The light of sound

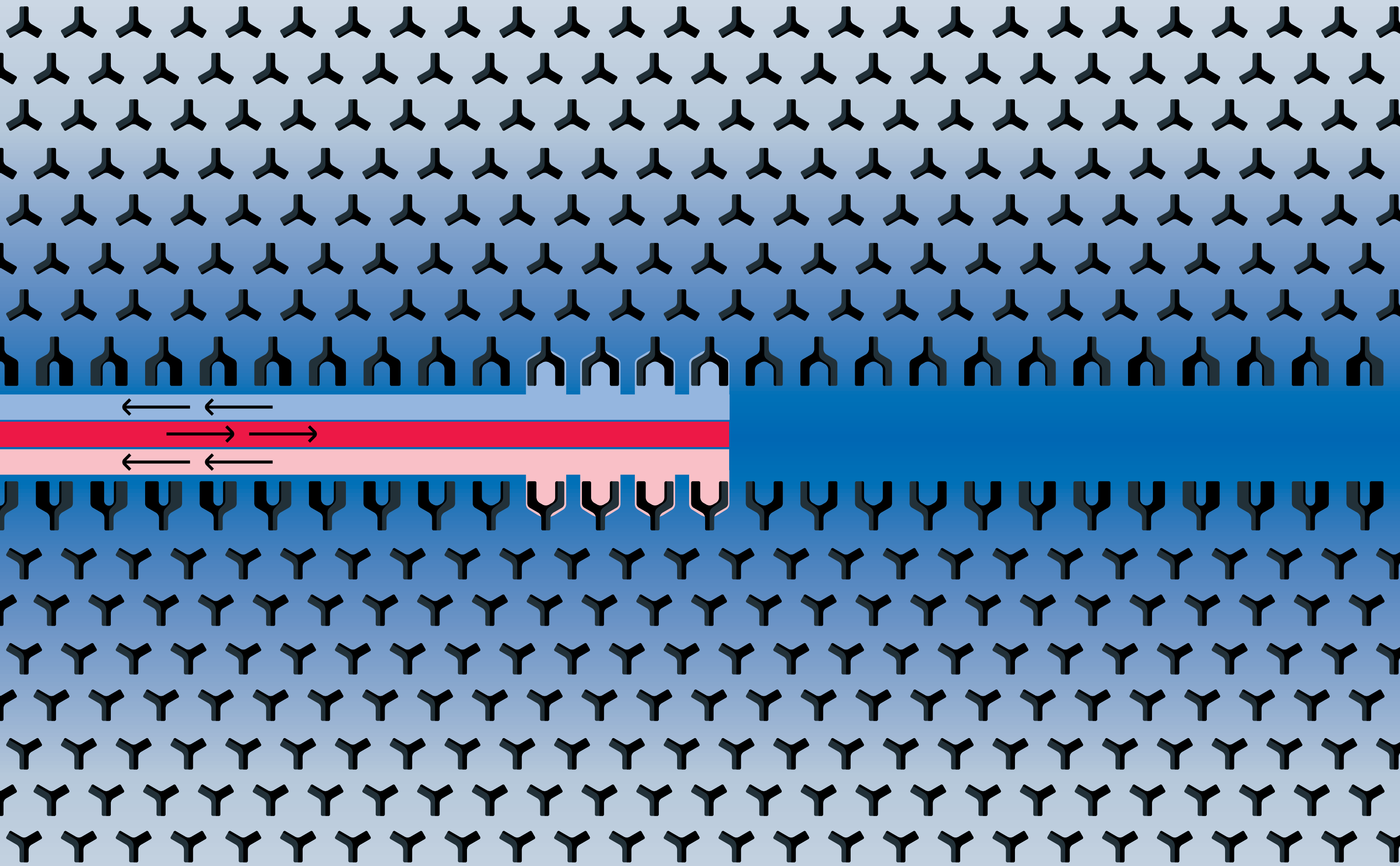

ILLUSTRATION ALEXANDRE AFFONSO/PESQUISA FAPESP MAGAZINE

Controlling interactions between photons and phonons could generate more refined lasers and facilitate quantum information processing

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The drawing shows the cavity inside the optomechanical crystal, where light waves (*in red*) interact with mechanical waves in the structure. This interaction produces two beams of light that travel in opposite directions: one pink beam and one blue beam

When it propagates through a material, a laser beam of significant intensity slightly modifies the density of the physical medium and generates small vibrations. These acoustic oscillations distort the material and can alter the original characteristics of the light beam. Two recent scientific articles to which Brazilian physicists contributed presented the experimental progress in controlling the interactions between light waves (photons) and acoustic or mechanical waves (phonons) within a physical medium. This phenomenon is briefly described above.

"The papers describe advancements that could facilitate the development of devices for quantum communication systems," said Gustavo Wiederhecker of the Gleb Wataghin Physics Institute at the University of Campinas (IFGW-UNICAMP). Wiederhecker coauthored one of the articles and heads the QuTIa Quantum Technologies Program at FAPESP, under which the two studies were performed.

The first article, which was published in Nature Communications on March 15, presents a silicon crystal that is designed to very quickly dissipate heat and increase efficiency when information based on qubits (quantum bits) is processed. The second article, which was published in *Physical Review Letters* on March 21, reported a new strategy for manipulating the polarization of light, indicating the (vertical or horizontal) plane on which its electromagnetic waves vibrate. This advancement could be useful for producing thinner, purer laser beams, which could theoretically increase the data transmission capacity in optical fibers.

Both studies were conducted by physicists from UNICAMP in partnership with American universities. Despite different approaches, both studies have contributed to the development of optical devices that can perform quantum transduction through acoustic oscillations. The process uses mechanical vibrations to convert quantum information between two forms of energy, from one wavelength of the electromagnetic spectrum to another. To create a quantum network, qubits encoded in microwave frequencies must be converted to quantum bits that work with visible light, without significant loss of information.

This is the focal point of the *Nature Communications* article, which suggests that quantum transduction can be performed using a silicon crystal with which light can interact along a plane in two dimensions. Until now, transducers have always been crystals whose structure allows for interactions with light in one dimension, but only in a given direction. The disadvantage of these one-dimensional crystals is their propensity for residual heating. The material absorbs some of the light energy, making the transduction process less efficient. "Our crystal was designed to 'talk' to the superconducting qubits and to dissipate heat very quickly," explains Thiago Alegre of IFGW-UNICAMP. He coauthored the paper with André Primo, who completed his PhD under Alegre's supervision in 2024, and colleagues from Stanford University, USA.

To control the increase in temperature, researchers designed a two-dimensional optomechanical crystal with structures referred to as "boomerangs" and "daggers." Boomerangs, which are more external, function as shields against interactions between the crystal and the environment, preventing mechanical disturbance. The more internal dagger structures trap the light inserted into the crystal with an optical fiber. In addition to confining the photons, the daggers also vibrate, generating acoustic waves. The phonons arising from this vibration interact with the photons between the daggers and connect to them. Owing to this quantum coupling, any change in the state of the photons causes an almost instantaneous change in the phonons, and vice versa. The result is that within this device, it is possible to convert information contained in light to acoustic vibrations.

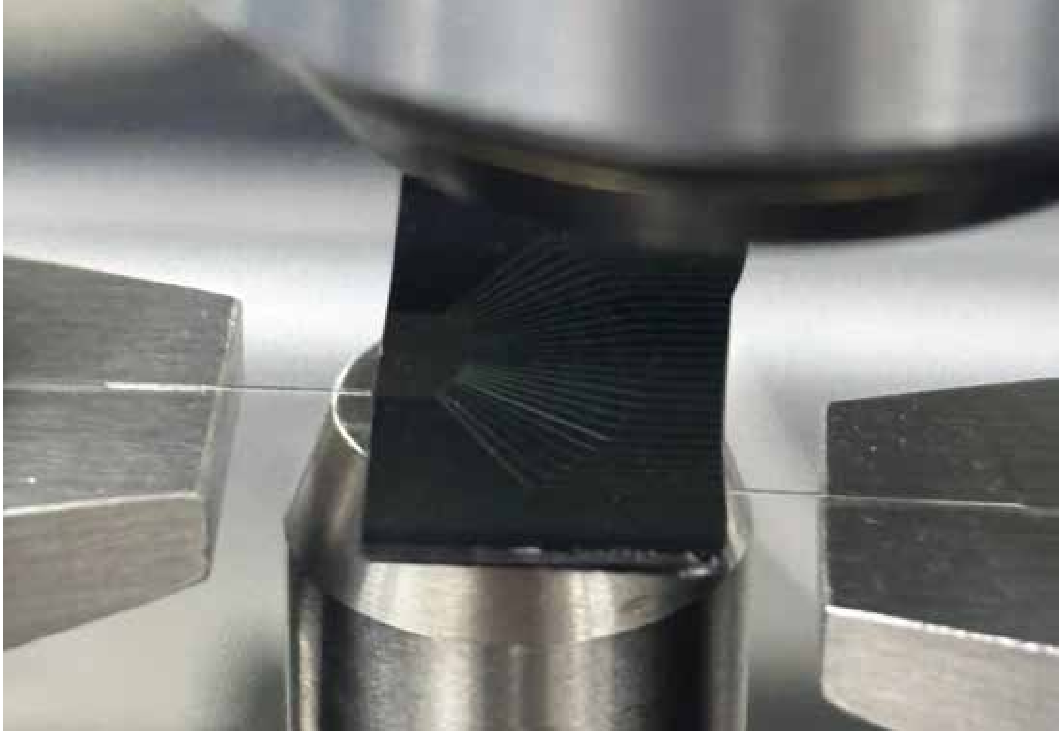
Transmitting information between quantum processors typically requires superconducting materials that operate at microwave frequencies and extremely low temperatures, near absolute zero (-273.15 degrees Celsius). A microwave transmission line between these devices would have to operate at similar temperatures, because at these frequencies, quantum information becomes disorganized at higher temperatures. In practice, the cooling required to build longer quantum networks of more than a few meters hits a thermal barrier.

The geometry of the crystal proposed by UNICAMP and its partners overcomes the problem of residual heating, but it still needs to be refined so that it can handle the conversion of quantum information from one form of energy to another. The team has not been able to fully control the acoustic vibrations of the crystal during the process of converting data from microwave frequencies to visible light frequencies. If this goal can be achieved, it will be possible to transmit quantum data via lasers over extensive fiber optic networks. "Fibers are excellent thermal insulators, and information carried by light is not disturbed by temperature variations," stated Primo.

Anderson Gomes, a physicist from the Federal University of Pernambuco who did not participate in the study, reported that the research is highly original. "It extends the frontier of knowledge in optomechanics," he said. "It is the first step toward demonstrating transduction with a two-dimensional silicon crystal."

The second article addresses a phenomenon known as Brillouin scattering, which occurs when the properties of a light shining on a medium are altered due to the effect of the material's

Image of a waveguide created at UNICAMP (*black rectangle*) and attached to two optical fibers



acoustic vibrations. The result of this interaction between photons and phonons is that the scattered light can have a different frequency (color) than the incident light. In the field of communications, the manipulation of this type of scattering, which was proposed in 1922 by the French physicist Léon Brillouin (1889–1969), is currently used to measure temperature and pressure in optical fibers.

In the article published in *Physical Review Letters*, physicists directed a laser beam into lithium niobate ($LiNbO_3$) waveguides to change the polarization of light (the plane on which its electromagnetic waves vibrate). This type of alteration can produce purer, finer lasers, which tend to be more efficient at transmitting information. Waveguides are structures that confine and direct the propagation of electromagnetic waves (usually lasers) or mechanical vibrations.

Lithium niobate, a material often used in telecommunications, has a microscopic hexagonal structure similar to a honeycomb and is anisotropic; that is, any changes in the orientation of its structure affects the way it interacts with light. Waveguides are typically constructed from isotropic materials such as silicon nitride (Si_3N_4), which interact with electromagnetic radiation in the same way regardless of the orientation of their structures.

In addition to being anisotropic, lithium niobate was chosen for the experiments because of another desirable characteristic: it is piezoelectric; that is, it produces electrical charges when it vibrates or is subjected to mechanical stress. Experiments performed at the Integrated Photonics Laboratory of the IFGW indicate that changing the incline of a $LiNbO_3$ waveguide alters the intensity of light scattering. The electromagnetic frequency of the scattered waves also relies on the wave scattering angle.

In lithium niobate waveguides, light interacting with vibrations is scattered in cross-polarization. If the initial laser beam is horizontal, the light reflected by the phonons of the physical medium is vertically polarized and vice versa. "This way of manipulating the information transmitted by light could be useful for manufacturing waveguides that function as polarization converters," notes the study's lead author, physicist Caique Rodrigues, who completed his PhD at UNICAMP in early 2025, supervised by Wiederhecker. Rodrigues coauthored the paper with Wiederhecker, Alegre, and four other researchers from the UNICAMP optics group, as well as colleagues from Harvard University, USA.

Cleber Mendonça, a physicist from the São Carlos Physics Institute at the University of São Paulo (IFSC-USP) who did not participate in the study, suggests that the results reinforce the possibility that the polarization of light could be manipulated with something similar to an optical key. "It could thus be possible to select the light polarization that would or would not propagate inside optical fibers," he remarked. ●

The projects and articles consulted for this report are listed in the online version.

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