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Acoustic metasurface creates quiet locations in a room FREE

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microwave field over a narrow range and watching for changes in the fluorescence.[4] That has the benefit of speed, and one can even track multiple resonances at the same time by using a different oscillation period for each of them.[5] However, the technique is limited to measuring magnetic field changes of just a few microteslas, and furthermore, it requires the resonance line shapes to be constant over time. Fluctuations in the optical laser power can cause changes in the line shape and are thus a significant source of error.

Frequency following

Braje and colleagues' design improves on the second technique by incorporating closed-loop feedback circuits to allow the oscillating microwave frequencies to follow the resonances as they move. Naturally, that enhancement allows operation over a much larger range of magnetic field. Moreover, because of the difference in the way the resonant frequencies are derived from the measured signal, it frees the measurement from the assumption of constant laser power and constant line shape. Attenuating the laser power by even a factor of 20 doesn't change the ultimate field measurement; a normal 5% drift in laser intensity has virtually no effect at all.

For their demonstration, the researchers used a piece of diamond 2 mm on each side and containing an estimated trillion NV centers of all four orientations. Using the trick of different frequency-oscillation periods, they probed the resonances two at a time. They always measured the +1 and −1 resonances of the same orientation simultaneously, which is important for removing the effect of temperature drift. And they cycled through the four orientations with a dwell time of 0.1 s on each.

To tell the orientations apart, they applied a strong bias field of 7 mT. As shown in figure 2a, that caused the eight resonance frequencies to separate over a range of several hundred megahertz. A typical field to be measured, up to tens or hundreds of microteslas, imposes relatively small additional frequency shifts; the resonances remain distinct, and in principle a stronger bias field would allow an even larger dynamic range.

Figure 2b shows how the NV magnetometer can measure both the magnitude and the direction of an external field. In response to 10 μT fields applied sequentially in the z, y, and x directions, the resonances exhibit distinct patterns of frequency shifts. The response is fast and stable over time, with little noise. The measurement is overdetermined—four NV orientations are used to reconstruct a three-dimensional field vector—and that redundancy can be helpful in correcting for lingering sources of instrumental error.

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Acoustic metasurface creates quiet locations in a room

With its tunable panels, the specially designed surface can sculpt soundscapes on the fly.

The sound in a room is a complicated superposition of waves reflected and scattered off the ceiling, walls, and other objects. Changing how those waves interfere with each other offers a way to control a noisy environment

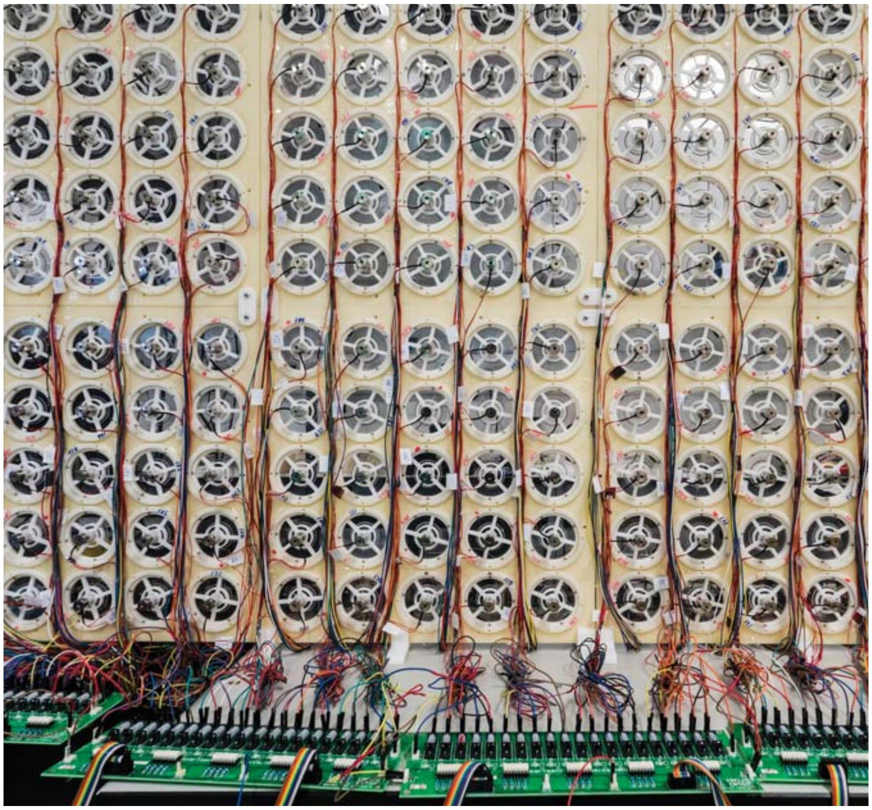

FIGURE 1. A NEWLY DEVELOPED ACOUSTIC METASURFACE consists of 360 membrane resonators, each 27 mm in radius and 0.1 mm in thickness. This photo shows about a third of the total surface. The full array has an area of less than 1% of the enclosing room's total wall, floor, and ceiling area and creates a centimeter-scale quiet zone at a chosen location. Four membrane units are grouped together as one unit, controlled by programmable electronics. (Photo by Guancong Ma.)

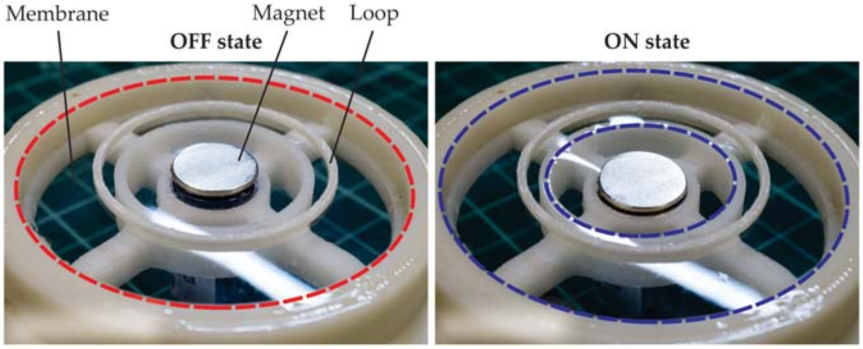

FIGURE 2. MEMBRANE ON AND OFF STATES. Each acoustic metasurface membrane, to which a magnet has been attached, can be electrically switched between two states by changing the polarity of the voltage across an electromagnet, which sits beneath the white frame in these photos. In the OFF state, the magnet is free and the transparent membrane has one fixed boundary at the edge (red circle). In the ON state, the magnet is snapped onto the electromagnet and the membrane has two fixed boundaries (blue circles). The loop just outside the inner boundary is part of the electromagnet's support. (Adapted from ref. 1.)

and make selected locations much quieter.

Noise-canceling headphones use active noise control. Their electronics damp environmental noise by generating and playing back sound waves 180° out of phase with the ambient sound waves. Active noise control can also be done without headphones; it can use microphones to detect the noise level and then signal loudspeakers to generate acoustic waves that cancel or modify the detected acoustic field. But active control measures consume energy, compromise sound quality, and do not achieve complete silence because of feedback time lag or phase errors.

To precisely control sound-wave propagation in a room, scientists have developed acoustic metamaterials whose surfaces have mechanical properties designed to reflect, transmit, or delay sound waves so that waves manipulated by one part of the material interfere with those manipulated by another part (see the article by Mike Haberman and Matthew Guild, Physics Today, June 2016, page 42). Acoustic metamaterials provide an interference effect similar to that of active noise cancellation but without the need for additional acoustic waves.

Guancong Ma and colleagues at the Hong Kong University of Science and Technology and Mathias Fink of the Langevin Institute in Paris have put that idea into practice. They designed and built a screen-like metasurface, with a surface area less than 1% of the enclosing room's total wall, floor, and ceiling area, that damps a single-frequency noise source to create a quiet zone at a designated location.[1] The surface's effective properties can be changed in real time to adapt to changing noise sources or to focus on different locations.

A crucial ingredient in Ma and company's approach is a technique that has emerged in the past decade for controlling light propagation through scattering environments. Optically opaque media, such as biological tissues and white paint, scatter any light that penetrates them. Much of the light is reflected, but some is transmitted as a dim blur. The acoustic wave field in an enclosed, reverberating room is similarly complex.

Highly tunable digital arrays known as spatial light modulators can be used to measure and undo a medium's scattering effects on a reflected or transmitted beam. Spatial light modulators consist of matrices of micromirrors or liquid-crystal cells, each of which imparts a physical phase shift to the portion of light it reflects or transmits.

In 2007 Allard Mosk and Ivo Vellekoop of the University of Twente in the Netherlands demonstrated that wavefront shaping works for focusing optical waves in a complex medium.[2] They placed a spatial light modulator with 3000 phase-modulating pixels between a laser and their sample, a layer of white paint. By independently manipulating each pixel, the researchers achieved a thousandfold increase in intensity reaching a photodetector on the other side of the paint (see Physics Today, September 2008, page 20).

Active control

Given that visible light waves can be focused by a phase modulator, changing the propagation of other types of waves, electromagnetic or not, could be possible. In 2014 Fink, Geoffroy Lerosey, and colleagues at the Langevin Institute used similar wavefront shaping to focus microwave radiation onto a cell-phone antenna for wireless communications. Their spatial microwave modulator comprised an array of reflective elements placed on the wall of the room.[3]

The microwave modulator's success led Fink to collaborate with Ma and colleagues to develop a similar design for manipulating sound waves. The result, shown in figure 1, was an acoustic version of a spatial light modulator.

The team's modulator consists of a 2.3 m^2 array of 27-mm-radius membranes, each connected to an electromagnet, that resonate when excited by a sound wave. Switching the polarity of a voltage across the electromagnet either pins or releases the central part of the membrane, which shifts the resonance to 850 Hz or 450 Hz, respectively. Figure 2 shows the configuration of a membrane in its pinned, or ON, and released, or OFF, states.

An incident sound wave with a frequency above or below the membrane's resonant frequency undergoes a phase shift as it passes through the membrane. For example, a 600 Hz wave transmitted through the activated membrane undergoes a positive phase shift, and one transmitted through the deactivated membrane undergoes a negative shift. The difference in the phase shifts is nearly 180° and results in destructive interference.

The team built an array of 360 membranes and positioned it in the middle of a room. Four membrane units were grouped together as one unit, controlled by programmable electronics. Team members measured the sound amplitude with a small microphone placed at a fixed point. The measurements provided feedback to a control system that determined which membranes should be activated to yield an acoustic wave having the smallest amplitude at the location of the microphone.

By optimizing the surface, the researchers were able to create a quiet zone in which a 636 Hz sound wave was reduced by 21 dB, or nearly 95%. A localized quiet zone can be seen in figure 3. Before the optimization, the pressure field had a relatively uniform distribution, which is evidence of the disordered nature of a reverberating sound. In a similar experiment, the researchers showed that they could also amplify the 636 Hz sound to create an acoustic hot spot at a chosen location.

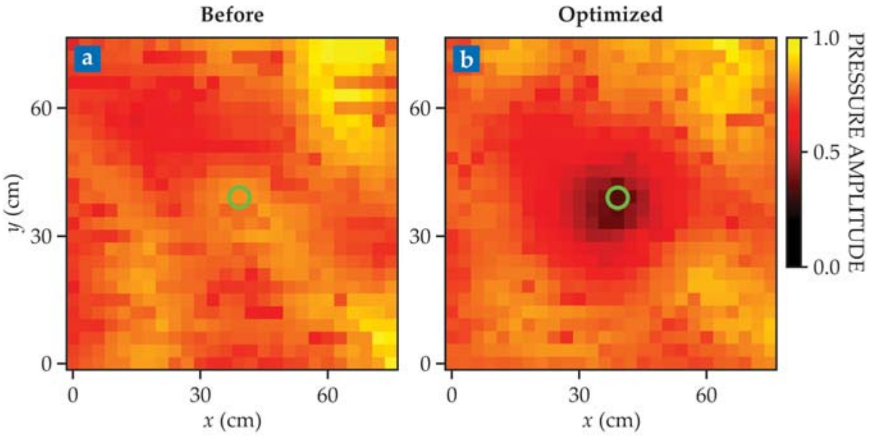

FIGURE 3. AVERAGE ACOUSTIC PRESSURE AMPLITUDES measured in a 75 cm by 75 cm area. **(a)** The pressure distribution before optimizing the metasurface is roughly uniform, characteristic of reverberating sound. **(b)** The metasurface is optimized to minimize the pressure amplitude at 636 Hz. A local minimum is created at the position marked by the green circle. (Adapted from ref. 1.)

How effective?

"Active noise control is an obvious benchmark to compare Ma's results to, and may already produce comparable results," notes Matthew Guild of the US Naval Research Laboratory in Washington, DC. He refers to 20-year-old results[4] from an experiment that reduced the total noise level in a room by 14.4 dB. That experiment used three sensors and three loudspeakers—all of which must be continuously powered—to emit sound waves with the correct phase to cancel the sound field. In contrast, a tunable metamaterial surface avoids instability and consumes minimal energy unless the membranes are switching.

Steven Cummer and colleagues at Duke University, including Bogdan Popa now at the University of Michigan, designed an array of 10 piezoelectric membranes controlled by electronics to manipulate the phase of a transmitted acoustic wave.[5] Although the material's spatial properties could be changed rapidly to the desired values, the feedback system could not automatically tune those properties in real time. "Ma's research is a heroic experimental effort and a great implementation of a concept that has not been shown in audio frequency acoustics before," says Cummer.

Says Fink, "In our case, the spatial properties of the metasurface can be changed in real time to maximize energy in some location or to create a silent zone. This makes them quite attractive for various applications." Creating quiet zones anywhere in a room could provide a versatile noise-abatement solution, and creating acoustic hot spots at positions with high absorption could reduce the average sound level in a room.

The metasurface offers a way to damp the noise from a single-frequency source. The researchers are working on a different feedback system that will also make it possible to tune broadband frequencies. The optimized system might, for example, be programmed to pick out the states of membranes that lead to the smallest spectral sum for a chosen frequency regime. The team also plans to design a surface that works for reflected waves and can be fixed on the wall, rather than a screen-like surface that manipulates transmitted waves. Such a design, the researchers say, could offer a way to alter a room's acoustic quality without an overhaul of the interior design.

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