The emerging field of phonon management allows novel phononic materials and devices to control sound and heat.

The phonon is the physical particle representing mechanical vibration and is responsible for the transmission of everyday sound and heat. Understanding and controlling the phononic properties of materials provides opportunities to thermally insulate buildings, reduce environmental noise, transform waste heat into electricity and develop earthquake protection.

The concept of phonons was introduced in 1932 by Soviet physicist Igor Tamm. The name phonon comes from the Greek word φωνή (phonē), which translates to sound or voice because long-wavelength phonons give rise to sound. The name is based on the word photon. Shorter-wavelength higher-frequency phonons are responsible for the majority of the thermal capacity of solids.

The study of phonons is an important part of condensed matter physics. Phonon is a collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, like solids and some liquids. Phonons play a major role in many of the physical properties of condensed matter, like thermal conductivity and electrical conductivity.
Phonons may sometimes be thought of as particles, and sometimes as vibrational waves, analogous to the dual wave and particle nature of light. Physically, the phonons are manifested as a wave of density variation passing through a material, like the wave of compression that travels along a child’s Slinky toy when you stretch it out and give one end a shove.

Edwin L. Thomas, head of MIT’s Department of Materials Science and Engineering says phonons, which exist in all solids, are usually a nuisance that must be disposed of with cooling systems. They have been “denigrated and ignored, but they could be the future star attraction if we can train them to do tricks for us.”

The development of new ideas for phonon management—combined with the ability to design and fabricate composite materials from the macroscale to the nanometre scale—has fuelled recent progress in sonic and thermal diodes, acoustic and thermal metamaterials, optomechanical crystals, hypersonic phononic crystals, thermoelectrics and thermocrystals. These advances have greatly increased our ability to manage the phononic spectrum at all relevant frequencies: sound, ultrasound, hypersound and heat.

The emerging field of phonon management has great potential for innovations in materials and devices that can precisely manipulate sound and heat. Our ability to control electrons and photons has driven major technological revolutions in past decades; perhaps from our new ability to control phonons precisely we may expect analogously surprising and exciting consequences.
Microscopic devices that control vibrations could allow smaller mobile devices

Nanoscale devices can manipulate vibrations in much the same way that conventional electronics manipulate electrons. To make modern communications possible, today’s mobile devices make use of components that use acoustic waves (vibrations) to filter or delay signals. However, current solutions have limited functionalities that prevent further miniaturization of the mobile devices and constrain the available communication bandwidth.

Now, a research team led by Chiara Daraio, Caltech professor of mechanical engineering, has developed new versions of these components with abilities previous incarnations did not possess. The components, known as phononic devices, could find uses in new kinds of sensors, improved cell phone technologies applied physics, and quantum computing.

The phononic devices include parts that vibrate extremely fast, moving back and forth up to tens of millions of times per second. The team developed these devices by creating silicon nitride drums that are just 90 nanometers thick. (A human hair is about a thousand times thicker.) The drums are arranged into grids, with different grid patterns having different properties.

Daraio, along with former Caltech postdoctoral scholar Jinwoong Cha showed that arrays of these drums can act as
tunable filters for signals of different frequencies. They also showed that the devices can act like one-way valves for high-frequency waves. The ability to transmit waves in only one direction helps keep the signal stronger by reducing interference.

These findings open opportunities to design new devices—such as phononic transistors and radio-frequency isolators—based on phonons instead of electrons, Cha and Daraio say.

Their findings appears in two papers published in the journal Nature Nanotechnology (“Electrical tuning of elastic wave propagation in nanomechanical lattices at MHz frequencies”) and Nature (“Experimental realization of on-chip topological nanoelectromechanical metamaterials”).

**Phonon Devices**

With the recent progress in synthesis and characterization of smallscale materials, it is now possible to fabricate phononic crystals with periodicities ranging from centimetres to nanometres. These advances have significantly increased the ability to manage the phonon spectrum, where the frequencies that can now be controlled extend from 10³ Hz to 10¹² Hz, a range of nine orders of magnitude.

The wide range of control over phonon frequencies—comparable to the wide range of control over electromagnetic frequencies—allows the realization of many exciting devices that can manipulate phonons at all relevant frequencies:
sound, ultrasound, hypersound and heat.

**Hypersound and heat control by phononic crystals**

Sound and heat can both be described as mechanical vibrations transmitted through the atomic lattice. One difference between them, however, is that most sound waves oscillate at low frequencies (kilohertz) and propagate over large distances, whereas most heat vibrations oscillate at high frequencies (terahertz) and travel small distances. These different features lead scientists and engineers to employ different strategies to control sound and heat propagation.

Essentially, macroscale and microstructured materials are able to manipulate sound and hypersound (very high-frequency sound, with \( f < 1 \text{GHz} \)) frequencies, whereas to control heat, nanostructures are generally required. The development of sonic and thermal devices thus requires the design, fabrication and characterization of composite materials ranging from the centimeter scale to the nanometre scale.

Over the past two decades, the propagation of sound waves with frequencies in the range from kilohertz to megahertz has been efficiently controlled by phononic crystals—artificial periodic structures made of two elastic materials. Although these structures were initially designed to control sound, in recent years small-scale phononic crystals have been successfully used to control hypersound and heat. In phononic crystals, mechanical waves with frequencies within a specific range are not allowed to propagate within the periodic
structure. This forbidden frequency range—the ‘phononic bandgap’ (PBG)—allows sound to be controlled in many useful ways in structures that can act as sonic filters, isolators, waveguides or resonant cavities.

Newly developed phononic crystals and metamaterials are both able to control phonon transport successfully at low and high frequencies in the phononic spectrum, ranging from sound to heat transfer. There is, however, an important difference between phonon management based on phononic crystals and that based on metamaterials. Whereas in phononic crystals the structure periodicity is generally of the same order as the wavelengths of the phonons to be controlled, in metamaterials the structure length scale can be smaller.

This means that if we want to control large wavelengths in the phononic spectrum, such as earthquake or tsunami waves, it would be more appropriate to use metamaterials, because the required periodicities for phononic crystals would be exceedingly large. On the other hand, if we want to manipulate the short-wavelength limit, that is, heat flow, then both thermocrystals and thermal metamaterials may be appropriate choices depending on the structure length scale and intended applications, because heat flow can be controlled by using millimetre-scale metamaterials or nanometre-scale thermocrystals.

Researchers at MIT and elsewhere have succeeded in creating a synthetic crystal that can very effectively control the transmission of heat — stopping it in its tracks and reflecting it back. This advance could lead to insulating materials that could block the escape of heat more effectively than any present insulator.
This crystal structure was built using alternating layers of silicon dioxide (the basis of the dielectric layers in most microchips) and a polymer material. The resulting two-component material successfully reflected phonons — vibrational waves that are the carriers of ordinary heat or sound, depending on their frequency. In this case, the phonons were in the gigahertz range — in other words, low-level heat.

No material is ever going to be perfect, but even a material that reflects back a very high percentage of heat could be a big improvement over present insulators. For example, a shell of such material could be used to maintain the temperature in a package of delicate research instruments in a frigid environment.

How far off are such applications? “It’s close, if you don’t worry about price,” Thomas says — which may be the case for some uses such as spacecraft, or instruments deployed in Antarctica. And as the technology develops and as production gets scaled up, prices could eventually come down far enough to enable more widespread applications.

References and Resources also include:


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