Catching and Guiding an Elastic Rainbow

Two experiments demonstrate a promising platform for trapping, sorting, and directing vibrational energy.

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In a rainbow, sunlight separates into colors because each wavelength of light follows a different path. This familiar image has inspired an analogous idea in wave physics: A designed material can slow down different frequency components of a broadband signal at different positions, thereby sorting the signal in space. This concept, known as rainbow trapping, was introduced as a route to storing light in metamaterials [**1**] and has since motivated efforts to control sound, vibration, and other classical waves. But rainbow trapping has been difficult to realize for elastic waves—vibrations that temporarily deform a material as they move through it. Many rainbow designs have relied on vibrational modes confined to a sample's edges or interfaces, limiting the available trapping area, or have lacked a way to access and route energy once it has been localized.

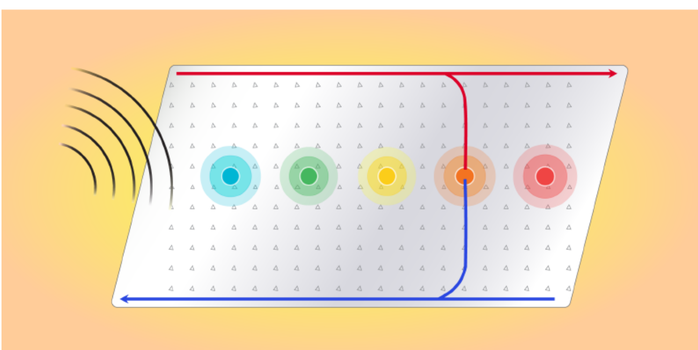

Figure 1: An elastic wave (black) enters a square lattice of slightly misaligned triangular elements (gray). Synthetic magnetic and electric fields (not shown) cause different frequencies of the wave to localize at different positions in the material's bulk. The result is a so-called elastic rainbow (colored regions). Meanwhile, a topological edge state (red arrow) moving along the material's upper boundary selectively couples to one localized mode and routes that mode's energy to the opposite topological edge state (blue arrow) moving along the lower boundary.
Credit: APS/Carin Cain

Now two teams have taken complementary steps toward overcoming these limitations. Yafeng Chen at Tongji University in China and colleagues have created and directly visualized an elastic rainbow in which different megahertz-frequency vibrations stop at different positions [**2**]. Meanwhile, Riyi Zheng at the South China University of Technology and colleagues have shown that a similar rainbow can be captured and redirected using topological edge states [**3**]. Together, these two studies transform elastic rainbow trapping into a platform for sorting, confining, and guiding vibrational energy.

The physics behind these results stems from Landau levels—the discrete energy levels available to electrons in a thin slab subjected to an out-of-plane magnetic field. Some Landau levels are almost flat: Their energy changes very little with momentum. States associated with such flat bands have a group velocity close to zero, allowing wave packets to propagate very slowly and become localized [**4**, **5**]. Elastic waves do not respond directly to magnetic fields, but carefully patterned structures can imitate their influence by generating synthetic fields, often called pseudofields. This ability to reproduce magnetic-field-like physics without a real magnetic field has become a powerful tool for controlling classical waves.

Two such pseudofields worked together in both new studies. A pseudomagnetic field created elastic Landau levels, while a pseudoelectric field shifted their frequencies across the sample. This combination caused different frequencies of elastic waves to become localized at different positions, forming an elastic rainbow (Fig. **1**) [**6**]. Whereas previous rainbow schemes were based mainly on edge or interface modes [**7**, **8**], these Landau modes could occupy the sample's bulk, offering more space for simultaneously controlling multiple frequencies. The bulk, however, is useful only if its localized modes can be excited, selected, and connected to an output pathway—precisely the issue addressed by the two studies.

Chen and colleagues implemented this idea in a patterned aluminum plate. Two gradual changes to the geometry of the material's unit cell, applied along perpendicular directions, independently controlled the two pseudofields. Crucially, the pseudomagnetic field was nonuniform, which broadened the momentum range over which the relevant Landau levels remained flat. This expanded flat region provided a more effective landscape for slowing down and localizing elastic waves. The team's calculations revealed an unusual progression: Energy initially traveled through the central part of the sample, then spread toward the upper and lower boundaries of the pseudomagnetic-field region as the waves slowed down. Near the stopping point, the flat portion of the Landau levels dominated, and the group velocity approached zero. This evolution—in contrast to a simple abrupt halt—reflects the combined roles of the flat and nonflat parts of the bands.

The researchers sent elastic waves of frequencies near 1.1 MHz through their plate and then used laser scanning to reveal the waves' fate. Different frequencies produced vibration patterns centered at different positions, in close agreement with the team's numerical simulations. The measurements therefore provide direct evidence of a bulk elastic rainbow, while the calculated mode evolution explains how the traveling waves turned into localized states. Importantly, the experiment makes this phenomenon—usually discussed through band diagrams—visible as a real-space map of vibrational energy.

Zheng and colleagues addressed the natural next question: Once a bulk rainbow has formed, can a selected color be reached and its energy guided elsewhere? In contrast to the other study, the researchers realized their rainbow in a silicon chip. Their key addition was a pair of topological edge states: one carrying energy in one direction along the material's upper boundary, and the other carrying energy in the opposite direction along the lower boundary (Fig. **1**).

In the team's experiment, the upper edge state traveled rightward until it encountered the bulk Landau mode of the same frequency. Frequency matching and spatial overlap allowed the edge state to couple to that localized mode. The wave energy then crossed the sample and emerged at the material's lower boundary, where it continued leftward along that boundary. Because different frequencies coupled at different positions, the bulk rainbow was effectively turned into a frequency-dependent routing map. The behavior was reproduced at several frequencies, and tests with defects and disorder showed no obvious backscattering of the elastic waves under the conditions examined. The team's results establish a functional bridge between bulk localization and topological edge transport.

Viewed together, these studies offer more than just two versions of the same effect. Chen and colleagues enlarged the flat-band region and directly revealed how bulk localization develops. Zheng and colleagues connected such localized modes to topological transport channels. The former experiment improved the rainbow itself; the latter showed how to catch and use it.

Substantial challenges remain before elastic rainbows can have practical applications. Energy loss in the material, fabrication imperfections, and limited spatial overlap between the edge and bulk modes can all reduce the efficiency of rainbow trapping and of energy transfer. The structures are also static, so the stopping positions and routing paths of different frequencies are fixed after fabrication. Piezoelectric components, tunable boundaries, and other active elements could make the pseudofields reconfigurable and allow frequencies to be redirected on demand. Even before that step is reached, these experiments suggest a path toward compact elastic-wave processors that separate frequencies, concentrate energy, and deliver selected signals to different locations. In this emerging picture, an elastic rainbow is no longer only something to observe; it is also something to catch, connect, and use.

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