

sharpness of the memory signals, the researchers scanned γ_o more slowly in the vicinity of the known training amplitudes. But the memory doesn't depend on that aspect of the readout protocol—they could just as easily have scanned γ_o at a constant rate to detect an unknown γ_t .

Curiously, trained rafts behave like untrained rafts even for $\gamma_o < \gamma_t$ (or γ_{ti} for the two-memory raft). That means not only that training at γ_t has no effect on the raft response at $\gamma_o < \gamma_{ti}$, but that shearing at $\gamma_o < \gamma_t$ —which rearranges some of the bubbles—doesn't disrupt the memory of γ_t . Both of those features remain to be fully understood.

Cryptic memory

"We expected to see memory in this system," says Ganapathy. "But personally, I expected to see a clear memory signature only beyond the yield point, because that is where the system has been reconfigured enough to be subsequently read out." In fact, the memory works equally well for γ_t just above and just below γ_y : All three of the memory signatures shown in figure 2 are for strains less than γ_y . On the other hand, the memory works poorly for val-

ues far from γ_y in either direction.

That unexpected behavior offers a new path to exploring the nature of the yielding transition itself. Deforming a material at or above the yield strain doesn't make all of it yield uniformly; some parts flow freely while others remain rigid. Previous experiments from Ganapathy's group⁵ showed that at γ_y , spatial correlations between the flowing and rigid regions are maximized, and the system's relaxation time diverges, just like at the critical point of a second-order phase transition. And recent simulations have shown that shearing a model glass at γ_y helps it find its way into an ultra-stable, low-energy (but still disordered) configuration.⁶

There's something about γ_y , it seems, that efficiently rearranges particles and explores the space of possible configurations. What that has to do with memory depends on where and how the memory is stored in the system. If, for example, memory of each γ_t value is encoded at a particular length scale, that could help explain how the system can remember multiple γ_t values at the same time and why shearing at γ_y , which accesses all length

scales, strengthens the memory signature.

But that's all speculation for now, because it's still not clear what makes a trained raft structurally different from an untrained one. So far, the only known way to tell them apart is by performing the readout protocol. Despite their best efforts, the researchers haven't found a way to tell the two apart based on the positions of the bubbles alone. An audience member at one of Ganapathy's talks once asked if the effect might somehow be exploited in cryptography. "I don't know the answer," he says, "but there might be advantages to this form of memory."

Johanna Miller

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A strain-based antenna paves the way for portable long-range transmitters

The piezoelectric device improves on the efficiency limits of small, conventional metal antennas without sacrificing bandwidth.

Very low-frequency (VLF) radio waves can carry signals through land and water with little attenuation. Unlike higher-frequency electromagnetic waves used for most communications, VLF waves are reflected by the ionosphere, and the space between it and Earth's surface acts as a waveguide through which the waves travel beyond the horizon. So, whereas higher-frequency waves travel in straight lines, VLF signals follow Earth's curvature and can transmit information to locations hundreds of kilometers away. The military uses VLF waves for navigation and communication with aircraft and submarines.

Although VLF signals are routinely generated, their use is limited by an antenna's size. To be reasonably efficient, an antenna's length should be at least a tenth of the signal's wavelength. For VLF waves, which are 3–30 kHz, the length would be more than a kilometer. Antennas whose length is much less than the signal's wavelength are considered "electrically small." They can still transmit VLF waves, but their nonradiative losses are large compared with the signals they transmit, so electrically small antennas are much less efficient than their larger counterparts. The VLF antennas used by the military are hundreds of meters tall, and even at that size they're electrically small. If they were portable, VLF antennas could be used by divers underwater, or by soldiers moving through underground mines or caves.

With their new piezoelectric antenna, Mark Kemp and coworkers at SLAC and

their two industrial collaborators, SRI International and Gooch and Housego, are trying to get the best of both worlds.¹ Their prototype 9.6-cm-long lithium niobate transmitter, shown in figure 1, is much smaller than the approximately 10 km wavelength of the signal it generates, but it is more efficient than similarly small metal antennas. Although increased efficiency would normally be accompanied by a reduced bandwidth, modulating the antenna's resonant frequency allowed the researchers to maintain an effective bandwidth comparable to that of a small metal antenna.

Vibrating crystals

Piezoelectric crystals are often used as electronic oscillators because they vibrate with precise frequencies. Quartz crystals, for example, began being used about a century ago for timekeeping and as frequency references for radio sta-

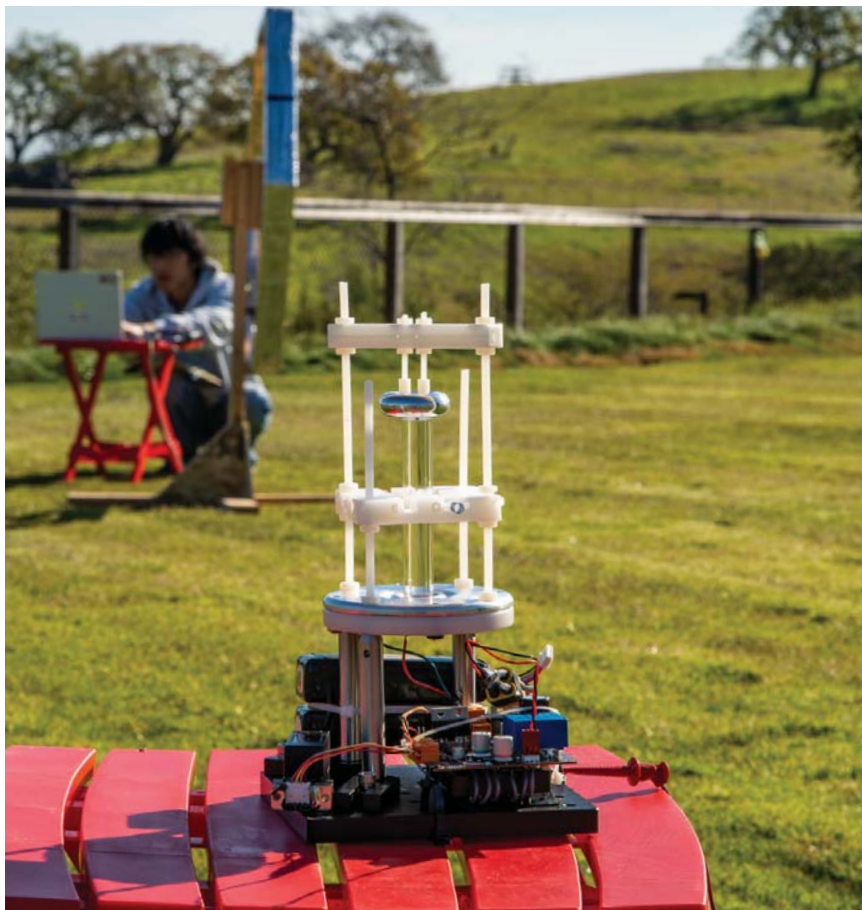


FIGURE 1. THE PORTABLE PIEZO-ELECTRIC TRANSMITTER in the foreground uses mechanical oscillations in a lithium niobate crystal (clear rod) to generate very low-frequency radio waves. Researchers had to take the transmitter to a remote location far from buildings and power lines to get accurate measurements of its field. In this photo, Alex Nguyen is using a receiver to measure and determine how the field drops off as a function of distance. (Photo courtesy of Dawn Harmer/SLAC.)

tions. Vibrations in piezoelectric crystals are generated by an electric field that causes the atoms to shift in each unit cell and thereby deform the crystal. That shift also causes charge separation, and a voltage difference develops between the ends of the crystal. When the field is removed, the crystal returns to its original state. Oscillating the electric field generates a periodic voltage and strain.

If the field oscillates at the piezoelectric resonance of the crystal, which depends on its mechanical and electrical properties, the deformation and peak voltage are maximized. In a quartz watch, the timing of those voltage peaks determines the length of a second.

The LiNbO_3 crystal used by Kemp and colleagues works on the same principle. Applying an alternating voltage causes the crystal to vibrate at its resonant frequency. The vibration induces a large electric field in the crystal because of LiNbO_3 's strong electromechanical coupling. As the electric field in the crystal oscillates, the crystal radiates as an electric dipole, just like a wire antenna. However, whereas conventional antennas radiate because they carry a current of flowing charges, strain-based antennas radiate because of a displacement current, or time-varying electric field, cre-

ated by bound charges in the material.²

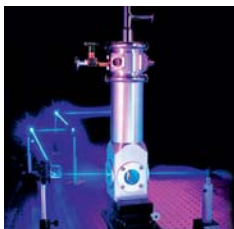
Connecting an antenna directly to an impedance-mismatched power source causes signal reflection and the formation of standing waves in transmission lines.³ Impedance matching the source and the antenna by adding the right combination of capacitors and inductors minimizes the problem and maximizes the power radiated by the antenna. But those additional circuit elements can be bulky and have their own associated losses. For a metal VLF antenna that would be small enough to carry, the size of and losses from the circuitry would be prohibitively large.

A piezoelectric resonator, however, eliminates the need for extra impedance-matching elements. The crystal behaves like an electrical circuit with a resistor, inductor, and capacitor, and the effective circuit's impedance can be tuned by varying the crystal's size, stiffness, and mechanical friction. A large impedance-matching inductance is therefore embodied by the antenna itself.

A measure of success

Radiation efficiency is proportional to the energy radiated and inversely proportional to its nonradiative losses. Switching to a piezoelectric material reduced the nonradiative losses in Kemp and coworkers' antenna by a factor of about 300 compared with a similarly sized metal antenna. That improvement came from using LiNbO_3 , which has low mechanical elastic losses, removing the impedance-matching circuit, and choosing to excite a particularly low-loss vibrational mode in the antenna.

Reducing nonradiative losses should improve the overall efficiency of the antenna. But confirming that expectation requires measuring the radiated field at a distance comparable to the wavelength, which the researchers have not yet done. "Measuring the fields precisely is a challenge," says Kemp. "Any RF interference or materials around the transmitter and receiver can significantly alter the measurement. For many of our experiments, we had to go out to fields far



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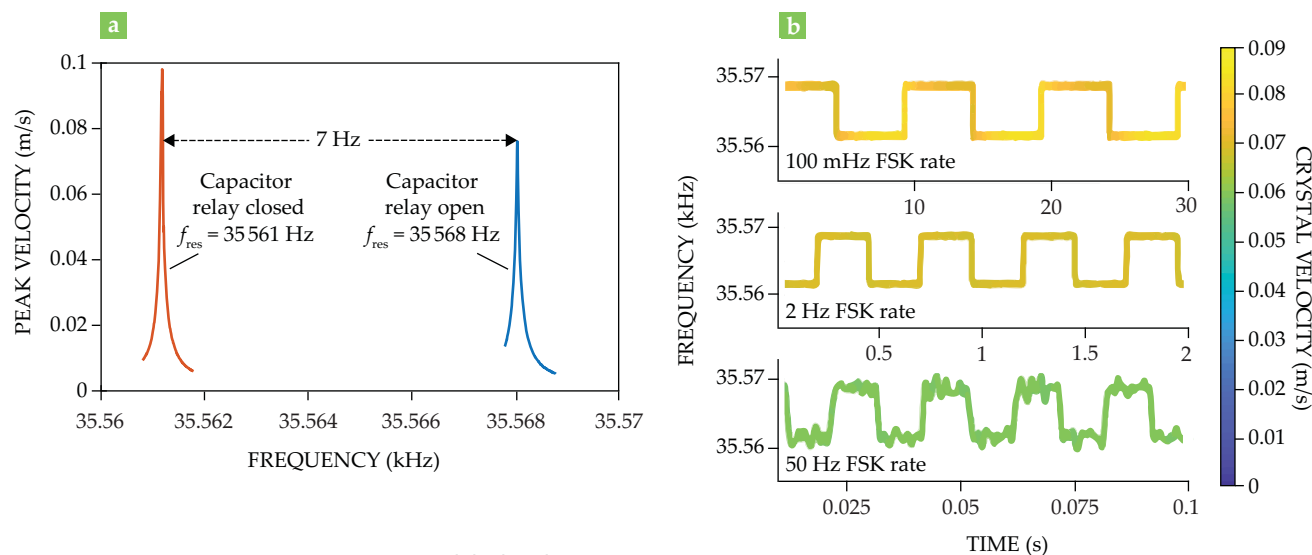


FIGURE 2. ANTENNA MODULATION increased the bandwidth of the piezoelectric transmitter. **(a)** Opening and closing a capacitor relay changes the resonant frequency f_{res} of the transmitter and allows it to oscillate at two easily distinguishable frequencies. **(b)** Frequency-shift keying (FSK)—alternating between two distinct frequencies—can encode information in narrowband signals. The transmitter’s two resonant frequencies are easily distinguishable at all three FSK rates shown. However, at higher FSK rates, the velocity at which the crystal oscillates, and therefore the antenna’s power output, decreases. (Adapted from ref. 1.)

away from power lines and buildings.” Measurements of the field out to 80 m indicate that, like a metal antenna, the piezoelectric antenna radiates as a dipole. The researchers are therefore optimistic that upcoming far-field measurements will confirm their antenna’s 300-fold increase in efficiency.

Reducing nonradiative losses is important for increasing efficiency, but unfortunately it also decreases the antenna’s bandwidth. The piezoelectric resonator’s bandwidth is just 84 mHz, which would be prohibitively small for using frequency modulation to transmit audio signals. Even large VLF antennas have limited bandwidths and are used only for text-based messages. Information is often encoded in the signal using frequency-shift keying (FSK)—alternating between two distinct frequencies. In that case, the transmitter doesn’t need to work at a wide range of frequencies. It just needs to transmit strongly at two frequencies that can be distinguished from each other.

To improve the antenna’s effective bandwidth—the separation between us-

able transmission frequencies—the researchers modulated its resonant frequency f_{res} between two values by coupling it to a capacitor through a relay. Modulating f_{res} between 35.561 kHz and 35.568 kHz, as shown in figure 2a, gave the antenna an effective bandwidth of 7 Hz, which is 83 times as large as the intrinsic bandwidth of one of the resonances. The two peaks are far enough apart that modulation between them can easily be distinguished, as shown in figure 2b. The signal starts to degrade at higher FSK frequencies that are similar to those typically used in VLF transmissions; the researchers suspect that effect is due to the speed of the relay that connects the external capacitor in the current prototype.

Like all antennas, piezoelectric antennas are inherently reciprocal, meaning that they can serve as both transmitters and receivers. But antenna modulation breaks that reciprocity. If the resonant frequency of the antenna isn’t modulated along with the transmitter, it will only receive one of the frequencies. But knowing when to modulate the receiver would require already knowing the incoming signal pattern. Small conventional receivers already exist though, so the lack of reciprocity is not a problem.

The next phase

Although strain-powered antennas were first proposed more than 50 years ago,⁴

Kemp and his collaborators took up the project recently thanks to the A Mechanically Based Antenna (AMEBA) program. Announced by the Defense Advanced Research Projects Agency in 2016, the AMEBA program drives fundamental research into mechanical antennas and antenna miniaturization, an area that hasn’t seen much progress in recent years.⁵ In line with the program’s goals, Kemp says, “We target human-portable, long-distance communication with as small of a package as possible.”

The researchers’ project recently moved out of exploratory phase I and into developmental phase II, so they expect to continue pushing the limits of electrically small antennas. “At each phase, we will further increase the bandwidth and radiated power,” says Kemp. A larger frequency separation would allow for better signal quality at higher FSK rates and give the researchers more flexibility in choosing a modulation scheme. In the coming year, they expect to improve both metrics by a factor of 10.

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