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Viewpoint

"Snowflake Crystal" Traps Light and Sound

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Experimentalists trap optical and acoustic oscillations together in a two dimensional structure that will make it easier to study their coupled behavior.

Subject Areas: **Optics, Metamaterials, Acoustics**

A Viewpoint on:
Two-Dimensional Phononic-Photonic Band Gap Optomechanical Crystal Cavity
Amir H. Safavi-Naeini, Jeff T. Hill, Seán Meenehan, Jasper Chan, Simon Gröblacher, and Oskar Painter
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Research on cavity optomechanics, which concerns the interaction between light and mechanical vibrations in confined geometries, has blossomed during the past few years [1]. Potential applications include coherent microwave–optical conversion, sensitive mechanical measurements, quantum information processing, mechanical storage of light pulses, and coupling between different quantum systems, as well as new tests of the foundations of quantum mechanics. Of the many different optomechanics platforms, one of the most promising comprises "optomechanical crystals." In *Physical Review Letters*, Amir Safavi-Naeini *et al.*[2] and his colleagues in Oskar Painter's group at the California Institute of Technology, Pasadena, exhibit a novel two-dimensional (2D) structure of this type.

The engineering of wave propagation by means of periodic patterning of materials has been applied for some time to optical and acoustic waves, leading to photonic and phononic crystals, respectively. Optomechanical crystals that combine the two have emerged in the last few years, as shown earlier by the Painter group [3]. They demonstrated that optical and vibrational modes of high quality can be created in this manner at the same micrometer-sized spot, producing an optomechanical coupling that exceeded that of previous devices by orders of magnitude. This has already been employed successfully in the demonstration of optomechanical laser cooling to phonon numbers below unity [4], close to the ground state, as well as other tasks. These first devices were fabricated by one-dimensional (1D) periodic patterning of freestanding nanobeams.

Extending optomechanical crystal structures to two dimensions would allow a greater variety of designs to be built, and the first steps have already been taken. For example, "phonon shields" reduce energy loss in mechanical resonators, as reflected in their "quality factor," which is roughly the number of oscillations before the energy leaks away. Researchers achieved this by surrounding the resonators with structures that have an acoustic band gap around the frequency of resonance, so that phonons cannot propagate and escape [4]. The new work reported by Safavi-Naeini *et al.* presents the first structure that has both an optical and an acoustic band gap [2]. The design is based on a triangular lattice of snowflake-shaped holes in a silicon slab. Alternatively, it can be viewed as an array of triangles connected by thin bridges of material (Fig.1).

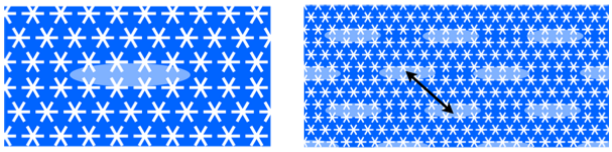

FIG. 1: A planar slab of silicon with a periodic arrangement of snowflake-shaped holes (here viewed from above) forms a two-dimensional optomechanical crystal. (Left) By disrupting the alignment between successive horizontal lines and (not visible) locally altering the structure along that linear defect, Safavi-Naeini *et al.* produced a single localized defect mode (indicated here by a shaded ellipse) for optical radiation at the same place as a localized vibrational mode of the structure. (Right) In the future, a periodic arrangement of such defects could produce an "optomechanical array," with photons and phonons tunneling between each pair of neighboring sites (exemplified by the arrow) and interacting with each other. (APS/Florian Marquardt)

The acoustic modes can be understood in terms of a simple model in which individual oscillators (the triangles), each with its own set of mechanical modes, are connected with springs (the bridges). As the bridges become thin, the structure becomes floppy, and the speed of sound waves, and thus their maximum frequency, decreases. At the same time, the band formed by coupling the finite-frequency normal modes becomes narrower. As a consequence, an acoustic band gap is produced between these two bands.

For the electromagnetic waves, a 2D slab can never

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support a complete band gap, since waves traveling nearly perpendicular to the plane will always escape. However, careful engineering can ensure that waves traveling inside the plane see a pseudo-band-gap, and that any localized modes of interest have very little overlap with the waves that can escape, so the optical quality factor will remain high.

In their new snowflake-crystal design, the authors first disrupted the regular arrangement to create a linear defect in the 2D periodic structure, which, on its own, would form a 1D waveguide. They then modified this structure along the waveguide direction to create localized modes. This approach simplifies the design, avoids overlap with waves that radiate out of the slab, and makes the structure more robust against disorder.

The authors measured two localized mechanical resonances with frequencies near 9 gigahertz, with a mechanical quality factor of more than 10^5, that couple strongly to an optical mode. This optical mode retains its energy for several cycles of the mechanical oscillation, so the device is firmly in the resolved-sideband limit, which is important for many applications such as sideband cooling or state transfer. The parameters of this device, including the large coupling strength between the optical and mechanical modes, are comparable to the record values that the group had previously attained for their 1D structures. Achieving them in a 2D device is very significant. For one thing, the planar geometry is much better at handling the heat load from residual laser absorption, because the heat can be transported away more easily. In addition, there is a lot of room for adding optical and acoustic waveguides and other localized modes to the structure.

Creating such 2D structures opens the door towards larger-scale optomechanical arrays and circuits, which would combine many optical and vibrational modes. The coupling between those localized modes can be pictured in terms of photons or phonons tunneling from site to site, depending on the overlap of the tails of the modes, similar to the situation for localized electronic orbitals. A periodic array of such defect modes will yield an optomechanical band structure for photons and phonons. The properties of this superlattice can easily be tuned in *situ* by varying the strength of the laser driving all the cells, in essence producing an optomechanical metamaterial. The features that could be explored range from slow light [5] to engineering optomechanical band structures [6] for observing graphene-type Dirac physics or generating synthetic magnetic fields for photons. In addition, optomechanical networks [7], long-range collective interactions [8], and transport [9] might be studied in such devices.

Even more intricate dynamics will be observed in the nonlinear regime. This regime would be reached if such an array is driven by a laser at higher frequencies (blue-detuned) from the optical resonances, taking the system beyond the instability towards self-induced mechanical oscillations. Coupling many such oscillators in an array gives rise to synchronization and pattern formation, as well as quantum many-body dynamics of photons and phonons [10].

The new 2D snowflake crystal structures will likely become the preferred experimental platform for exploring many of these theoretical proposals.

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Florian Marquardt is full professor of theoretical physics in the Department of Physics at the University of Erlangen-Nuremberg, Germany. After receiving his Ph.D. from the University of Basel, Switzerland, in 2002, he worked as a postdoctoral researcher at Yale University (2003–2005). From 2005 to 2010, he headed a junior research group at the Ludwig Maximilian University Munich, before moving to Erlangen. His research topics at the intersection of nanophysics and quantum optics include quantum transport, decoherence, quantum many-body physics, and the fields of nano- and optomechanics.

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