The Light and Sound Fantastic

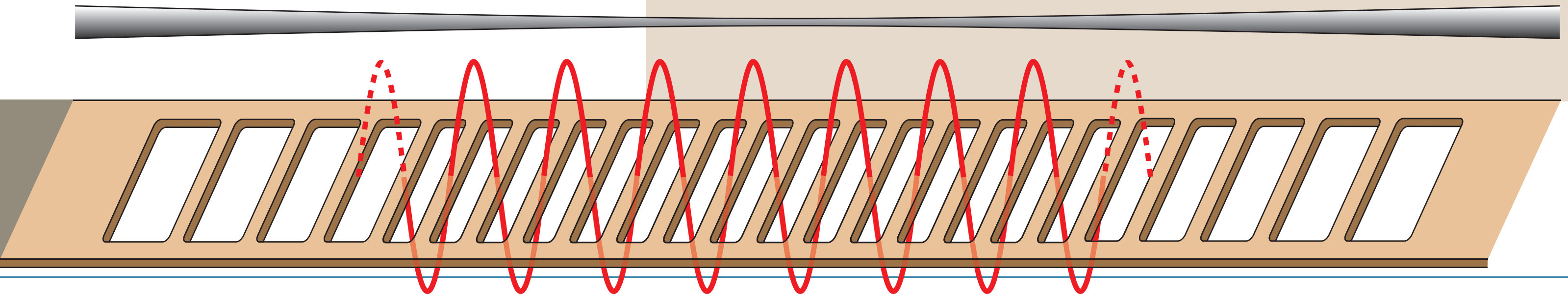
By Douglas L. Smith

A "dabbling" in quantum mechanics leads to a marriage of sound and light on a chip. This could open the door to using sound energy in ways we can't even imagine yet.

Self-styled psychic Uri Geller "bends" spoons with his mind. Associate Professor of Applied Physics Oskar Painter (MS '95, PhD '01) bends silicon with light. In both cases, concentration is the key. Painter's light is trapped in a nanoresonator—a set of tiny spaces each only half the light's wavelength long. Each photon rattles around for a billionth of a second or so, bouncing back and forth some million times in the process.

Trapping light is nothing new, but these cages are so insubstantial that the photons' gentle push makes them flex—vibrate, in fact. They ring, they buzz, they hum, and although this sound is not audible, it is indeed a sound—packets of sonic energy, or pho*n*ons. In fact, converting the photons into phonons—and phonons back to photons again—is as easy as penciling an "n" in over the "t."

Below: Photons can only run along the bridge for as far as their wavelength matches the planks' spacing. The optical fiber taper is in the background.
Opposite: Grad student Matt Eichenfield aligns a microchip with the optical fiber at the test station.



"What is new here is the ability to manipulate sound in a circuit with the same level of control, and in almost the same way, that we manipulate light or electrons," says Painter's collaborator Kerry Vahala (BS '80, MS '81, PhD '85), the Jenkins Professor of Information Science and Technology and professor of applied physics. "It helps to level the playing field for these three different particles—electrons, photons, and phonons." In other words, the door is now open to using all three information carriers on the same piece of silicon, swapping between them as best suits your purpose. Says Painter, "All three can live on the surface of a microchip and can be connected, much like wires can, in your microelectronic circuit."

Any such circuit's phononic components would not be digital, at least not yet, but that's OK. Says Vahala, "In the beginning, electronics were entirely analog. Analog components like oscillators and amplifiers are still vital to modern radio, microwave, and lightwave communications. In fiber-optic systems, lasers provide an electronic-to-optical translator so that digital signals are transmitted through an essentially analog optical system. And now we've created a translator that can shift sound into coherent light, and light into coherent sound."

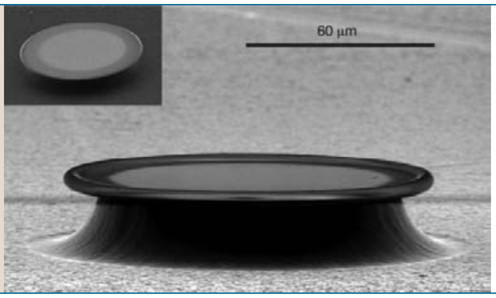
This translator, properly called an optomechanical crystal, looks somewhat like the uninviting rope bridge in an Indiana Jones movie . . . while it still has all its floorboards, *before* anyone sets foot on it. The bridge spans what is essentially a bottomless chasm in the microchip, with the spacing between the 16 floorboards at the midpoint of the bridge being one-half the wavelength of the light to be trapped. The floorboards get farther apart on either side of this zone as you move toward the safety of the banks, a mirror-mimicking design that keeps the light confined at midspan. Photons run with a fixed stride—their wavelength—and if the available footing doesn't match their pace, they have to turn back. Thus no light leaves the bridge; furthermore, none creeps in from the silicon banks on either side.

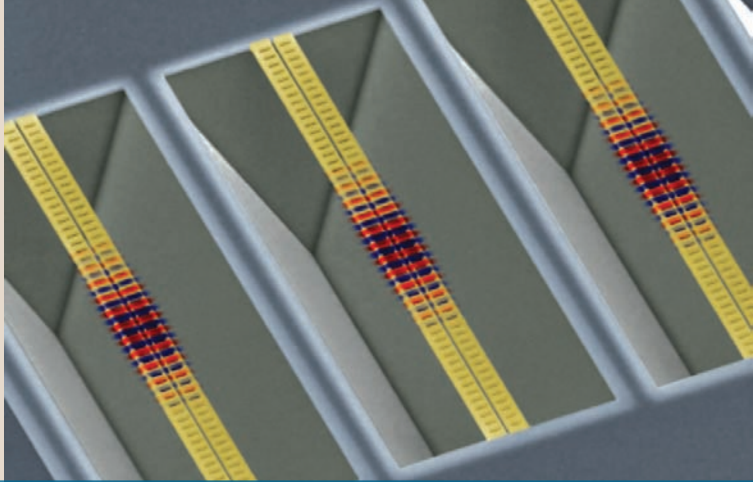
Which brings us to the question of how the light gets into the bridge in the first place. Just after getting his PhD in 2001, Painter was briefly a postdoc in Vahala's lab. At the time, Vahala's group was beginning to make tiny doughnut-shaped optical resonators on chips—little rings of silicon around which photons could race. The question arose of how to feed in the light, and Vahala recalled a possible technique that had been briefly described in a 1997 paper by a group led by Philip Russell, then at the University of Bath. "Oskar was deeply involved in perfecting this optical taper technology here at Caltech," says Vahala.

The optical taper is simplicity itself. Take a standard fiber-optic line some 125 microns (millionths of a meter) thick, heat it in a hydrogen flame so as not to affect the glass chemically, and stretch it thin, thin, thin until it's only about one micron in diameter. Says Vahala, "It's so narrow you can literally think of the light as being pushed out of the fiber." The light's electromagnetic field extends slightly beyond the confines of the glass, leaking out like water from an old, overpressurized garden hose that begins to split along its length. "About one percent of the light can't fit through the pipe, so to speak," Vahala continues, "so there's a little bit of optical energy available in the air outside the glass." If you put the taper parallel to, and within about a micron of, your resonator, some of that "outside" light can be siphoned off into the resonator. It doesn't take much, says Vahala. "A very tiny fraction of a percent is enough. It's like giving a very tiny nudge to a pendulum at the same point in its swing every time—eventually you get a huge effect."

The next step came around 2004, when the doughnut-resonator studies took an unforeseen turn. As the photons chased their tails around the ring, the doughnut was found to actually expand and contract slightly. It turned out that the photons were transferring energy to the doughnut, causing it to vibrate. These oscillations, in turn, imprinted themselves onto the light leaking from the resonator back into the taper. (The light bleeds out of the resonator for the same reason it leaks out of the taper—the resonator is too small to completely contain the electromagnetic field.) Meanwhile, Painter, by then an assistant professor, was mining the vein he had started as a PhD student—trapping and manipulating light on a chip using micromachined structures called photonic crystals. Painter approached Vahala about applying the same methods to engineer a mechanical system that would oscillate with the oscillating light.

One of Vahala's original optical resonators sits on its silicon pedestal. The light is trapped in the bulge that circles the rim, and the out-of-focus horizontal gray line in the foreground is the fiber-optic taper. The scale bar is 60 microns, or millionths of a meter.
(From D. K. Armani et al., *Nature*, Vol. 421, pp. 925–928, Feb. 27, 2003. Reprinted by permission from Macmillan Publishers Ltd.)





A rendering of three optical zippers on a microchip. (Fiber tapers not shown for clarity.) Each bridge is about 30 microns long and one micron wide. The gap down the middle is 120 nanometers, or billionths of a meter. The red and blue bands show the light's phase. When the two bridges are in phase, as seen here, they are pulled toward each other and the zipper zips up. When the light is out of phase, the bridges repel each other and the zipper unzips.

THE BRIDGES OF MATTHEW EICHENFIELD

Painter's original notion was simply to make the bridge sway, as if it were being buffeted by a high wind. The collaboration's first project, built by grad student Matt Eichenfield (MS '07) and postdoc Ryan Camacho, consisted of two parallel silicon-nitride bridges—two independent resonators—spaced 120 nanometers, or billionths of a meter, apart. Simulations by grad student Jasper Chan had shown that the bridges should shove each other sideways as a consequence of the trapped light's tight confinement. Again, some of the electromagnetic field leaks out, but now the field's intensity falls off so rapidly that the gradient itself exerts a perceptible force on the other bridge.

As Vahala explains, "If you scanned a light meter across a tightly focused laser beam, the light intensity would be seen to rise and then fall again. And if a small particle of glass passed through that little spot, there would be a very weak force exerted by the light field that would actually pull the glass in toward the center of the spot. The higher the intensity, the deeper the potential well." (Biologists use lasers this way to shove DNA strands, viruses, and even living cells around with so-called optical tweezers.)

Chan's simulations showed that the two bridges could sway in sync with each other, bending in the same direction at the same time, or they could move in opposite directions, spreading apart like a zipper unzipping. The device was thus promptly dubbed the "optical zipper," a much catchier name than the usual "optomechanical cavity." The zipper worked as predicted, and Eichenfield was the lead author on the *Nature* paper that announced it on May 28, 2009.

As the bridges moved, the width of the gap between them changed, and the properties of the light field in that cavity changed as well. The resulting pulses, one per sway, could be read off by measuring the light coming out of the taper lying suspended alongside the bridges—very much the way the whole field had started four years earlier—and the dribble of light directly revealed the zipper's changing position.

In turn, the constantly changing field in the gap affected the zipper's motion. Says Camacho, "Imagine you pluck a note on a guitar, and then you shine a laser pointer on the string and it goes from a low A to a high A. Or vice versa. We can get a factor of 10 increase or decrease in the vibrational frequency." Under the right conditions, says Painter, a single photon can produce a force 15 times stronger than gravity. If that force is 180 degrees out of phase with the motion, it in effect tightens the string, making it vibrate at a much higher frequency. Says Painter, "One structure we studied naturally resonated at 8 megahertz. When we sent in 100 microwatts of optical power, which produces something on the order of 1,000 stored photons in the cavity, the resonance frequency increased to 19 megahertz—simply because of the light. It no longer behaved like silicon nitride, which is pretty stiff stuff already, but as if it were stiffer than diamond. We can cause the zipper to vibrate at a frequency that is predominantly determined by the light field, almost independent of the material it's made out of."

BRING ON DA NOISE

So the zipper is twanging like a guitar string, but that's not the only sound it's making. Says Painter, "About a year ago, Matt realized that there's a second set of mechanical vibrations that we should look at." It turns out that the individual floorboards also have vibrational modes. Sound gets trapped in the floorboards for the same reason that light gets trapped in the spaces between them—as the floorboards get farther apart, their spacing no longer matches the sound's wavelength, trapping the energy. And because the trapped phonons and photons have the same wavelength, the two sets of waves can swap energy back and forth—even though their frequencies are quite different.

Since these vibrations are purely internal affairs, you don't need a zipper to study them. Eichenfield, Chan, and Camacho built a bunch of lone bridges, and the successful interconversion of photons to phonons and back again was worth a second *Nature* paper (published on November 5, 2009), and a PhD thesis for Eichenfield. The phonons in these bridges vibrated at around two gigahertz—in the microwave range, in terms of electromagnetic frequencies—while the photons were at 200 terahertz, or just to the infrared of visible light.

> “Imagine you pluck a note on a guitar, and then you shine a laser pointer on the string and it goes from a low A to a high A. Or vice versa.”

As it happens, coupling sound waves to microwaves is already big business in the telecommunications field. Your cell phone plucks your conversation out of the unremitting babble in that very crowded region of the electromagnetic spectrum by using a gadget called an acoustic delay filter. The phone’s internal antenna is a thin metal sheet deposited on a piezoelectric crystal, which is a material that expands or contracts when an electric field is applied to it. The electromagnetic waves in the antenna set up corresponding ripples in the crystal that propagate along its surface in all directions. Waveguides split these surface waves, sending them along numerous routes of various lengths. When the sound waves get recombined at the end of their journeys, the differences between their arrival times allow the phone to discriminate between the jammed-together frequencies in the original microwave signal, tuning in to the one band carrying your call to the exclusion of all others.

What makes this possible is that the sound waves in the crystal propagate 10,000 times more slowly than the electromagnetic waves in the metal, so a tiny difference in the phonons’ path length will have a noticeable effect on their arrival times. If you sent the original microwaves racing down those same paths, they’d still show up neck-and-neck at the finish line. Says Painter, “Your phone has a large number of these little filters built into it. People have wanted to do the same thing with light for a long time.”

Like the airways, the pathways in fiber-optic cables are limited commodities, and there is no end in sight to the steadily increasing demand for finer and finer slices of the bandwidth. An optical delay could relieve data congestion, enable very narrow-band filters, and in general let us cram a lot more data streams into each fiber, says Vahala. “There’s an intense interest in trying to achieve long delays in a tiny amount of space—long being hundreds of nanoseconds, which doesn’t sound like much, but if you think of it in terms of propagation distance, a foot per nanosecond for light, you’re talking about hundreds of feet. This is a task that’s not particularly well suited for electronics, as it turns out. One of the approaches for the last couple of decades has been based on taking optical fiber, spooling it up tight—literally on little fishing-line spools—and then very carefully trimming it to length. And I mean *very* carefully—in some applications controlled to tens of microns.” Says Camacho, “The idea is to be able to use photons over long distances, and phonons over chip distances, and then have a box that converts them back and forth on the chip.”

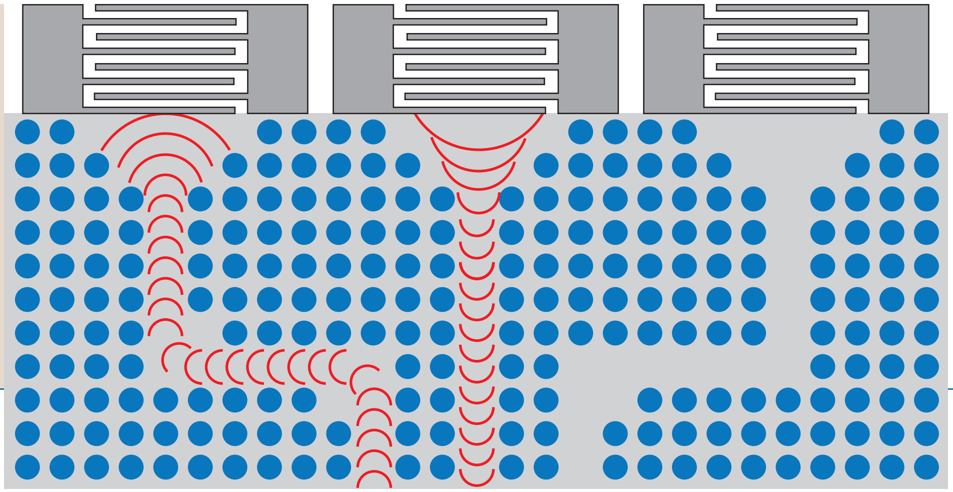
Controlling the delay lengths for phonons on a microchip is much easier—not only

The pinch mode has the lowest vibrational energy. Here the bridge’s floorboards flex toward and away from their neighbors in pairs, like a series of parentheses: ()()()()().

The accordion mode has an intermediate amount of energy. Here the floorboards bend toward and away from the center as if they were nested parentheses, like this: ((((())))).

The highest-energy mode is the breathing mode, in which the floorboards expand and contract along their lengths, causing the side beams to bow outward and then inward.

PICTURE CREDITS
26, 32 — Bill Youngblood; 27, 30 — Doug Cummings; 28, 31 — Jasper Chan and Matt Eichenfield; 29 — Matt Eichenfield and Jasper Chan



In today's phononic chip prototypes, piezoelectric combs (dark gray) send and receive sound waves (red) that travel through the chip (light gray) via waveguides defined by patterns of holes (blue). The circuitry in the chip is not drawn to scale—if it had been, the holes would be too small to see. (Adapted from Olsson and El-Kady, *Measurement Science and Technology*, Vol. 20, 012002, 2009, with permission of IOP Publishing Ltd.)

because they travel so much more slowly, but because all you have to do, in the simplest scenario, is drill tiny, precisely spaced holes in the chip using standard industrial techniques. The holes, when laid out in the proper pattern, act as the waveguide by defining the walls of the "pipe" that confines the sound waves. Quite elaborate sonic plumbing systems can be created this way, at least in principle. Says Eichenfield, "Phonons don't leak out into the world. They are confined to the surface of the chip, so they stay where you put them. And phonons can go around 90-degree corners, which photons can't do."

The problem has been the transducers—the devices that get the sound into and out of the waveguides. The state of the art is an "interdigitated transducer," which is essentially two sets of tiny metal-coated piezoelectric combs with their teeth interlocked. Again, the piezoelectric teeth convert sound waves into electrical impulses and vice versa. But the combs are huge, in chip-making terms—200 by 800 microns or more. They're so big that they perturb the system, says Eichenfield. "You've got to create this giant structure, lay down metal, and so on. But an optomechanical crystal transduces itself. You don't have to put anything extra on the chip."

Eichenfield envisions a moat carved around the portion of the chip containing the photonic circuit, defining its boundaries, and with bridges across the moat at the exits and entrances to the waveguides—sort of like a simplified map of the island of Manhattan. A bridge could act as a receiver that collects phonons from the circuit and turns them into light to be sent to the outside world by the adjoining fiber-optic taper, or the bridge could be a phonon "laser" aimed into the circuit. In a laser, trapped photons bounce between two mirrors, one of which is a little bit leaky. As the photons slosh back and forth, they entice other photons to join them, producing an intense, coherent beam of light that exits through the leaky mirror. Similarly, a properly spaced set of floorboards on one side of the nanoresonator will act as a partial reflector. Pumping energy into the bridge from its adjoining taper will send a beam of phonons into the chip. And once on the chip, the phonons could be mixed and manipulated alongside photons and electrons.

> Like Schrödinger's much-abused cat, who is neither alive nor dead but both together until you open its box to look, the bridge is nowhere in particular until you observe it.

QUANTUM BRIDGES COOLING DOWN

There are plenty of potential applications beyond signal processing. A bridge could be used as a molecule-specific zeptogram-scale mass sensor, for example. A zeptogram has nothing to do with the Marx Brothers; instead, the prefix comes from the Latin *septem*, "seven." A zeptogram is 10^{-21} grams—the mass range of a smallish protein, such as a molecule of hemoglobin A. To detect your quarry in this case, you'd simply paint the bridge with a hemoglobin-specific binding agent and sit back. When a passing hemoglobin got snared, the added mass would slow the pinch mode's acoustic frequency just a shade—by some 700 parts in two billion. And as the motion changed, the light field would change, allowing you to "watch" the protein attach and detach itself on a microsecond timescale. This could be a very handy tool for studying the molecular ballets involved in such things as a drug interacting with its receptor, or a protein catalyzing a biological process.

While Painter's lab hasn't tried this yet, in 2006 a zeptogram-scale sensor based on a vibrating nanobeam—a bridge without the holes, basically—was developed at Caltech's Kavli Nanoscience Institute (KNI) by grad student Ya-Tang Yang (MS '00, PhD '06), then-staff member Carlo Callegari, grad student (now staff scientist) Philip Feng (MS '01, PhD '07), Kamil Ekinci of Boston University (a former Caltech postdoc), and Michael Roukes, professor of physics, applied physics, and bioengineering and the KNI's codirector.

These bridges could also find uses in fundamental physics experiments—they are so close to being immaterial that they can be made to behave quantum mechanically. In the quantum world, you can accurately measure either position or momentum, but not both. If the bridge were to be cooled to its lowest possible energy state, there would remain what's called the zero-point motion—"a little wave packet that describes the 'fuzziness' of the structure, so to speak," says Painter. "In our case, it's on the order of a few femtometers," or quadrillionths of a meter. Like Schrödinger's much-abused cat, who is neither alive nor dead but both together until you open its box to look, the bridge is nowhere in particular until you observe it. Says Painter, "It's in a whole distribution of positions all at once, and then if we measured it, we'd cause it to be in one position only—it's deflected or it's not, or it has a certain amount of vibrational energy or it doesn't. And what's fun about these mechanical systems is that you really can ask the question, 'Well, was the beam here, or was it over there?' I mean, that's a very simple question."

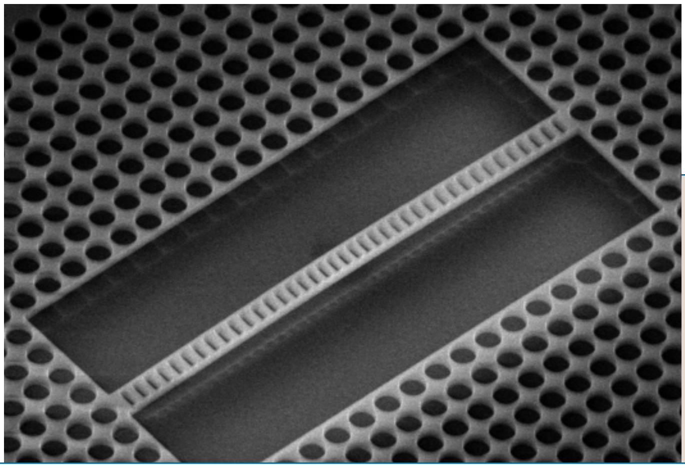
A couple of dozen research groups around the world are racing toward the quantum ground state. The current leader is Caltech's Keith Schwab, associate professor of applied physics, who with colleagues at Cornell, the University of Maryland, and McGill University has cooled a different nanobeam design to the point where, says his web page, "we expect the device to spend 21 percent of its time in the quantum ground state." (The work appears in a *Nature* electronic preprint dated July 16, 2009, linked to his publications page.)

Easy access to the quantum world could lead to uses in quantum communication, which offers the potential for providing a secure, uneavesdroppable way of transmitting information, and quantum computing—manipulating the quantum states of photons and atoms to store and process information in ways that present-day computers simply can't. In 2006, H. Jeff Kimble, Caltech's Valentine Professor and professor of physics, Vahala, and a slew of grad students and postdocs collaborated on a project to see if photons—and thus potentially information—could be transferred from one of Vahala's ring resonators across

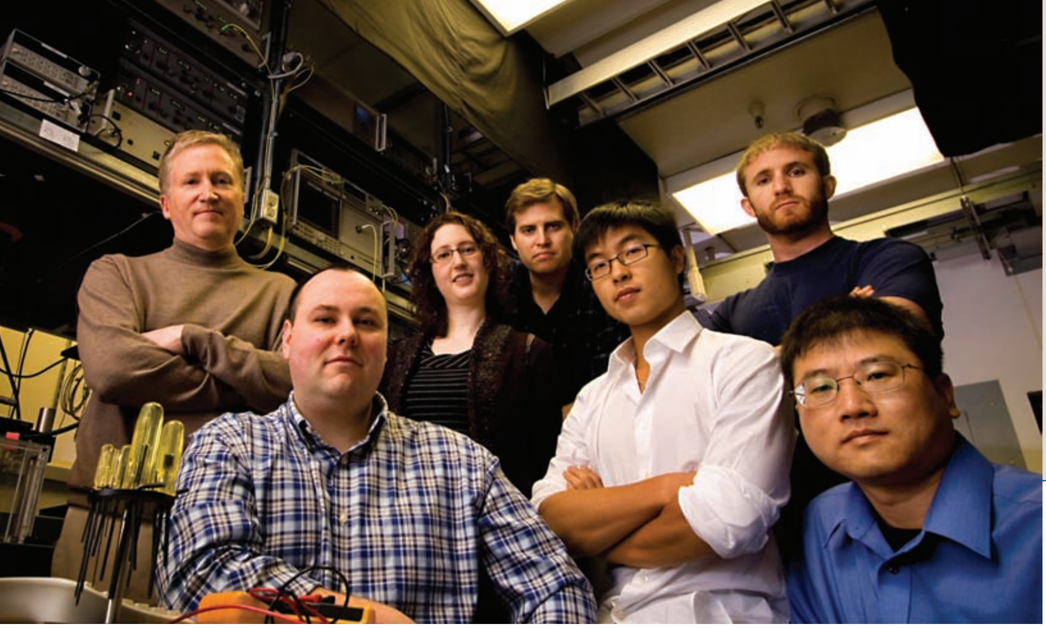
THE KAVLI NANOSCIENCE INSTITUTE

Painter's and Vahala's labs make their nanodevices in the Kavli Nanoscience Institute's clean rooms in the subbasement of the Steele Laboratory of Electrical Sciences. The KNI has a state-of-the-art set of all the standard chipmaking and test equipment you'd find in an integrated circuit factory, available to the entire Caltech/JPL community. "It's a very important facility for our work," says Painter. "We couldn't have done any of this without it." His group uses the Class 1,000 suite, meaning that there are fewer than 1,000 particles of 0.5 microns or larger per cubic foot of air. For comparison, typical Pasadena air can have 1,000,000 particles that size per cubic foot. (There's also a Class 100 suite, but, he says, "It's not like we're doing 50 lithography steps on a 12-inch-diameter wafer, and every single element has to work.")

The KNI was founded in 2004, and it provides equipment and expertise to support researchers in fields ranging from biotechnology to astrophysics. Besides Roukes, the KNI's other codirector is Painter's old prof, Axel Scherer, the Neches Professor of Electrical Engineering, Applied Physics, and Physics.



An electron micrograph of an optomechanical crystal. In this case, the holes in the silicon supporting the bridge act as insulation, keeping the outside world from interacting with the system. Such a setup could be used for quantum-mechanical studies.



From left: Vahala, Painter, grad student Jessie Rosenberg, Camacho, Chan, Eichenfield, and postdoc Qiang Lin. Rosenberg and Lin study a different class of optical resonators that look like two of Vahala's rings stacked on top of each other with a gap in between.

some 45 nanometers of empty space to a passing cesium atom. (Cesium atoms are to quantum-physics experiments what fruit flies are to genetics experiments.)

In these experiments, postdocs Takao Aoki, Barak Dayan, Warwick Bowen, Andrew Parker, and Tobias Kippenberg (MS '00, PhD '04) and grad student Elizabeth Wilcut (PhD '10) would suspend over the resonators a cloud of a few million cesium atoms cooled to 10 millionths of a degree above absolute zero—the temperature at which all atomic vibrations cease. Every five seconds, the lasers responsible for levitating the cloud would be shut off, and a few dozen cesium atoms would plunge like tiny apples through the electromagnetic field generated by the light circulating in the rings. As the atoms fell, each one could trade a quantum of energy with the light field and, indeed, they did.

Painter foresees using the zipper's gap to catch atoms or even larger things, such as "a little nanoparticle of glass, for instance, of maybe a billion atoms. We could use the light fields to trap it and cause it to vibrate at any particular frequency. We could potentially cool it to the quantum-mechanical ground state very easily, even at room temperature, because it's got no tethering to the outside world. The only thing it couples to is the light field." He adds, "We can couple various different quantum systems to each other and to electronics, and my vision is that this will be a beautiful bridge that will enable a lot more quantum technologies.

"This field of reseach is blossoming at Caltech," Painter continues, "because we have a number of groups bringing together expertise in areas as diverse as nanofabrication and quantum optics. I think the next few years are going to be tremendously productive. I find it fascinating that we can work in areas that touch upon fundamental quantum physics and at the same time have a real impact on engineering and technology."

As just one example of the potential impact, "we've basically built a phonon laser on a chip," says Eichenfield. "What's it good for? That's like asking what a laser is good for. When Charles Townes [PhD '39, Nobel laureate in physics, 1964] invented the maser, which eventually gave birth to the laser, he didn't envision CDs, or supermarket checkout scanners, or using them to write your name on the diamond in an engagement ring. We're in the ruby-laser era with these. We can make 10^{12} phonons per second with a frequency-to-linewidth ratio [the measure of a laser's coherency] of a few million. That's about where lasers started. In a few years, we'll be putting out phonons on a level with commercial lasers." Adds Camacho, "Optomechanical crystals are a really juicy subject that nobody saw coming. I remember the day when Matt came to my office and showed me his simulations on his laptop, and said, 'Hey, look—the vibrational modes are *right there*. Just sitting there.' It's just really cool, and it's been much easier than we anticipated." Chimes in Eichenfield, "It uses standard fabrication techniques and it operates at microwave frequencies, which makes it technologically relevant, because that's what the telecommunications industry uses. So we've basically produced a whole new technology out of our dabblings in quantum mechanics." e&s

Oskar Painter earned his BS from the University of British Columbia in 1994, and his MS (1995) and PhD (2001) from Caltech, all in electrical engineering. He ventured briefly into the outside world to cofound a company that applies photonics to telecommunications before becoming an assistant professor in 2002.

Kerry Vahala arrived at Caltech as a sophomore in 1977, and has been here ever since. He got his BS in applied physics in 1980 and his PhD in '85, with a small detour for an MS in electrical engineering in '81. He became an assistant professor in 1986 and the Jenkins Professor in 2002.

The work was funded by grants from the Defense Advanced Research Projects Agency and the National Science Foundation.