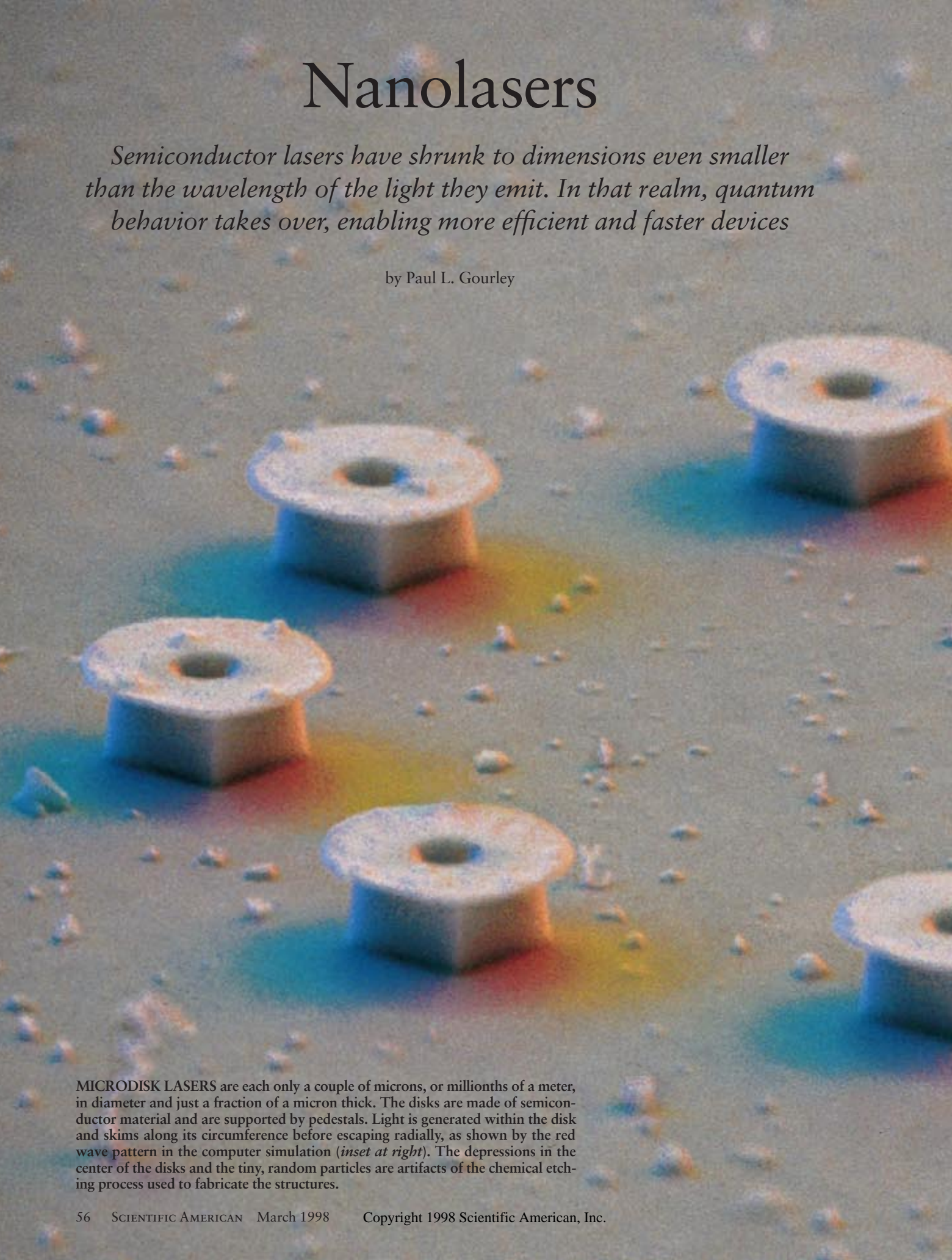


Nanolasers

Semiconductor lasers have shrunk to dimensions even smaller than the wavelength of the light they emit. In that realm, quantum behavior takes over, enabling more efficient and faster devices

by Paul L. Gourley



MICRODISK LASERS are each only a couple of microns, or millionths of a meter, in diameter and just a fraction of a micron thick. The disks are made of semiconductor material and are supported by pedestals. Light is generated within the disk and skims along its circumference before escaping radially, as shown by the red wave pattern in the computer simulation (*inset at right*). The depressions in the center of the disks and the tiny, random particles are artifacts of the chemical etching process used to fabricate the structures.

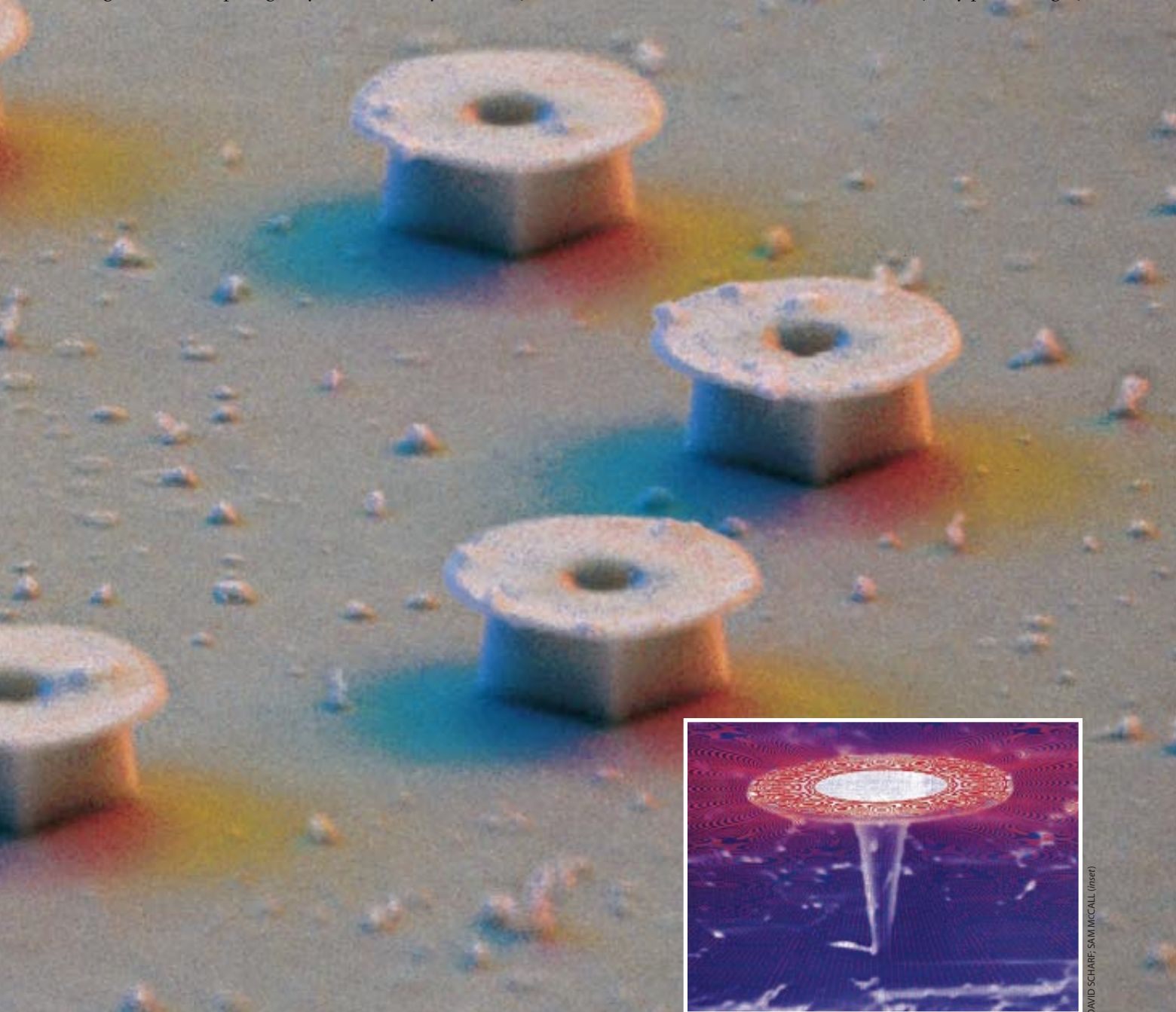
For decades, silicon transistors have become smaller and smaller, allowing the fabrication of tiny but powerful chips. Less well known is the parallel revolution of semiconductor lasers. Recently researchers have shrunk some of the dimensions of such devices to an astonishing scale of nanometers (billionths of meters), even smaller than the wavelength of the light they produce. At such sizes—less than one hundredth the thickness of a human hair—curious aspects of quantum physics begin to take over. By exploiting this quantum behavior, researchers can tailor the basic characteristics of the devices to achieve even greater efficiencies and faster speeds.

Nanolasers could have myriad applications, for instance, in optical computers, where light would replace electricity for transporting, processing and storing information. Even though light-based computing may not occur anytime soon, other

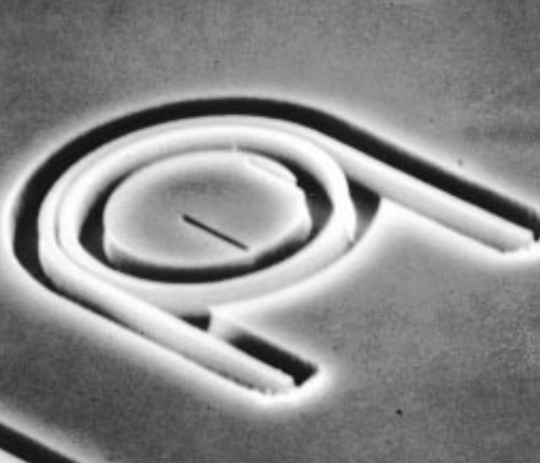
uses, such as in fiber-optic communications, have now become increasingly practical. With other researchers, I am also investigating the new lasers for novel purposes, such as the early detection of disease.

Jumping Electrons

Although nanolasers push the boundaries of modern physics, the devices work much like their earliest ancestor, a contraption fashioned from a rod of dark ruby more than 35 years ago. Essentially, a lasing material—for example, a gas such as helium or neon, or a crystalline semiconductor—is sandwiched between two mirrors. The substance is “pumped” with light or electricity. The process excites the electrons in the material to hop from lower to higher energy levels. When the electrons return to the lower stations, they produce light,



DAVID SCHARF; SAM MCCALL (inset)



SENG-TONG HO/Northwestern University

MICRORING LASER is surrounded by a U-shaped glass structure that guides the light out of the device in two parallel beams along the legs of the U. The laser is essentially an extremely thin semiconductor wire—with a rectangular cross section of 400 by 200 nanometers, or billionths of a meter—curled into the shape of an ultrathin doughnut.

which is reflected between the mirrors.

The bouncing photons trigger other “excited” electrons—those in higher energy states—to emit identical photons, much like firecrackers that pop and set off other firecrackers. This chain reaction is called stimulated emission. (Hence the name “laser,” which is an acronym for “light amplification by stimulated emission of radiation.”) As the number of photons grows, they become part of a communal wave that intensifies, finally bursting through one of the mirrors in a concentrated, focused beam.

But not all the photons take part in this wave. In fact, many are emitted spontaneously, apart from the chain reaction. In a large space—to a subatomic particle, the size of a typical laser cavity is immense—photons are relatively free to do what they want. Thus, many of the free-spirited photons are literally on a different wavelength, and they can scatter in all directions, often hitting the sides of the laser and generating unwanted heat instead of bouncing between the mirrors. For some types of lasers, only one photon in 10,000 is useful.

Because of this enormous waste, a certain threshold of energy is necessary to ensure that the number of excited electrons is large enough to induce and maintain stimulated emission. The requirement is analogous to the minimum amount of heat needed to bring a pot of water to boil. If the hurdle is not cleared, the laser will fail to attain the self-sustaining chain reaction crucial to its operation. This obstacle is why semiconductor lasers have required relative-

ly high currents to work, in contrast to silicon transistors, which are much more frugal. But if semiconductor lasers could stop squandering energy, they could become competitive with their electronic counterparts for a host of applications, including their use in computers.

Recently the concept of “thresholdless” operation has become increasingly favored by many physicists. Proposed by Yoshihisa Yamamoto of NTT Basic Research Laboratories and Stanford University and Takeshi Kobayashi of Osaka University in Japan, thresholdless operation calls for all photons, even those spontaneously born, to be drafted into lasing duty. In theory, the device would require only the tiniest amount of energy, almost like a special kettle that could boil water with the heat of just a single match. Researchers disagree about the best design of such a laser. The consensus, though, is that the dimensions must be extraordinarily small—on the order of the wavelength of light emitted—so that the devices could take advantage of quantum behavior.

A New Generation

The groundwork for thresholdless operation was set in the late 1970s, when Kenichi Iga and other researchers at the Tokyo Institute of Technology demonstrated a radically different type of semiconductor laser [see “Microlasers,” by J. L. Jewell, J. P. Harbison and A. Scherer; *SCIENTIFIC AMERICAN*, November 1991]. Popularly referred to as microlasers because of their micron-size dimensions, these devices are cousins to the semiconductor diode lasers widely found in compact-disc players. (“Diode” refers to a one-way flow of electricity during operation.)

Microlasers, however, differ from their common diode relatives in several fundamental ways. The latter are shaped like rectangular boxes that must be cleaved, or diced, from a large wafer, and they issue light longitudinally from the cut edges. Microlasers are smaller, cylindrical shapes formed by etching, and they emit light from the top—perpendicular to the round layers of semiconductor material that make up the device. Therefore, microlasers produce more perfectly circular beams. In addition, they can be built and tested many at a time in arrays on a wafer, similar to the way in which computer chips are fabricated. In contrast, diode lasers must generally be tested individually after

having been diced into separate units.

Perhaps more important, microlasers exploit the quantum behavior of both electrons and photons. The devices are built with a “well”—an extremely thin layer of semiconductor only several atoms thick. In such a minute space, electrons can exist only at certain discrete, or quantized, energy levels separated by forbidden territory, called the band gap of the semiconductor. By sandwiching the quantum well with other material, researchers can trap electrons and force them to jump across the band gap to emit just the right kind of light.

Microlasers must also imprison photons to function. To accomplish this feat, engineers take advantage of the same effect that causes a transparent window to display a faint reflection. This phenomenon results from glass having a higher refractive index than air—that is, photons move more slowly through glass. When light passes between materials with different refractive indices, some of the photons are reflected at the border. The mirrors of microlasers consist of alternating layers of semiconductors with different refractive indices (such as gallium arsenide and aluminum arsenide). If the layers are just one quarter of a wavelength thick, the geometry of the structure will allow the weak reflections to reinforce one another. For the coupling of gallium arsenide and aluminum arsenide, a dozen pairs of layers will bounce back 99 percent of the light—a performance superior to that of polished metal mirrors commonly found in bathrooms.

Already the first crop of microlasers has found commercial applications in fiber-optic communications. Other uses are currently under investigation [see *box on page 60*]. Meanwhile ongoing work continues to refine the structures. In one recent device, certain layers are selectively oxidized, which helps to raise the population of excited electrons and bouncing photons in the well area, resulting in an operating efficiency greater than 50 percent. In other words, the laser is able to convert more than half the input energy into output laser light. This performance far exceeds that of semiconductor diode lasers, which are typically not even 30 percent efficient.

Microlasers have led to a new generation of devices that exploits electronic quantum behavior further. Scientists have now built structures such as quantum wires and dots that confine electrons to one and zero dimensions, re-

spectively. (Wells restrict them to two.) Additionally, in a fundamentally new device called the quantum-cascade laser, researchers at Bell Laboratories have strung together many quantum wells, like a series of small waterfalls. In such a laser, an electron returning to a lower energy state will not take one big band-gap jump but multiple smaller ones, emitting a photon at each successive hop—thereby increasing the lasing chain reaction. An exciting feature of this innovative laser is that it allows engineers to tailor the type of light produced by adjusting the width of the wells; therefore, the electronic band gap of the material—a property ordained by nature—no longer dictates the kind of photons produced.

In a separate but related track of research, scientists have been exploring quantum-optical behavior. To do so, investigators have had to shrink some of the dimensions of the devices to smaller than even the wavelength of the light emitted. In that microscopic world, photons are restricted to certain discrete states, similar to the restraints placed on electrons trapped in quantum wells.

A Short Guitar String

Large lasers emit various types of photons, just as a long guitar string, when strummed, produces a sound consisting of a fundamental frequency (cor-

responding to the pitch) and many overtones. But as the guitar string is made shorter, the pitch becomes higher and the number of overtones decreases until the process reaches a limit decreed by the thickness and type of material of the string.

Similarly, physicists have been shrinking lasers to restrict the number of states, or modes, that the photons can inhabit. A limit to this miniaturization is one half the wavelength of the light emitted, because this dimension is the smallest for which the light is able to bounce between the mirrors. At this minimum boundary, photons would have just one possible state, corresponding to the fundamental optical mode of the device. Because of this Hobson's choice, every photon would be forced to contribute to the communal wave (the fundamental mode) that intensifies into the beam of light that finally bursts through one of the mirrors. In other words, no photons would go to waste: the laser would be thresholdless.

With colleagues at Sandia National Laboratories, I observed such quantized photon states in experiments more than a decade ago. By bringing the end mirrors of a microlaser closer, we were able to squeeze the broad spectrum of photons emitted into just a few optical modes. We showed that these modes occurred at wavelengths whose integral multiples were equal to the round-trip

distance between the mirrors, in the same way that a guitar string can vibrate with four or five wavelengths between its fixed ends but not with four and one-sixth wavelengths. Furthermore, we verified that we could enhance these effects by moving the mirrors closer, approaching the limit of one half wavelength (hundreds of nanometers). But these devices were not yet thresholdless. Even the most advanced microlasers, which might now be legitimately called nanolasers, allow about 100 photonic states—much improved from the tens of thousands of options available to photons in conventional diode lasers but still not acceptable for entrance into thresholdless nirvana.

To achieve that ideal, researchers have recently begun to investigate other nanometer-scale geometries. One such design is the microdisk laser, developed by Richard E. Slusher and his colleagues at Bell Labs. With advanced etching processes similar to those used to fabricate computer chips, the Bell Labs researchers have been able to carve an ultrathin disk a couple of microns in diameter and just 100 nanometers thick. The semiconductor disk is surrounded by air and supported by a tiny pedestal, making the overall structure look like a microscopic table.

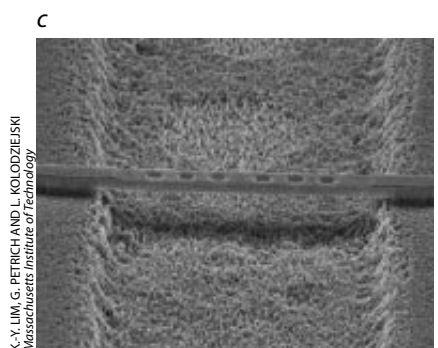
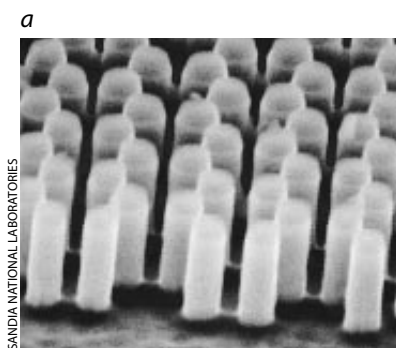
Because the semiconductor and air have very different indices of refraction, light generated inside the disk reflects

Photonic Lattices Block Light

Tiny gallium arsenide posts will block infrared light when the individual columns are arranged in a hexagonal lattice of just the right spacing (a). The periodicity of the structure, combined with the difference in the speed of light through the semiconductor posts and the surrounding air, results in multiple refractions and reflections that effectively block light over a range of wavelengths, as shown in a light-scattering micrograph (b) of a similar lattice (inset in b).

The concept also works in one dimension, as demonstrated by

a semiconductor bridge punched lengthwise with holes (c). Light traveling across the bridge is blocked by the one-dimensional "array" of holes, which are analogous to the posts in the hexagonal lattice. By purposely introducing a "defect"—the slightly larger spacing between the two holes in the center of the bridge—researchers can change the reflection and refraction pattern within the structure. The irregular spacing circumscribes a minuscule "box," with a volume of only a twentieth of a cubic micron, that could be developed into a laser. —P.L.G.

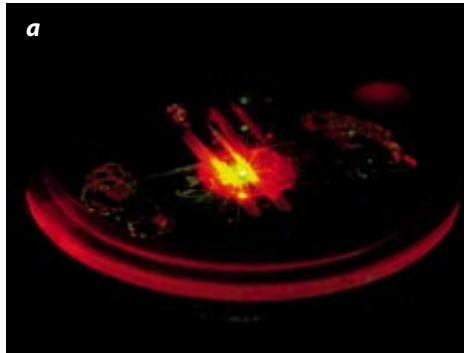


Biocavity Lasers for Disease Detection

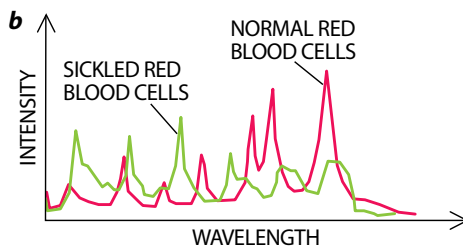
As semiconductor lasers continue getting smaller, faster and more efficient, they will enable an increasing number of novel applications. One possibility is the detection of disease. At Sandia National Laboratories, my colleagues and I have developed a “biocavity laser” (a), which can, for example, be used to distinguish cancerous cells from normal ones.

The device is basically a microlaser—a tiny piece of gallium arsenide sandwiched between two mirrors. Infrared light that the semiconductor compound emits will repeatedly bounce between the mirrors, intensifying until it finally bursts out of the structure in a concentrated laser beam. To build a biocavity laser, we placed a thin layer of human tissue between the gallium arsenide and one of the mirrors. The organic material becomes part of the device itself, acting as an internal lens to focus the light. Thus, the size, shape and composition of the cells alter the laser beam by introducing overtones that result in a unique spectral signature. Doctors can use that information to distinguish between diseased and healthy tissue because the two types will result in different light spectra (b), just as a piccolo and flute playing the same note can be discerned by the distinct sound spectra of overtones produced by the two similar—yet unique—instruments.

Recently Anthony McDonald, Guild Copeland and I at Sandia



SANDIA NATIONAL LABORATORIES; JOHNNY JOHNSON (diagram)



worked with my brother Mark Gourley, an immunologist at the National Institutes of Health, to patent a portable, handheld version of the biocavity laser that doctors can use to analyze blood without having to send samples to a laboratory. In the device, blood flows through tiny grooves, each just a tenth the width of a human hair, that have been etched into one of the mirrors. By analyzing the resulting laser beam, the device can quickly detect the presence of crescent-shaped red blood cells—an indicator of sickle cell anemia. Doctors could also use the laser to study nanometer-scale changes in the cellular structure of blood that might be caused by the AIDS virus.

In other experiments, biocavity lasers have also been able to discriminate between normal and cancerous cervical cells, as in Pap smears. Further advancements might even lead to a device for analyzing DNA.

The new technology boasts several advantages over conventional methods of tissue analysis, which require chemical staining to make cellular structures visible under microscopic examination in the lab. Such techniques rely heavily on qualitative human vision and are thus prone to error. In contrast, biocavity lasers produce simple, straightforward spectra that a handheld device can analyze almost instantly in clinics, offices and research laboratories, as well as in the field.

—P.L.G.

within the structure, skimming along its circumference. The effect is similar to the “whispering gallery” sound waves first described by Lord Rayleigh more than a century ago. The physicist explained how conversations can be heard at opposite ends inside the great dome of St. Paul’s Cathedral in London because the audible vibrations reflect off the walls and reinforce one another.

The tiny size of the microdisk restricts the photons to just a limited number of states, including the desired fundamental optical mode, while the whispering-gallery effect confines the photons until the light wave generated has built up enough energy to burst outside the structure. The result is extremely efficient operation with a low threshold. In fact, these microdisk lasers have worked with only about 100 microamps.

A variation of the microdisk is the microring laser, which is essentially a photonic wire curled into the shape of an ultraskinny doughnut. Seng-Tiong Ho and his colleagues at Northwestern

University used microlithography to etch such a semiconductor structure with a diameter of 4.5 microns and a rectangular cross section measuring only 400 by 200 nanometers. To improve the quality of the light emitted, the Northwestern researchers surrounded the microring with a U-shaped glass structure that guides the photons out in two parallel beams along the legs of the U.

These novel devices have proved how the size and shape of a nanolaser can affect its operation by controlling the quantum behavior of the photons emitted. Investigators have recently pushed the technology even further, shrinking photonic wires to an amazing volume of just one fifth of a cubic micron. At that dimension, the structure has fewer than 10 photonic states—which approaches the conditions required for thresholdless operation.

Although these new nanolasers have reduced the *types* of photons to quantum-mechanical levels, they have not decreased the *number* of photons to

such limits. With a small enough population, the behavior of light can be fundamentally altered for useful purposes. In recent landmark work, researchers at the Massachusetts Institute of Technology have shown that single excited atoms of barium can be fed one by one into a laser, with each atom emitting a useful photon. This incredibly efficient device is able to work with just 11 photons bouncing between the mirrors. Physicists are currently investigating such novel quantum optics for semiconductor nanolasers.

Stopping Light Periodically

A radically different approach to the design of nanolasers is to build a structure with materials that alternate at regular tiny intervals. If designed properly, the periodic modulation will imprison light by repeatedly reflecting it within the structure. This concept was first deployed by scientists who engineered the layered mirrors of micro-

lasers, which contain light in one dimension. Eli Yablonovitch, now at the University of California at Los Angeles, and researchers at the Department of Energy Ames Laboratory at Iowa State University extended the principle into two and three dimensions by proposing new structures called photonic lattices.

The overall concept is based on a phenomenon observed in the early 1900s by the father-and-son team of William Henry Bragg and William Lawrence Bragg. The English physicists, who shared a Nobel Prize in 1915, studied how x-rays striking a crystal will backscatter in a manner dependent on the periodic structure of the crystal lattice. In what is now known as Bragg's law, the two scientists stated that the intensity of reflected radiation depends on three factors: the wavelength of the x-rays, the spacing of the atoms in the crystal and the angle at which the x-rays strike the lattice.

Applying this knowledge to optical frequencies, investigators such as Thomas F. Krauss and Richard M. De La Rue of the University of Glasgow have shown that a lattice of two different alternating materials will backscatter light in a similar way. Furthermore, by using materials of very different indices of refraction and by selecting the right periodic spacing between those substances, researchers have shown that they can tailor and extend the range of wavelengths that the device reflects, in effect creating a "photonic band gap" similar to the forbidden territory of electrons in semiconductors.

At Sandia, Joel Wendt, Allen Vawter and I fabricated such a structure by building a hexagonal lattice of gallium arsenide posts—a design that was developed by John D. Joannopoulos and other researchers at M.I.T. By taking into

account the different indices of refraction of gallium arsenide and the surrounding air, we determined the exact spacing of the posts necessary to trap infrared light.

Although we have demonstrated the feasibility of confining light in this two-dimensional array, we have not yet been able to turn the structure into a laser. One possible way to do so would be to pump one of the posts, making it emit light, which would then be repeatedly reflected (and effectively contained) by the other posts in the array. Basically, the lattice would act like the parallel mirrors in a traditional laser.

Using a reverse design in which the "posts" are made of air and the surrounding material is a semiconductor, the M.I.T. researchers have fabricated a tiny silicon bridge (470 nanometers wide and 200 nanometers thick) etched lengthwise with a single row of microscopic holes. Light is confined to traveling across the structure because of the difference in indices of refraction between the semiconductor and the surrounding air.

The M.I.T. scientists, including Joannopoulos, Pierre R. Villeneuve and Shanhui Fan, used computer simulations to determine the precise periodic spacing of the holes in order to define a one-dimensional array suitable for confining infrared light. Furthermore, the researchers introduced a "defect" into the lattice by making the distance between two adjacent holes near the center of the strip slightly larger. The irregularity creates a fundamental optical mode within the minuscule volume circumscribed by the nonuniform spacing. This "box" might one day be developed into a laser cavity, with the adjacent holes acting like mirrors. Amazingly, the box is a mere twentieth of a cubic micron.

The M.I.T. group has since refined the structure, building it on a glass base, and has verified the computer simulations with experimental results.

Other work has investigated photonic lattices that vary periodically in three dimensions. But such structures have been difficult to build because microfabrication techniques such as electron-beam lithography are more suited for the two-dimensional patterning of chip-making. Still, three-dimensional photonic lattices would theoretically confine light in all directions—an ideal feature for a thresholdless laser.

Whither Optical Computers?

In addition to higher efficiency, thresholdless operation could lead to ultrafast devices, which can be switched on and off instantaneously because they require such little energy for lasing to occur. In other words, waiting for a pot of water to boil can be brief if just one match will do the trick. Already some lasers can be switched on and off faster than 20 billion times a second.

Such blinding speeds are a natural for fiber-optic communications. Other applications will arise as these devices continue to become even faster, smaller and more energy-efficient. Thresholdless lasers, now a distinct possibility because of recent advances in the fabrication of structures of nanometer scale, hold great promise as components for transmitting, storing and manipulating information—that is, as the crucial building blocks for an optical computer. Ironically, advances in the shrinking of silicon transistors have enabled substantial improvements in semiconductor lasers, which could one day power computers and replace those tiny electronic circuits with optical ones. 5A

The Author

PAUL L. GOURLEY is currently with Sandia National Laboratories, where he has been a principal investigator in the laboratory's fundamental work in semiconductor vertical-cavity, surface-emitting lasers. He earned an undergraduate degree in physics from the University of North Dakota and M.S. and Ph.D. degrees in physics from the University of Illinois. A fellow of the American Physical Society and the Optical Society of America, Gourley has received awards from *R&D* magazine for his invention of the biocavity laser and from the Department of Energy for his work in semiconductor photonics. His research interests include the study of semiconductor devices such as nanolasers and their various applications, particularly those in the biomedical field.

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