OPTICS

# Putting Light's Light Touch to Work As Optics Meets Mechanics

**Forces exerted by light can set tiny objects aquiver, a phenomenon scientists hope to harness in the burgeoning field of cavity optomechanics**

The effect appeared unexpectedly. In 2005, Kerry Vahala, an applied physicist at the California Institute of Technology (Caltech) in Pasadena, and his team were experimenting with microtoroids—little glass disks that resemble dinner plates with fat, rounded rims. Light can circulate around the rim, and each microtoroid resonates with laser light of a specific wavelength and frequency, just as an organ pipe rings at a distinct pitch. But the researchers found that the light passing through such a doohickey also warbled up and down in intensity at a much lower frequency (*Science*, 15 July 2005, p. 366).

Eventually, the researchers found the source of the radio-frequency warbling: Pressure from the light within the toroid was making it vibrate. "We were not looking for this [mechanical effect] at all," Vahala says. "There was no precedent for it aside from some theoretical speculation."

That light-and-motion connection has spawned a new field. Scientists have long used laser light to move atoms and molecules—Nobel laureate and U.S. Secretary of Energy Steven Chu developed "optical tweezers" that can uncoil DNA. But researchers are now using light to control the motion of larger humanmade objects built of materials like glass or silicon. A device must be both a fine "optical cavity" that rings with light and an outstanding "mechanical resonator" that, like a pitchfork, vibrates readily at a precise frequency. Researchers can then use light to control vibrations or vice versa.

Such "cavity optomechanics" might be used to coax vibrating machines to hum to the odd rules of quantum mechanics, which ordinarily govern the realm of atoms and molecules. More practically, optomechanical widgets might process optical signals or serve as frequency standards. One team has even used them to make a kind of laser for vibrations. Other exciting results are sure to come, says Oskar Painter, an applied physicist at Caltech: "This wave hasn't crested yet."

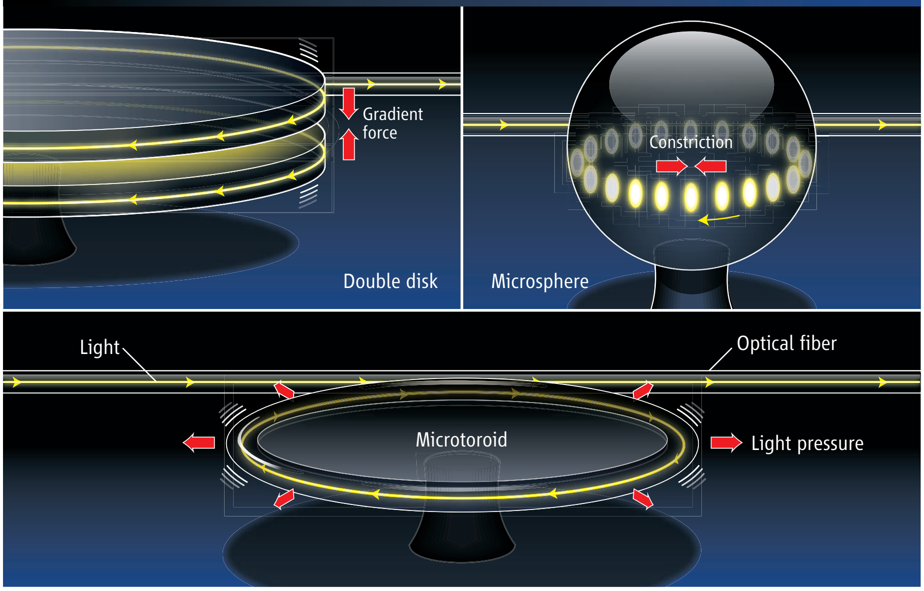
### All aquiver

Light can shake an object in several ways. In Vahala's gizmo, light's pressure does the trick. A toroid will resonate with light bled in from an optical fiber if its circumference equals a multiple of the light's wavelength. As light accumulates, its pressure stretches the toroid (see figure, below). But that stretch spoils the resonance, so the circulating light wanes, the pressure eases, and the toroid shrinks. The cycle of expansion and contraction repeats at a rate set by the stiffness of the disk, typically millions of cycles per second, and makes the light leaving the cavity warble.

Light can also trigger vibration by making a material contract. Tal Carmon, an applied physicist at the University of Michigan, Ann Arbor, and a colleague circulated light in a 100-micrometer-wide glass sphere. In a chicken-or-egg process called stimulated Brillouin scattering, the light set off a vibration moving in the same direction, while the vibration "scattered" light into a second wave of a longer wavelength going the other way. The overlapping light waves created a moving pattern of bright spots that caused the glass to contract and amplified the vibration, as the team reported on 19 March 2009 in *Physical Review Letters*.

Light is a wimpy mover and shaker; a laser beam with a power of 1 watt exerts a force of just 6 nanonewtons. To respond to such feeble shoving, an object must resonate with light, so that each photon circulates in it thousands of times, greatly enhancing the photon's mechanical effect. The device must also ring with vibrations, so a small force repeatedly applied can cause a large movement. Only recently has it been possible to combine those properties. "These structures weren't around 15 years ago," Vahala says.

FORCES EXERTED BY PHOTONS




**Give it a shake.** Light can set a micrometer-sized object vibrating by exerting pressure (*bottom*), creating sideways pushes or pulls (*top left*), or causing material to constrict.

SOURCE: A. CHO/*SCIENCE*

Light exerts a sideways "gradient force" as an insulating material feels a pull to where the light is most intense, like an actor who craves the spotlight. For example, if one toroid lies atop another, then gradients in the light leaking between them can pull their edges together or push them apart, as Michal Lipson, an applied physicist at Cornell University, and colleagues reported online 15 November 2009 in *Nature*. If the toroids are springy, then that force can also trigger their edges to flap up and down in a cycle akin to the one pressure causes in a single toroid, as Painter reported on 31 August 2009 in *Physical Review Letters*.

### Cool it!

Now that the gadgets exist, physicists want to see what they can do. Many are trying to coax them to wiggle quantum mechanically. According to quantum theory, a vibrating object, or "oscillator," can absorb energy only in discrete "quanta" whose size is set by the vibration frequency. The object can't

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stand still, either; it will always possess an inextricable half-quantum of energy and hum with "zero-point motion." Physicists hope to spot that unquenchable quaking as a step toward more-bizarre states of motion, such as one in which an oscillator is in two places at once.

Each quantum is minuscule. So to remove every possible one and reach the "ground state," physicists must cool an oscillator to nearly absolute zero. Ironically, Vahala's observation that light can trigger vibrations opens the way to cooling an oscillator by shining a laser on it. The trick is to reverse the process, says Tobias Kippenberg of the Swiss Federal Institute of Technology, Lausanne. "The fact that you could use this for cooling was immediately clear," he says.

To trigger a vibration in, say, a toroid, the light's frequency must be tuned slightly higher than the toroid's resonant frequency. To still a vibration, the light's energy and frequency must be lowered—optimally, by the frequency of the vibration. To enter the toroid, a photon must then make up the energy it lacks by absorbing a quantum of energy from the toroid. The scheme works because, thermodynamically, "a laser beam is a very cold object," says Jack Harris of Yale University. "A good laser is at 0 kelvin."

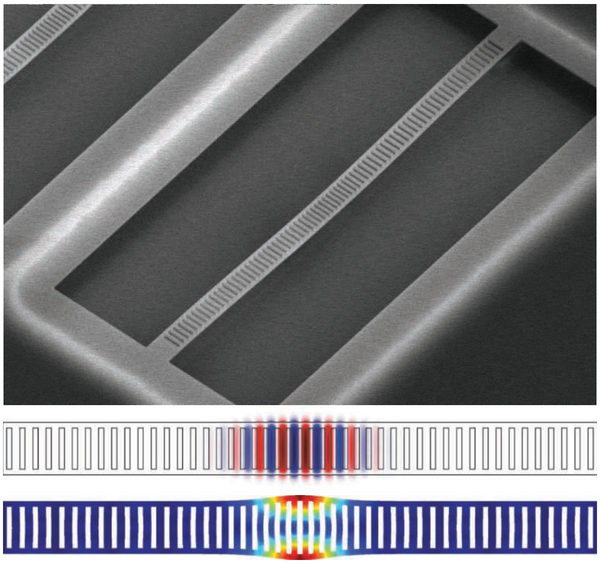
Last year, three groups used laser cooling to reduce an oscillator's energy to a few dozen quanta. However, they were beaten to the ground state by a team that simply chilled an oscillator with a very high frequency—and hence large quanta—in a liquid-helium refrigerator (*Science*, 29 January, p. 516). But optical methods still have advantages, says Markus Aspelmeyer of the University of Vienna. "That's why the result has only encouraged us," he says.

Laser cooling alone might chill an oscillator to the ground state, Aspelmeyer says. That might make it possible to run an array of oscillators not deep within a helium refrigerator but on a more-accessible optical table to process information encoded in the quantum state of light. And optical methods might do things that other methods can't, Harris says. For example, he has devised an optical scheme to watch the quantum jumps when an oscillator absorbs individual quanta. Optomechanical devices could also generate exotic quantum states of light, Harris says, such as "squeezed" states that suppress the random lumpiness of the photons in the light.

CREDIT: M. EICHENFIELD *ET AL.*, *NATURE* 462 (5 NOVEMBER 2009)

**Other vibes**

Optomechanical gizmos might serve myriad other purposes, too. "I'm very excited about the applications of these structures," says Cornell's Lipson. A double-toroid makes a low-power optical switch, she says, as one laser beam can change the size and optical frequency of the thing and control the passage of another beam. A jiggling toroid makes a frequency standard that's immune to electrical interference. It works as a "downconverter" to extract a radio signal encoded in an optical carrier beam, as Mani Hossein-Zadeh, an applied physicist at the University of New Mexico, Albuquerque, reported on 15 February 2008 in *IEEE Photonics Technology Letters*.



**Conceptual bridge.** The array of holes in a bridgelike optomechanical crystal (*top*) traps light (*middle*) and vibrations, transferring energy from one to the other.

Meanwhile, other researchers are working on more speculative ideas. In the 1990s, physicists pioneered "photonic crystals," materials riddled with holes through which photons travel like the electrons in a crystalline solid, with only certain energies allowed. Similar holey "phononic crystals" control vibrations in the same way. Now, Caltech's Painter and his colleagues have combined the two, as they reported online 18 October 2009 in *Nature*.

Their optomechanical crystal consists of a ladderlike beam of silicon about 30 micrometers long and 1.3 micrometers wide (see figure, above). The spacing between rungs shrinks slightly near the beam's middle, creating a "defect" that traps both light of a certain frequency and vibrations shaking at about 2 billion cycles per second. Again, light forces set off vibrations, which reveal themselves in a warbling of the light.

Next, the team used optical gradient forces to couple the jiggling of two parallel bridges, tuning their combined motion to a so-called dark state that neither emits nor absorbs light, as they reported 7 February in *Nature Photonics*. That feat raises the possibility of snaring a light pulse in that dark state. "We've got exactly what we want, which is the ability to store a photon pulse and then release it," Painter says. Physicists had previously stopped light in atomic vapors, but optomechanical crystals are easier to control and could be used for all-optical quantum information processing, he says.

Physicists have even fashioned the equivalent of a laser for vibrations. In a laser, a light-emitting material sits between two mirrors. The atoms in it are boosted from their ground state to a more energetic, excited state by, say, applying a voltage, and as they "de-excite," the atoms emit photons, which bounce between the mirrors. Passing through the material, the photons trigger excited atoms to emit more photons of the same wavelength and direction. Such "stimulated emission" produces a torrent of identical photons that is the laser beam.

Twisting that idea, Caltech's Vahala amps up vibrations using jumps between optical states of two toroids placed side by side. As light bleeds from one to the other, their resonances meld into a lower frequency one and a higher frequency one, just as the electronic orbitals of two identical atoms meld and split when the atoms form a molecule. Adjusting the toroids' spacing, the researchers tune the frequency difference to equal the frequency at which one toroid shakes, as they reported 22 February in *Physical Review Letters*. When they then pump in enough high-frequency light, the vibrations amplify themselves by stimulating jumps to the low-frequency optical state.

Where all these efforts will lead remains to be seen. Some researchers say that, technologically, optomechanical devices have yet to do anything that electronics can't do. "I don't see anything that's a breakthrough at this point," Hossein-Zadeh says. However, the tiny machines may find uses in basic research in various fields of physics. "These little widgets will be a part of science, even outside of what we call cavity optomechanics," Vahala says. Now that physicists can shake things up with light, likely they'll find ways to use that trick.

**–ADRIAN CHO**