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Reversibly Deformable and Mechanically Tunable Fluidic Antennas

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This paper describes the fabrication and characterization of fluidic dipole antennas that are reconfigurable, reversibly deformable, and mechanically tunable. The antennas consist of a fluid metal alloy injected into microfluidic channels comprising a silicone elastomer. By employing soft lithographic, rapid prototyping methods, the fluidic antennas are easier to fabricate than conventional copper antennas. The fluidic dipole radiates with ≈90% efficiency over a broad frequency range (1910–1990 MHz), which is equivalent to the expected efficiency for a similar dipole with solid metallic elements such as copper. The metal, eutectic gallium indium (EGaIn), is a low-viscosity liquid at room temperature and possesses a thin oxide skin that provides mechanical stability to the fluid within the elastomeric channels. Because the conductive element of the antenna is a fluid, the mechanical properties and shape of the antenna are defined by the elastomeric channels, which are composed of polydimethylsiloxane (PDMS). The antennas can withstand mechanical deformation (stretching, bending, rolling, and twisting) and return to their original state after removal of an applied stress. The ability of the fluid metal to flow during deformation of the PDMS ensures electrical continuity. The shape and thus, the function of the antenna, is reconfigurable. The resonant frequency can be tuned mechanically by elongating the antenna via stretching without any hysteresis during strain relaxation, and the measured resonant frequency as a function of strain shows excellent agreement (±0.1–0.3% error) with that predicted by theoretical finite element modeling. The antennas are therefore sensors of strain. The fluid metal also facilitates self-healing in response to sharp cuts through the antenna.

1. Introduction

This paper describes a simple technique to fabricate reversibly deformable and mechanically tunable antennas by injecting a liquid metal alloy into elastomeric microfluidic channels. The metal, eutectic gallium indium (EGaIn, 75% Ga, 25% In by weight, melting point = 15.7 °C[1]), fills the channels rapidly at room temperature and possesses a thin oxide "skin" that keeps the fluid mechanically stable inside the channels despite the high surface energy of the metal.[2] We fabricated the channels using soft lithography,[3] a rapid prototyping method capable of producing antennas without any milling or etching. The elastomeric channels define the mechanical properties of the antenna since the metal is a low-viscosity fluid. Unlike conventional copper antennas, the fluidic antennas resist permanent deformation (i.e., the antennas return to their original state after removal of an applied stress) and can thus be deformed (stretched, bent, rolled, and twisted) reversibly without any hysteresis. The fluid metal ensures electrical continuity during deformation and "self-heals" in response to small cuts. Having a radiation efficiency of ≈90% over a broad frequency range (1910–1990 MHz), these fluidic antennas are as efficient as conventional dipole antennas with solid metallic elements. In addition, the resonant frequency of the antenna can be mechanically tuned by elongating (i.e., stretching) the elastomer, and can therefore act as a wireless sensor of strain. The fluidic antennas have the potential to enhance the emerging field of flexible electronics by enabling wireless communication capabilities. We demonstrate, characterize, and model the capabilities of these fluidic dipole antennas.

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2. Background

The rapid growth of applications requiring wireless communication or remote sensing has created demand for advances in antenna technologies. We sought to fabricate antennas that are highly flexible, stretchable, and reversibly deformable. Flexible antennas have the potential to enhance the emerging field of flexible electronics, which is primarily motivated by the desire to incorporate electronics into flexible substrates such as textiles, displays, and bandages. The ability to reversibly deform antennas may also enable new capabilities (e.g., rolling and unrolling for remote deployment, enhanced durability) and the ability to reconfigure the shape of an antenna mechanically (e.g., by elongation) provides a means of tuning its spectral response or sensing external forces. Bendable antennas are also of interest for ''smart antenna'' applications; that is, beam-forming and beam-bending antennas. These devices are useful in millimeter-wave applications (e.g., automotive radars, security, and surveillance systems, and high-data-rate wireless communication systems).[4] Mechanically scanned antennas—that is, devices in which a portion of the antenna is designed to bend out of plane—are being explored for these applications because they are less expensive, more efficient, and offer better control than electronic phase shifting arrays.[4–7]

Most conventional antennas are fabricated by milling or etching rigid sheets of copper into a static shape that dictates a singular function. Copper forms efficient antennas, but is poorly suited for flexible electronics because it fatigues when bent repeatedly and undergoes irreversible plastic deformation beyond strains of $\approx$2%.[8] Thin inorganic films[9,10] and semiconducting organic polymers[11–13] are the primary materials used for flexible electronic applications. These materials, however, are limited in the extent to which they can be stretched and do not exhibit the electrical properties required for efficient antennas. Flexible electronics have been formed by encasing thin coils of metallic wire in an elastomer.[14–20] These approaches take advantage of the ability to bend metals with sufficiently small cross-sections. Unfortunately, when thin films of metal are stretched they can form microcracks[21] or deform.[22,23] The use of coils also imposes an unnecessary design constraint for antennas and increases the complexity of fabrication.

Polydimethylsiloxane (PDMS), a silicone elastomer with a low Young's modulus ($<$2 MPa), has recently been used as a supporting substrate for copper to make flexible antennas.[4] The mechanical properties of the device are defined by those of copper (Young's modulus $\approx$130 GPa). Although the antenna can be bent slightly, it is not designed to be deformed (twisted, rolled, stretched) without inducing irreversible deformation or fatigue.

We sought to fully utilize the deformability of the PDMS substrate by replacing the solid metal components with a fluid metal, thus allowing significant deformation of the antennas as governed by the mechanical properties of the elastomeric substrate, rather than that of a solid metal. Importantly, the liquid metal has a thin, solidlike oxide skin on its surface that is well suited for microfluidics. The liquid metal fills microchannels rapidly at room temperature when the pressure applied to the inlet exceeds the force required to rupture the skin. Once the metal is inside the channel, the skin reforms and provides mechanical stability to the otherwise low-viscosity and high-surface-tension liquid (Hg, in contrast, withdraws from microchannels rapidly to minimize its surface area).[2] The use of fluid metal allows the elastomeric antenna to be deformed (stretched, bent, flexed, or rolled) significantly and reversibly without loss of electrical continuity; the resulting antennas are therefore durable. The fluid can flow in response to elongation of the elastomer, resulting in a reconfiguration of the geometry of the antenna and thus a shift in the resonant frequency. We demonstrate that the fluid metal forms highly efficient antennas that can be tuned via mechanical elongation without any hysteresis.

3. Experimental Design

We chose to fabricate a dipole antenna because the simplicity of the design allows changes in geometry (and thus resonant frequency) during stretching to be interpreted easily. The dipole structure can also be simulated numerically under multiple operating conditions using finite element method (FEM) modeling. Typically, the metallic elements of conventional planar copper antennas are fabricated by mechanical stamping and forming of a sheet of metal or through a sequential multistep process of plating a conductive layer of copper on a dielectric substrate, etching the desired antenna element, and milling the antenna assembly from the host dielectric substrate. As a result, the rapid generation of large sets of prototype antennas may incur a significant cost. We fabricated the antenna by injecting fluid metal into an elastomeric microfluidic channel formed by soft lithograpy.[3] This fabrication method allows for rapid prototyping of new antenna designs, and a single ''master'' can be replicated to produce many identical antennas.

We used PDMS (Sylgard 184 kit, Dow Corning) as the antenna substrate. PDMS is a commercial elastomer that is used routinely for preparing microfluidic channels.[24] It is highly elastic, and possesses a low modulus and low surface energy; these properties enable it to conform to surfaces. PDMS has a low dielectric constant (2.67) and a high loss tangent (0.0375).[25] Dipole antennas, however, do not have resonant fields within the surrounding dielectric, and therefore the field densities inside the PDMS are low. PDMS is thus a suitable casing for dipole antennas.[4]

We used EGaIn as the conductive element of the antenna, which has several advantages compared with other conductive materials such as water, solder, or mercury. Microfluidic channels are typically used to manipulate aqueous solutions. Although saline water is electrically conductive, it is poorly suited for antenna formation because it can evaporate and the conductivity is relatively low compared to metals. Mercury could be used to fill the channels, but it is toxic and its high surface energy prevents it from forming mechanically stable structures (i.e., mercury withdraws from the channel to minimize its surface area).[2] EGaIn is a low-viscosity (approximately twice the viscosity of water) liquid metal alloy at room temperature with a relatively high conductivity ($\sigma = 3.4 \times 10^4$ S cm^{-1} [26,27]). For comparison, the conductivity of copper at room temperature is 5.96×10^5 S cm^{-1}.[28] Unlike solder, EGaIn does not need to be heated prior to injection, and it maintains its fluidity after injection, which is critical to maintain continuity during deformation. Unlike mercury, EGaIn has a low level of toxicity [28] and is well-suited for forming conductive and mechanically stable structures in microfluidic channels.[2,29] The thin passivating oxide layer (i.e., it does not grow thicker with time)[30,31] that forms on EGaIn provides mechanical stability to the liquid metal such that it can maintain its nonspherical structure in the microfluidic channels despite its high surface tension. EGaIn is therefore a suitable metal for microfluidic applications.

4. Results and Discussion

We fabricated dipole antennas by injecting EGaIn into PDMS microchannels. A dipole antenna consists of two conductive rods

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of equal length that are aligned along their long axis and separated by an insulating gap. A dipole resonates with a wavelength, λ, that is approximately twice that of the total antenna length, L ($\lambda = 2L$) and is inversely proportional to the resonant frequency ($\lambda = c\nu^{-1}$, where ν is the resonant frequency, and c is the speed of light). The total length of the antenna (≈54 mm) was chosen such that it resonates at a frequency (≈2 GHz) within the range of the detector.

Figure 1a is a schematic diagram of the process used for fabricating a fluidic dipole antenna. We used photolithography to generate a ''master'' pattern of the dipole on a silicon wafer using a negative photoresist (SU-8, Microchem). The pattern consisted of two 150 μm thick (as verified by profilometry), 25.4 mm long, and 0.5 mm wide lines aligned along their long axis and separated by 2 mm. Curing a PDMS prepolymer against this topographically patterned substrate (i.e., replica molding)[3] produced an inverse replica of the master. After exposure of the replica to oxygen plasma, we sealed it to a flat PDMS substrate (~1 mm thick), producing a microfluidic channel into which we injected the liquid metal. An additional thin layer of PDMS sealed the inlet and outlet holes of the channel to assist with handling.

An Agilent E5071B ENA series network analyzer measured the spectral properties of the antenna. We used a balanced-to-unbalanced (balun) transformer to convert the ''unbalanced'' (i.e., grounded) coaxial cable from the network analyzer to the ''balanced'' (i.e., ungrounded) antenna.[32] The input to the balun is a coaxial connection, and the output is a pair of balanced electrical leads. Solder typically connects the leads from the balun to copper antennas, but in this case, the leads could simply be inserted into the fluidic antenna elements. The network analyzer transmits incident electromagnetic waves into the antenna and measures the amount of energy reflected back to the analyzer as a function of frequency. The reflection coefficient, Γ, is the ratio of the reflected wave to the input wave. It is common to express the reflection coefficient in decibels, using the expression $20\log|\Gamma|$, which is also termed return loss. The frequency with the lowest return loss is the resonant frequency.

We characterized the spectral properties and efficiency of the fluidic antenna in the ''free space'' position (i.e., not stretched or clamped). The antenna resonated at approximately 1962 MHz with ≈90% radiation efficiency as measured by a far-field, anechoic chamber. The radiation efficiency is defined as the ratio of total power radiated by the antenna to the power delivered to the input of the antenna. An efficiency of 100% implies that all of the input power is radiated by the antennas without any losses. An efficiency of 90% is expected for a similar dipole with solid metallic elements. These results, therefore, indicate that the electrical losses of EGaIn within PDMS channels are insignificant.

The fluidic antennas can be deformed reversibly (stretched, bent, rolled, wrapped, folded) without any loss of electrical continuity (cf. Fig. 1b,c). We characterized the spectral characteristics of the antenna before and after deforming the antenna in the following ways: 1) stretching (up to 40% strain); 2) twisting along the long axis by 90°; (3) folding in half; and (4) rolling. Without exception, the antenna exhibited the same spectral response before and after deformation. Furthermore, the resonant frequency did not change significantly during deformation. These observations demonstrate that the fluidic antennas are reversibly deformable and suggest that they are durable because of the lack of hysteresis.

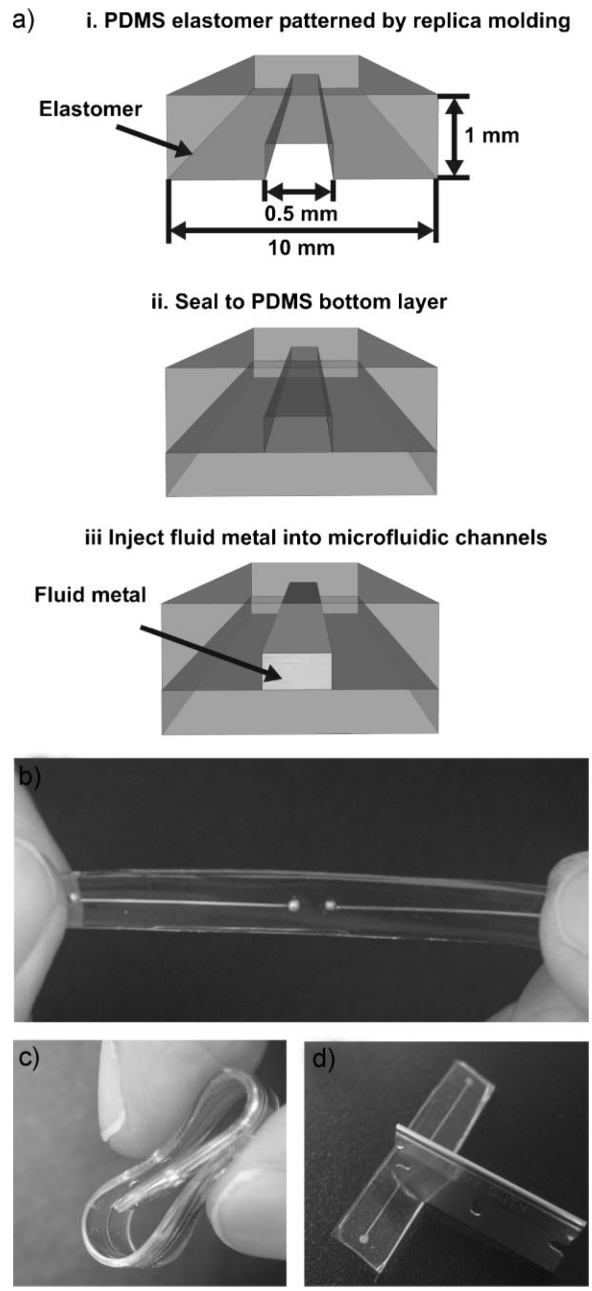

Figure 1. a) Fabrication process of a reversibly deformable dipole antenna. PDMS elastomer cured on a topographically patterned substrate produces two adjacent microfluidic channels (only one shown). After sealing the PDMS channels to another piece of PDMS, injection of liquid metal alloy into the microfluidic channels produces a dipole antenna. b,c) Photographs of a prototype antenna being stretched and rolled. There is no hysteresis in the spectral properties of the antenna as it is returned to the ''relaxed'' state. d) The antenna self-heals in response to sharp cuts, such as those inflicted by a razor blade.

The fluidic antennas self-healed (i.e., they retained their conductivity) after being cut with a razor blade. We cut entirely through the metal portion of the antenna (perpendicular to the long axis), as shown in Figure 1d, but left some of the PDMS surrounding the antenna intact. After removing the razor blade, the electrical resistance through the antenna returned to its pre-cut value. Stretching the antenna slightly expanded the gap formed at the site of the cut and caused the resistance to be infinite. Within the gap, it was apparent that the razor blade created two distinct metal–air interfaces, suggesting that the metal remained flush with the cut interface (i.e., it did not reflow into or out of the channel). Observation of these exposed interfaces by optical microscopy showed that the oxide skin gets pinned at the edges of the opening in the channel created by the razor blade. When we relaxed the antenna, it returned to its original conducting state. The process of rebreaking (by stretching the antenna and thereby separating the metal interfaces in the cut region) and reconnecting the wire could be repeated. In contrast to previous work, which has shown that discontinuities in wires in microfluidic channels composed of solder can be healed by heating and sonication,[33] the fluidic antennas heal spontaneously. We were able to get the two metal interfaces to merge into a continuous element by intentionally pressing on the channels. As a control experiment, we embedded a thin copper wire (with similar cross-sectional area to the antenna) in PDMS and measured the electrical resistance before and after cutting through it with a razor blade. Approximately 40% of the time, the wire returned to a conductive state, and 60% of the time the resistance was infinite. These results suggest that while the elasticity of the PDMS is primarily responsible for reconnecting the broken wires, the soft interface of the fluidic antenna facilitates reliable healing.

We hypothesized that elongating an (uncut) antenna by stretching (Fig. 2) the elastomeric device would shift the resonant frequency towards lower frequencies. We built an apparatus to stretch the antenna to minimize human bias in the measurements. The device contained no metal parts to avoid electronic coupling with the antenna and thus simplify the interpretation of the results. The device consisted of two clamps composed of plastic (Delrin) onto which we affixed each end of the antenna. The clamps slid along glass rods parallel to the long axis of the antenna. Plastic screws exerted the force required to elongate the antenna in a controlled manner. A picture of the clamping fixture can be found in the Supporting Information.

We stretched the antenna from 54 to 66 mm (defined as the total end-to-end length of the metal in the antenna) by increments of 2 mm. We chose this range because it minimized the chances of tearing the device (discussed below) and thereby enabled the measurement of hysteresis in the device during strain relaxation (from 66 mm back to 54 mm). The liquid metal in the elastomer maintained its electrical continuity during stretching. Although the cross-sectional area of the antenna reduces during elongation

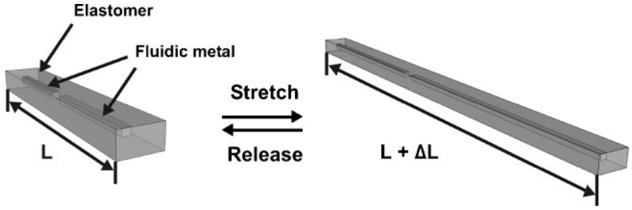

Figure 2. A schematic depiction of a dipole antenna before and after being stretched. The ability to stretch the antenna improves its overall durability and allows it to sense strain by the modulation of the spectral response during elongation.

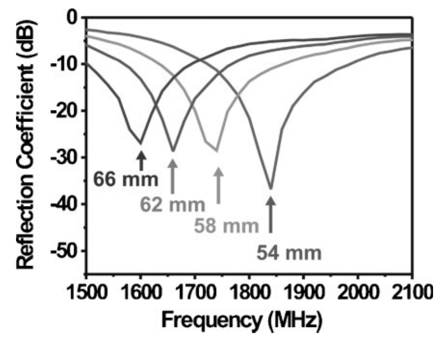

Figure 3. A plot of the measured reflection coefficient of the dipole both in its ''relaxed'' position (54 mm length) and mechanically elongated positions (58, 62, and 66 mm length) as a function of frequency. The ability to stretch the antenna allows the frequency to be tuned mechanically.

to maintain its total volume (the Poisson ratio of PDMS is 0.5[34]), the length of the metal is directly proportional to the length of elastomer.

Figure 3 shows that elongating the antenna modulates the spectral response; the antennas can therefore sense strain. We determined the resonance frequency of the antennas using the radio frequency network analyzer. A reflection coefficient (or return loss) below -10 dB is considered sufficient for effective radiation in commercial antennas. We recorded the spectral response as a function of the length of the antenna (measured using calipers) at 2 mm increments, but only plotted four series in Figure 3 for clarity. The resonant frequency at 56, 60, and 64 mm follow the same trends as those in Figure 3 and are included in the Supporting Information.

Stretching the antenna beyond $\approx$75 mm caused it to tear ($\approx$40% elongation at break). The theoretical extent of elongation depends on the type of PDMS and the way in which it is prepared.[35,36] In principle, PDMS can be stretched beyond 40% strain, but it is likely that the antennas failed prematurely because of small defects at the surface of the PDMS that focused the applied stress. The antennas typically failed in regions of the PDMS that had been compromised or cut during fabrication.

Figure 3 shows that the antennas behave as true dipole antennas in the frequency range predicted from simple scaling ($\approx$2 GHz). As expected, the resonant frequency of the antenna decreased with increasing antenna length (Fig. 4). The resonant frequency measured during the release of the applied strain did not exhibit any hysteresis. This result illustrates that the antenna is reversibly stretchable and the resonant frequency is indicative of the length of the antenna regardless of whether strain is increasing or decreasing.

We used an FEM simulator to model the resonant frequency of the dipole antenna as a function of induced strain. A computer-aided design (CAD) file input into the simulator identified the physical geometries and electric properties of each element within and surrounding the antenna. The FEM simulator generated a complex mesh of elements over the antenna and iteratively optimized an approximate solution to Maxwell's equations over the mesh until it achieved a solution with a sufficiently low error value. The model accounted for the geometry of the dipole (as a function of strain), the presence of the PDMS dielectric, and the surrounding clamping fixture. Figure 4 presents the simulated

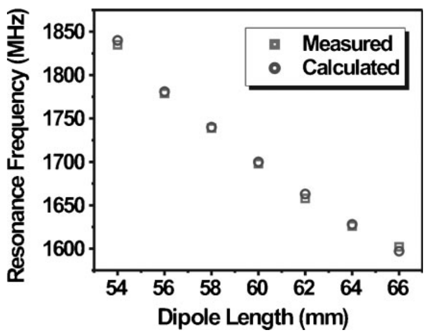

Figure 4. Resonance frequency of a fluidic dipole antenna as a function of the length of the antenna as modulated by stretching. The calculated values were modeled using finite element modeling.

resonance frequency with the measured resonance frequency. The difference between the simulated and measured resonance frequencies is insignificant ($\pm$0.1–0.3% at each point).

4.1. Advantages of Fluidic Antennas

Relative to conventional copper antennas, fluidic antennas have several advantages: 1) The antennas are reversibly deformable and durable. The elastomeric casing defines the mechanical properties of the antenna, and the fluid metal flows in response to deformation to ensure electrical continuity. 2) The fluidic antennas are mechanically tunable and sensitive to strain. 3) The liquid metal forms contacts with the baluns at room temperature without soldering. 4) The antenna self-heals in response to sharp cuts. 5) The fabrication of the antenna by soft lithography is simple and many antennas can be produced from a single lithographic master.

An additional attractive feature of fluidic antennas is the new ways in which they can be integrated into devices. We envision two general strategies. In the first approach, the fluidic antenna (casing plus liquid metal) is fabricated ex situ and subsequently integrated with a device. For example, the low modulus and low surface energy of PDMS allows the fluidic antennas to conform to numerous surfaces and substrates.[3] The flexibility of the antennas could also enable them to be wound or woven into devices. In the second approach, the fluidic antenna is fabricated in situ by injecting liquid metal into conduits that are part of the larger device structure. For example, microfluidic channels formed by sealing a mold (cf. Fig. 1) onto a substrate or capillaries in monolithic structures could be filled with liquid metal to form the fluidic antennas. The latter approach is distinguished from conventional approaches because the metallic elements are introduced in an additive manner and can be formed on demand by fluid injection. The ability of the liquid metal to form electrical contacts without solder or wire bonding further simplifies the integration of these antennas into devices.

4.2. Limitations

While the use of PDMS enables deformability, it is not ideal for situations that require static antennas. This problem can be overcome by placing the antenna on a solid support, which is facilitated by the conformable nature of the PDMS elastomer. There are also limits on the extent to which PDMS can be stretched. The fluidic antenna tore into two pieces after $\approx$40% strain; this value could be increased with optimized design and minimization of defects in the PDMS that otherwise focus stress, or by exploring other elastomers. The use of a fluid metal could also be worrisome for cases in which the antenna is severely damaged. Fortunately, the small amount of EGaIn in the antenna does not flow readily in the absence of a large driving force because of the presence of the mechanically stabilizing oxide skin. For example, EGaIn did not leak or spray out of the device when the antenna ripped beyond 40% strain nor did it flow when cut in half, as evidenced by the self-healing properties.

5. Conclusions

By injecting fluid metal into elastomeric microfluidic channels, we demonstrated a simple method to produce highly deformable and mechanically tunable antennas. The fluidic dipole antennas radiated with 90% efficiency and displayed a resonant frequency in excellent agreement with theoretical modeling. The shape of the antenna was reconfigurable and the resonant frequency could be tuned mechanically by elongating the antenna via stretching without hysteresis upon relaxation. This property may be useful for sensing strain wirelessly (e.g., sensing the expansion and contraction of bridges, or the detection of motion). The thickness of the elastomer could be tuned to change the mechanical properties of the antenna and thereby change the amount of strain induced by a given stress. Fluidic antennas can also withstand mechanical deformation without damage and can self-heal when cut. The flexibility of the antenna may allow it to be incorporated into specialized products, such as electronic fabric, without loss of ergonomic functionality, or to be rolled up for remote deployment. Fluidic antennas also have the potential to enhance the emerging field of flexible electronics by providing new sensing or wireless communication capabilities. The ability of the fluid metal to alloy with many metals could facilitate the direct electrical connection and incorporation of antennas onto substrates featuring electronic components.

Acknowledgements

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