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What lasers do for light, **sasers** promise to do for sound. *Andrew Watson* in on the lookout for the best way to build one.

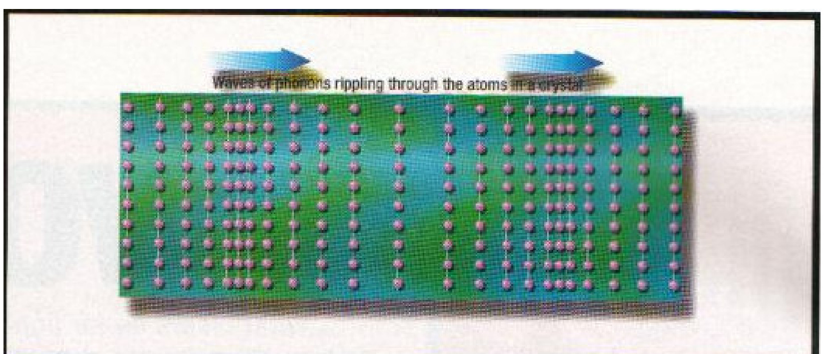
IT LOOKED something like a cross between a lamp and an organ pipe and it was the brainchild of Douglas Shields, an acoustic engineer at the University of Mississippi. His idea was simple: take a metre-long glass tube full of nitrogen gas, pump energy into the molecules with a crackling spark, and then inject a pulse of sound into the gas. He reckoned that as the pulse bounced up and down the tube, the gas molecules would release their pent-up vibrations, making the sound louder. And it worked, up to a point. "We did see evidence for amplification," Shields reports of the trials he ran in the 1980s. But he needed to pump in so much energy that the gas overheated, and the device went kaput.

Shields's amplifier eventually fell prey to the vagaries of research funding. "The programme sponsors wanted something useful out," says Henry Bass, one of Shields's co-workers and now director of the National Center for Physical Acoustics at the University of Mississippi. "At the time, it didn't seem like the device had anything to offer."

But while Shields has moved on to other things, physicists in labs from Belarus to Brazil have been pursuing similar ideas. The end result could be a huge range of applications, from acoustic microscopes that probe tiny circuits and sensors that listen in on submarines or high-energy particles, to devices that quieten the noise inherent in all electrical circuits.

The most promising of these applications rely on phonons quantum particles associated with all kinds of high-frequency compression waves, including ultrasound (see Diagram). Just as a packet of light waves can be viewed as a photon, so it is with the waves that permeate solid materials: a packet of these waves can be treated as a particle called a phonon. "Phonons are high-frequency sound waves," says physicist James Wolfe from the University of Illinois at Urbana-Champaign. And even in a grain of salt there are more than a million billion of them at any one time.

As these phonons bounce around in solids, they knock into anything that gets in their way, bumping into electrons and scattering from impurities or the edges of tiny crystal grains. Just as spectroscopists use light especially laser light to study the structure of atoms and molecules in gases and liquids, it should be possible to unravel the structure and properties of solids by finding out how they scatter and absorb beams of phonons. However, there's a problem: "Laser light has a well defined energy," says Wolfe. And spectroscopists can easily adjust the energy of their laser beams. Shine laser light onto a bunch of



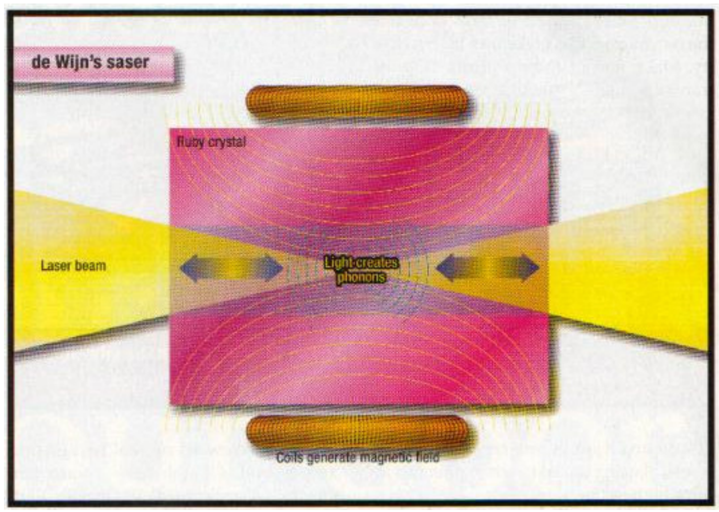
'Physicists could use a saser to search for the weird and wonderful particles believed to flood space and contribute to the dark matter of the Universe'

atoms, scan the energies of your photons, and you can probe their quantum energy states one at a time.

But devices that generate phonons simple oscillators or heaters, for instance are more like light bulbs than lasers. They emit a jumbled mix of phonons with different energies and directions that interact with a whole bunch of quantum states rather than with one or two. What is needed is a "saser" sound amplification by stimulated emission of radiation, or a laser for phonons.

In essence, lasers are intensely powerful and versatile amplifiers. Under the right conditions, a laser turns a trickle of light into an avalanche of identical photons. These photons reflect back and forth between the two mirrors that make up a laser's cavity. Make one of these mirrors slightly transparent and the light streams out as a bright, pencil-thin beam ("Inside Story", New Scientist, 4 April 1998, p 38, and Inside Science No 24, New Scientist, 17 June 1989).

Build a saser that is based on the same principles and you can create a "laser beam" of phonons with a narrow range of energies. "You might use phonons like light," says Wolfe, to pick out the fine detail in a material, in much the same way that you learn more about a tiny object by increasing the magnification on a microscope. A tunable beam of phonons could help physicists discover exactly how electrons vary their energy as a material heats up or cools down, for example. Eventually, says Wolfe, this could reveal the inside story of things like heat dissipation, electrical resistance and superconductivity.



Of all the researchers trying to build a saser that can emit a phonon beam, Harold de Wijn and his colleagues from the Debye Research Institute at Utrecht University in the Netherlands are probably the closest to their goal. "If we are being nice to ourselves, we say we have a saser," says de Wijn. "If we are a little bit more critical, then we say, well, there's a lot of work to be done."

De Wijn's saser is made from a 5 millimetre long rectangular crystal of ruby aluminium oxide lightly peppered with chromium ions. To freeze out unwanted sound waves that might interfere with the performance of the saser, de Wijn and his colleagues bathe their ruby block in liquid helium to cool it to 1.8 kelvin. Then they focus a laser beam into a spot near the centre of the crystal just a third of a millimetre across (see Diagram). At this point, electrons on the chromium ions absorb the light energy, jump to a higher energy level and then drop back to a lower level, giving out their excess energy as light.

To create phonons rather than photons, de Wijn switches on a powerful magnetic field that nudges the electrons in the chromium ions into slightly different energy levels. With the field switched on, the electrons absorb light but lose their energy in small steps rather than a single leap. These steps are too small to give a photon, but just enough to create vibrations in the crystal lattice making phonons rather than photons.

These phonons travel the length of the crystal and reflect off the end walls, making five or six passes in all. Each time they whizz through the region where the laser light is focused, they stimulate excited electrons on the chromium ions to lose their energy and give out more phonons the process known as stimulated emission. "The basic ingredients of a saser are there," says de Wijn.

So far so good: the phonons inside his ruby crystal behave just like photons in a laser cavity. The snag is that they remain imprisoned within the cavity as the sudden density change at the edge of the crystal acts like a highly polished mirror. To make the device useful, de Wijn must find a way for the phonon beam to escape into other materials. "You could just glue another crystal to it," he says. "But we haven't tried that yet."

Eventually, de Wijn might build sasers inside the material he wants to study, or the sasers may simply be stuck onto the side. He is also looking at ways to alter the shape of the ruby cavity to improve the amplification. Maybe, he suggests, simply making it shorter will do the trick. "This is all far away from applications at this point," he says. "All we want to do is show that it can be done."

At the University of Paris-South, Jean-Yves Prieur and his colleagues have put together a different sort of saser. Rather than relying on laser power, Prieur's saser has a pair of tiny piezoelectric transducers that convert a fluctuating voltage into high-frequency vibrations. These transducers are mounted on opposite ends of a small block of glass just 2 centimetres long. One creates a "pump" pulse that travels along the block, passing its energy to the atoms as it goes. Its partner creates a pulse of high-frequency phonons that stimulates the energised atoms to release this energy, amplifying the pulse in the process.

With its flat end faces, the block is meant to form a resonant cavity like de Wijn's crystal that will reflect the sound pulses back into the glass where they can stimulate still more phonons. Unfortunately, it hasn't panned out that way. "Multiple passes don't seem to work," says Prieur. When the pump pulse reaches the end of the cavity, it reflects back along the block and interferes destructively with the phonon pulse, eliminating some of the phonons it has just created. Despite this, Prieur's saser design can amplify a sound pulse by a factor of thirty or so.

Prieur's saser may eventually provide a source of phonons that will probe the interior of solid materials. Combined with a phonon detector such as a bolometer, these phonon sources could act as "acoustic microscopes" that can pick out tiny defects inside the material. You should be able to use phonons to stare inside integrated circuits or composite materials, says Wolfe. Small defects or breaks in a material interact strongly with phonons, so they stand out like beacons. This could be especially valuable for measuring the thickness and quality of the thin metal connections that make up the circuits within a microprocessor.

Sasers could also be the basis of sensitive particle detectors, Prieur suggests. As high-energy particles slam into a piece of silicon, they create faint ripples in the silicon's atomic lattice. Amplifying the ripples with a saser could turn such a device into an ultra-sensitive detector, analogous to a photomultiplier. Physicists could use it to search for the weird and wonderful particles believed to flood space and contribute to the dark matter of the Universe ("Space oddity", New Scientist, 16 January 1999, p 24).

Sergio Makler at Fluminense Federal University at Niteroi in Brazil is also building a saser. Five years ago, Makler, together with Russian theorist Mikhail Vasilevski at Nizhni Novgorod State University, outlined a device thousands of times smaller than even de Wijn or Prieur's tiny cavities. It is based on a quantum well, an artificial atom made from layers of semiconductors such as gallium arsenide that can trap an electron in quantised energy levels. Inject an electron into the well with a small voltage and it jumps between these energy levels, blasting out a stream of phonons at ultra-high frequencies.

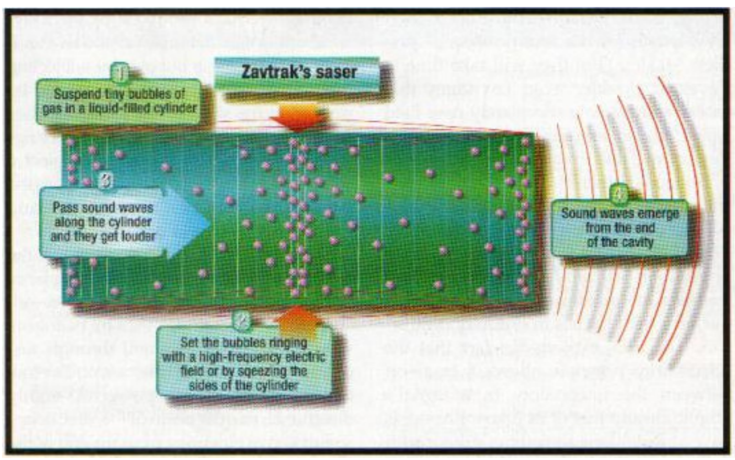
If Makler can make this device work he will have sidestepped the complexities of other saser designs. It could be incorporated into larger semiconductor devices at the manufacturing stage. Best of all, it will create high-energy phonons corresponding to frequencies in the terahertz region and beyond. Makler predicts that such phonons will reveal semiconductor structures just tens of nanometres across ideal for studying the details of microchips. At even higher frequencies, acoustic microscopes may eventually probe solids down to the atomic level.

Beams of high-frequency sound from a saser could also create acoustic holograms, Makler suggests. Analogous to light holograms created with two laser beams, these could provide a way to store vast amounts of information in a small space. "The data density would be high because of the short wavelength [of the sound waves]," predicts Makler. "But they will take time to develop." Makler even envisages that sasers will create a completely new field called "phonoelectronics". Phonoelectronic devices will talk to each other with beams of phonons rather than with light or electric current.

Franco Nori, a physicist from the University of Michigan, has another practical application in mind for phonons: suppressing the quantum noise that drowns out very faint signals in ordinary conductors. The trick exploits the fact that the uncertainty principle allows a trade-off between the uncertainty in a signal's amplitude and that of its phase. Physicists have already done something similar with "squeezed" light to reduce the energy in a vacuum below its normal background "zero" level ("Light gets a quantum squeeze", New Scientist, 19 October 1991, p 41). Reducing the noise levels in electronic devices such as silicon detectors or amplifiers, for instance, might allow them to pick out even the weakest signal. "Control a phonon beam and you may be able to suppress quantum noise," says Nori. "Maybe in five years' time. But we haven't fleshed out the theory yet."

As Shields showed more than a decade ago with his energised tube of nitrogen, sasers don't necessarily have to involve phonons. The principle works with lower-frequency vibrations too, where the particle nature of vibrational wave packets virtually disappears.

This is the line that Sergei Zavtrak, a physicist at the Belarussian State University in Minsk, is following. His idea

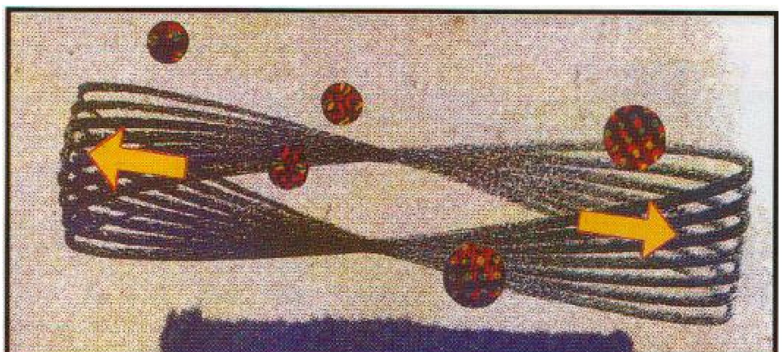


is for a device based on a cylindrical vessel filled with water containing billions of tiny gas bubbles perhaps produced by electrolysis. Zavtrak calculates that if you rhythmically squeeze these bubbles by subjecting them to a varying electric field or by squashing the sides of the container, they will resonate in response, just as a bell rings when you strike it. If you now inject a sound pulse, it will gather energy from the vibrating bubbles as it bounces back and forth through the cylindrical cavity.

Not only that: Zavtrak calculates that the bubbles will organise into a series of planes at right angles to the beam direction an "ordering" effect that is seen by biologists when they pass ultrasound through suspensions of cells. The final result, Zavtrak believes, should be a powerful, highly directional, narrow beam of low-frequency sound waves emerging from the end of the container (see Diagram).

"It's an interesting scientific concept," says Lawrence Crum, a physicist at the University of Washington in Seattle. "I expect something like what he proposes to work, but efficiency would be a real problem." Zavtrak has yet to build his bubble-based saser, but at British Aerospace's Sowerby Research Centre near Preston in Lancashire, Ron McEwan and his colleagues are intrigued by the idea of a powerful, directional source of sound. They suggest it could be used for tasks such as detonating explosives from afar, or as a weapon, to immobilise terrorists by stunning them with a blast of sound. But having attempted a few simple trials with a device based on Zavtrak's saser "just in the hope that we might stumble onto something that looked encouraging", they are not particularly optimistic about its prospects. How do you stop the bubbles from collecting together or rising to the top of the cylinder, for instance? "The theory appears to be there," says McEwan, "I just have misgivings about its practicality."

Zavtrak's unique amplification mechanism could also be used to amplify one set of frequencies among a soup of other sounds, explains Bass. "This might be especially useful in a very noisy environment," he says. One example is the detection of submarines, where you want to pick out the sound of an approaching vessel among



'Inject a sound pulse and it gathers energy from the vibrating bubbles as it bounces back and forth inside the cavity'

all the other noises of the ocean. But as Bass points out, such applications are still speculative, and no one yet knows whether

Zavtrak's device offers any advantages over conventional sonar equipment.

Sasers of all sizes are little more than a laboratory curiosity at the moment, but that doesn't dim the enthusiasm of their supporters. "They're new, and new territory had better be explored," says Nori. "Even the inventors of the laser did not come up with good reasons why they should study it." And you couldn't ask for a better role model than that.

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3. ***Stimulated emission of phonons in an acoustical cavity*** by Harold de Wijn and others, Physical Review B, vol 55, p 2925 (1997)
4. For information on ***squeezed phonons***, see Franco Nori's home page at: www-personal.engin.umich.edu/~nori/
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