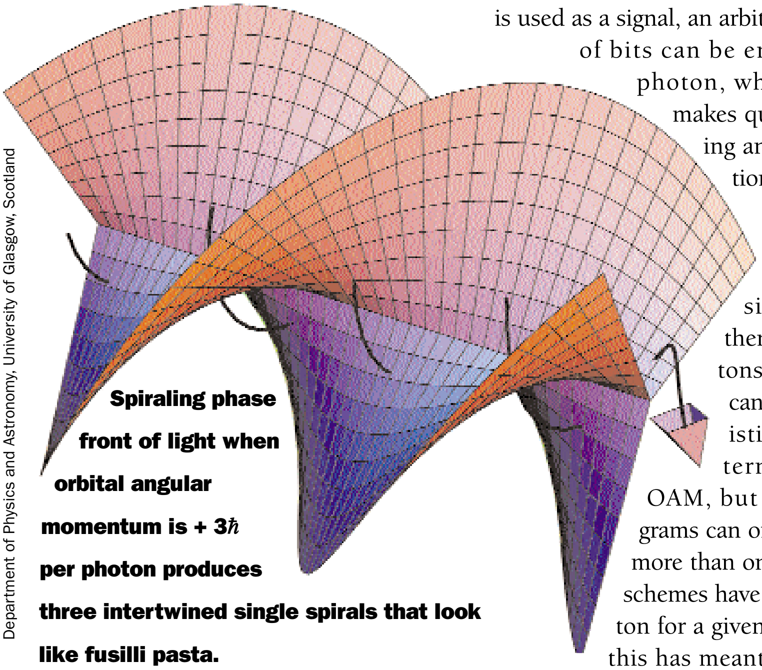
by Eric J. Lerner

Twisting single photons

Photons, like other particles, carry energy and angular momentum. Physicists have long known that a circularly polarized photon carries a spin angular momentum of $\hbar$—a fundamental constant equal to $h/2\pi$, where h is Planck's constant. But a decade ago, scientists calculated theoretically, and then demonstrated experimentally, that photons could also carry additional angular momentum, called orbital angular momentum (OAM)—in fact, an arbitrarily large amount of it in units of $\hbar$. OAM comes from the rotation of the phase front.



Spiraling phase front of light when orbital angular momentum is + 3$\hbar$ per photon produces three intertwined single spirals that look like fusilli pasta.

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"While the polarization spiral can only be a single spiral (in one direction or another), the phase front spiral can consist of an arbitrary number of intertwined single spirals; three intertwined single spirals, for example, would look like a fusilli pasta. Both polarization and phase front spirals travel through space and rotate around their respective axis," explains Johannes Courtial of the department of physics and astronomy at the University of Glasgow in Scotland. The greater the number of intertwined spirals, the larger the OAM.

This has a practical impact because the circular-polarization state of a photon (either clockwise or counterclockwise) can be used to convey information—one bit per photon. This is of particular interest in quantum computing schemes, in which single parts of individual photons can be used for quantum calculations. But if OAM is used as a signal, an arbitrary number (N) of bits can be encoded in each photon, which potentially makes quantum computing and other applications more likely.

The problem lies in reading the OAM from a single photon. If there are many photons, interferograms can reveal characteristic pinwheel patterns showing the OAM, but such interferograms can only be formed by more than one photon. Other schemes have tested each photon for a given OAM state, but this has meant that most photons would not be measured at all.

Now Courtial and colleagues at the University of Glasgow and the University of Strathclyde, also in Glasgow, have invented a way to sort OAM states with nearly 100% efficiency (*Phys. Rev. Lett.* **2002**, *88*, 257901-1). The device, which consists of a series of interferometers, rests on the idea of rotating the phase of the photon and then interfering it with itself. The photon input beam is split, and each half travels through a dove prism (a prism in the shape of a rhombus) before being recombined. The two half-beams are rotated relative to each other by an angle that is just twice the angle α between the two dove prisms.

If α, for example, is 90°, then the two half-beams will be rotated by 180°. In this case, when the OAM is an even number (that is, L is even where the OAM is $L \cdot \hbar$), the interference sends the photon out of the interferometer in one direction, and when L is odd, the photon goes in the other direction. Therefore, two OAM states can be distinguished for each photon in this manner.

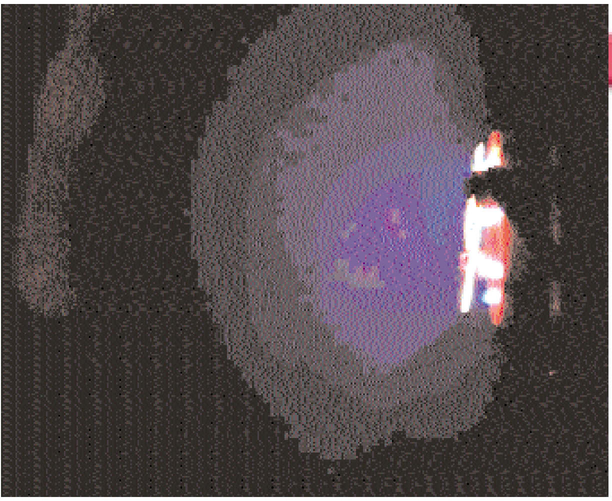
By stacking the Mach–Zender interferometers, as they are called, an unlimited number of different OAM states can be distinguished. In a second stage, sorted photons are sent through a second interferometer, with an α angle of just 45°, so four separate OAM states can be distinguished. In general, a photon carrying N bits of information can be "read" with N stages.

The ability to encode more information on each photon by this method may make such schemes as quantum computation and unbreakable coding more practical. When information is encoded by a single photon, no eavesdropper can intercept the information without destroying the photon. Ω

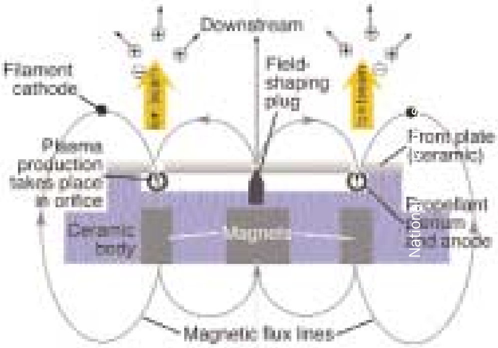
Pocket-size rocket

With the ultraminiaturization of sensors, the National Aeronautics and Space Administration (NASA) has long worked to develop microspacecraft that could deliver these tiny devices to distant worlds. A fleet of microspacecraft, for example, could return far more survey data from various sites on Mars than could a single large craft costing the same amount or more. To minimize fuel weight, plasma thrusters are needed that can deliver high exhaust velocity and, thus, more thrust per unit of propellant mass. But miniaturizing the units has proven difficult. The key problem is to efficiently ionize the propellant in a small space so that electric or magnetic forces can accelerate it.

Researcher John E. Foster at NASA's John Glenn Research Center (Cleveland, OH) may have developed a solution to the problem in the form of an extremely compact and efficient accelerator (*Rev. Sci. Instrum.* **2002**, *73*, 2020). The propellant is supplied through holes in a ring-shaped plenum 4 cm in diameter, which also serves as the positively charged anode. The anode ring is located above an annular magnetic cusp (a region of convergent magnetic field lines) created by a ring-shaped permanent magnet and a second disk-shaped magnet at the center of the ring. A heated ring filament, located above and outside the plenum



NASA John Glenn Research Center, Cleveland, Ohio



Electrons from the tiny cathode (glowing) spiral down the field lines toward the plenum anode and collide with neutral propellant atoms, creating ions that are accelerated downstream by the electrostatic potential.

anode, acts as an electron-emitting cathode.

The operation of the accelerators is based on the well-known principle that electrons can flow easily along magnetic field lines—which they circle around—but can move only with difficulty across field lines. Electrons from the cathode spiral down the field lines toward the plenum openings, where they collide with neutral atoms and ionize them. This frees the ions for acceleration by the electrostatic potential. But the electrons cannot move directly to the anode itself, which would short out the potential, because to do so they would have to cross the field lines. In addition, the sharp increases in magnetic field strength near the cusp create a magnetic mirror, which reflects most of the electrons back and traps them into an oscillation in which they continue to ionize more atoms. “The device traps electrons so well that 88% of the propellant is ionized,” says Foster.

Once the ions accelerate out of the cusp regions, they can recombine with electrons emitted from the filament. It is important that equal quantities of electrons and ions exit the accelerators, because if only ions did, a charge would build up on the spacecraft that would eventually prevent more ions from being accelerated.

In Foster’s experiments, xenon ions were accelerated to 80 eV or velocities around 11 km/s—higher than the 2 km/s available with chemical fuels and comparable to velocities obtained with larger plasma thrusters. “Right now I am looking at ways of increasing the beam current to scale up the total thrust,” says Foster. “We are also actively looking for missions that might use such a small thruster.” Ω

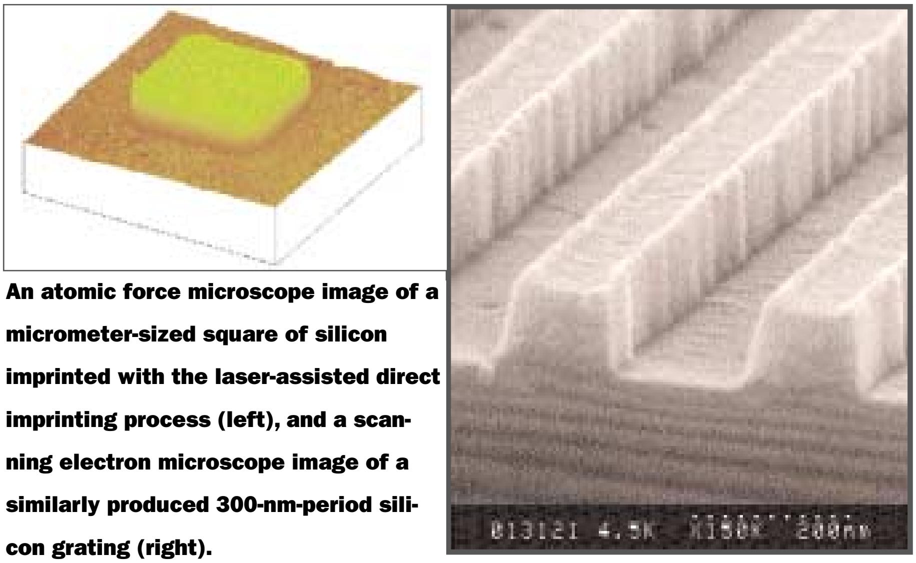
Printing on silicon

The semiconductor industry, although badly hit by a global downturn in demand, is still preparing for the expensive transition to new ways of making the tiny microcircuits that run all electronics. In a few years, the optical lithography process that has worked for decades will no longer suffice because the finest chip features, smaller than 50 nm across, cannot be resolved even with ultraviolet (UV) light. To reach shorter wavelengths, the industry plans to use soft X-rays, also called extreme UV or EUV. But this switch involves a complete change in manufacturing technology because lasers cannot produce EUV and conventional optics cannot focus it.

Researchers at Princeton University’s NanoStructures Laboratory may have devised a less-expensive alternative (*Nature* 2002, *417*, 835). Instead of exposing a photoresist material and etching away the part of the silicon not protected by the resist—as occurs in conventional lithography—Stephen Chou, Christopher Keimel, and Jian Gu use a 20-ns laser pulse to melt the silicon surface. A quartz mold, inscribed with the desired pattern, sinks into the molten silicon. Within 250 ns, the silicon solidifies into the mold’s pattern and the mold is withdrawn, leaving the completed design.

Because quartz is highly transparent to the 308-nm-wavelength laser light, there is no difficulty in shining it directly through the quartz mold. Once molten, silicon has a viscosity lower than that of water, so it flows swiftly and fills up the smallest details of the mold. In the Princeton experiments, small trenches 10 nm across were accurately reproduced as ridges in the silicon.

The quartz mold itself would have to be produced with X-ray or electron-beam lithography methods, and it would need features as small as those on the actual circuit. In contrast, the features of lithography masks are generally four times the size of those on the final device. However, the technology for making molds can be more expensive and slower than that for molding the chips



An atomic force microscope image of a micrometer-sized square of silicon imprinted with the laser-assisted direct imprinting process (left), and a scanning electron microscope image of a similarly produced 300-nm-period silicon grating (right).

Princeton University, Department of Electrical Engineering because each mold will produce thousands or even millions of chips during its lifetime.

The new technique, dubbed laser-assisted direct imprinting (LADI), would not require complex equipment to generate and focus X-rays, except for mold-making. It would also eliminate the etching step, thus providing additional cost savings and avoiding the use of large amounts of environmentally harmful chemicals.

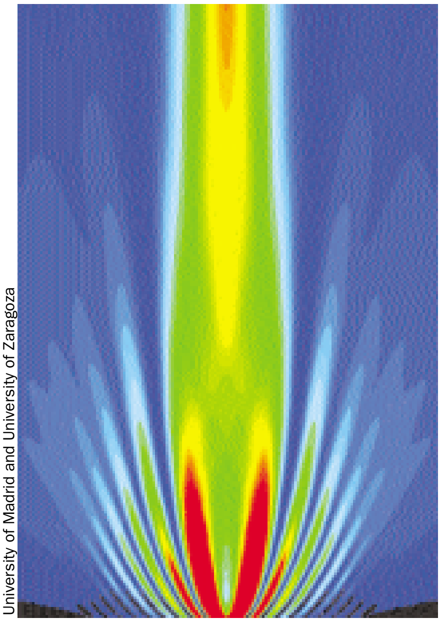
"Although the idea of melting the silicon may seem obvious, no one has thought of it before," says Keimel, a graduate student participating in the project. "Right now, we are looking at ways to extend the technology into patterning other materials used in integrated circuits, such as silicon dioxide, germanium, and metal conductors such as copper or aluminum." These substances have higher, and in some cases much higher, viscosity than silicon, but the researchers believe this will not pose a problem with very fine patterns because the distances the material must flow are so small.

This direct-print technique would involve substantial changes in manufacturing and design from the current expose-and-etch process. Given its simplicity and potential cost advantage, however, LADI may someday offer an alternative route to ultrafine-scale microcircuits. Ω

Light in tight places

Optical communication involves beaming light along controlled paths, just as electronics entails directing electrons. Electronic conduction can occur even at the scale of individual molecules, but there is a severe limit to the size of an aperture that light can pass through. Because of this well-known diffraction limitation, the passage of light drops sharply as the aperture diameter decreases below the wavelength of the transmitted light.

In addition, the light that emerges from an aperture narrower than half a wavelength is diffracted into a full half-sphere, making formation of a narrow beam impossible. The smallest wavelength of light easily focused is more than 400 nm—larger than the current scale of microelectronics. So the diffraction limit restricts the miniaturization of optical systems and creates problems in coupling light from tiny semiconductor lasers and light-emitting diodes (LEDs) into optical fibers.



University of Madrid and University of Zaragoza

Simulated profile of a light beam emerging from a subwavelength slit aperture in an optically thick silver film, surrounded by 10 parallel grooves of periodicity 500 nm.

But H. J. Lezec and T. W. Ebbesen, Louis Pasteur University (Strasbourg, France), R. A. Linke, NEC Research Institute (Princeton, NJ), L. Martin-Moreno, Universidad de Zaragoza (Zaragoza, Spain), and F. J. Garcia-Vidal, Universidad Autonoma de Madrid (Madrid, Spain) have found a way around this conventional diffraction limit, creating beams of light that are a factor of 5 narrower than allowed by the limit (*Science* **2002**, 297, 820). They did this by coupling the light to surface plasmons through a grooved bull's-eye pattern.

Surface plasmons are waves of electron density concentrated on the surface of metals. The researchers found that if a grating with a period equal to the wavelength of the transmitted light is inscribed on both surfaces around an aperture in a thin metal plate, the plasmons can be coupled to the light emerging from the aperture. In their experiments, the physicists passed light through a 300-nm-diameter hole surrounded by a bull's-eye groove pattern. The grooves in the bull's-eye were spaced 600 nm apart. (See *The Industrial Physicist*, June/July 2002, pp. 12–13, for another application of surface excitations.)

Remarkably, at a narrow range of wavelengths centered at 660 nm, light emerged from the aperture in a beam with a divergence of only 3°. Without the bull's-eye grooves, the divergence would have been the full 180° of a half-sphere. The light emerged from a region wider than the aperture, which showed that the metal was indeed emitting radiation, but the emitting region was about 750 nm across. To obtain a similarly narrow beam at this wavelength would require a conventional aperture 4,900 nm in diameter. The intensity of the light transmitted was also 10-fold higher than for a conventional aperture.

The experimenters explain this phenomenon as the result of the interference of light emitted from the rings of the bull's-eye with the light transmitted through the aperture. In effect, the bull's eye—by coupling the light through the plasmons and then reemitting it—acts in the same way as a phased-array radar, which produces a narrow beam of radiofrequency waves through the interference of a large array of small emitters. The full 4,800-nm width of the bull's-eye pattern is involved in shaping the beam, not just the 300-nm-wide aperture. Destructive interference prevents light from being emitted in any direction except that perpendicular to the surface and creates a narrow beam.

Collimated beams only a wavelength of light in diameter could greatly reduce the divergence of light from LEDs and semiconductor lasers to increase their coupling into optical fibers and produce miniaturized beams for microscopy and data storage. In addition, such tight beams might transmit data optically in the increasingly cramped space of microcircuits. Ω