 184). They designed a plate consisting of thousands of pinholes of various sizes and located their centers at the same distance from the axis as Fresnel zones. The size of the pinholes themselves was, of course, restricted by the same lithographic limitations as the width of the zones in a Fresnel lens.

But calculations had shown that the focal-spot size was determined by the spacing of the zone pattern and not by the diameter of the pinholes. Thus, by placing 20- to 40-nm pinholes in a pattern in which their centers are in zones only 6 nm wide, a much smaller focal spot can be generated. The size of the focal spot is limited only by the accuracy with which the pinholes can be placed, about 2 nm, which is much smaller than their diameters.

The pinhole array has another advantage. In Fresnel lenses, secondary maxima patterns create “halos” around the central focal spot. By adjusting the number of pinholes in each zone, maxima can be suppressed by several orders of magnitude, providing a much sharper focus.

There is one drawback to the photon sieves—only 15 to 20% of the radiation is passed through the sieve, as compared with the 50% that gets through the zone plates of a Fresnel lens. However, for many applications that use bright X-ray sources, this is not a large drawback.

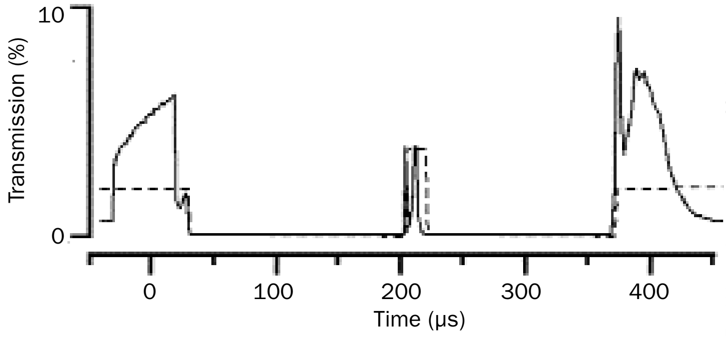
“We came up with this idea when we were looking for a way to exploit the extreme high intensity, monochromaticity, and coherence of the free-electron laser that we are planning to work with, which delivers 6-nm radiation,” explains Lutz Kipp of the University of Kiel, one of the researchers. “We’ve tested the idea experimentally using a helium–neon laser at 632 nm, and it works. So now we are planning to use it on a real free-electron laser.” The team calculates that the high-resolution focal spot will be best obtained with extremely monochromatic radiation, which the free-electron laser produces, with a bandwidth less than 1/10,000th its frequency. Ω

Stopping light in a solid

The ability to slow light to a crawl and even to “stop” it, thus freezing its quantum information for later release, caused excitement when researchers first achieved it in a gas in 1999. For one thing, quantum computing, which relies on preserving the quantum-mechanical phase of photons or other particles, could potentially use the stopped-light phenomenon as a quantum memory to store information.

For practical applications, however, it was highly desirable to stop the light in a solid rather than a gas, so that such devices could be integrated into the existing solid-state structures of microelectronics. This endeavor appeared difficult because to slow and stop light, lasers had to put atoms into particular energy states. And because solids have so many more atoms than gases for a given volume, excessively high laser power would be required to prepare all the atoms.

However, a collaboration between physicists at the Massachusetts Institute of Technology, Texas A&M University (College Station, TX), the Electronics and Telecommunications Research Institute (Daejon, South Korea), and the Air Force Research Laboratory (Hanscom Air Force Base, MA) has overcome this difficulty (*Phys. Rev. Lett.* **2002**, *88*, 023602-1). The researchers used rare-earth-doped insulators to generate an



Turukhin et al., *Phys. Rev. Lett.*, 88, 2, 023602-1, **2002**.

The speed of light (which is proportional to transmission) in an optically dense crystal is manipulated and "stopped" by switching a coupling laser on and off (dashed line).

extremely narrow absorption line that selected out only a few atoms with which the laser light could interact.

In the first step of the complex process, a coupling laser "burns" a hole of transparency in a broad absorption line by pumping electrons out of the absorbing energy states. This bleaches a transparent band, far narrower than the 4.4-GHz width of the absorption line. (The initial absorption band is broad because in a crystal, not all atoms are at exactly the same energy state. Inhomogeneities in the crystal modify the exact energy of each atom.)

Next, a second laser creates an antihole—an even narrower absorption line within the transparent hole. It does this by repumping a small number of electrons back into the absorbing energy states. But only those atoms whose energy states are exactly in resonance with the second, auxiliary laser get the repumped electrons and thus form part of the narrow absorption line. The new line is only a couple of megahertz wide, 1,000 times narrower than the initial line. "In this way, we have selected only a few atoms—about 1 in 1,000—to take part in the interaction," explains Alexey Turukhin, one of the researchers (now at JDS Uniphase, Eatontown, NJ).

These atoms are then prepared for the light-slowing interaction. A third, low-power probe laser carries the light to be slowed or stopped. The interaction of this light with the prepared atoms and the coupling laser beam produces a quantum phenomenon known as electromagnetically induced transparency in a frequency band only a few kilohertz wide. Reducing the bandwidth, in turn, produces an extremely high refractive index that slows the speed of the light to as low as 45 m/s. By manipulating the coupling laser's power, the slowed light can then be "stopped" and its quantum-phase information stored in the electronic structure of the crystal's atoms. Increasing the power of the coupling laser releases the stored photons.

In recent proof-of-concept experiments, the storage time was limited to 500 ms, but by improving the homogeneity of the underlying crystal, this time could be substantially extended, Turukhin believes, possibly creating a practical method for quantum-computing memory storage. Ω