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Stretchable Microfluidic Radiofrequency Antennas

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This paper describes a new method for fabricating stretchable radiofrequency antennas. The antennas consist of liquid metal (eutectic gallium indium alloy, EGaIn[1,2]) enclosed in elastomeric microfluidic channels. In particular, a microfluidic structure made of two types of elastomers (polydimethylsiloxane (PDMS) and Ecoflex (type 0030, Reynolds Advanced Materials)) with different stiffness has been developed to improve the stretchability and mechanical stability of the antennas. These antennas can be stretched up to a strain [defined as the percentage change in length or $(l - l_0)/l_0$] of 120 %. This high stretchability allows the resonance frequencies of the antennas to be mechanically tuned over a wide range of frequencies. The antennas can also be repeatedly stretched, while retaining a high efficiency (> 95 %) in radiation.

"Stretchability" in electronics has the potential to open new opportunities, particularly for large-area devices and systems, and in systems that require the device to conform to a nonplanar surface, or to bend and stretch while in use.[3–5] Compared to "flexible" electronics built on nonstretchable polymer or paper substrates,[6,7] stretchable electronics can cover almost arbitrarily curved surfaces and movable parts. Mechanical compliance may increase the comfort of the user for wearable electronics or implantable medical devices, and simplify the integration for a range of applications.[3–5,8] New approaches to stretchable electronics are now being developed. In a recent advance, Rogers et al.[4,5] described stretchable integrated circuits with elongation of up to 100 % using wavy, thin silicon ribbons on pre-stretched elastic substrates.

Antennas offer new, attractive applications for stretchable electronics; these applications might include reconfigurable antennas,[9] antennas for limited and nonplanar spaces,[10] and wearable sensors. Two methods are commonly used to build antennas for commercial applications. The most common method uses sheet-metal processing; in this method, a metal sheet is punched, bent, and welded into the desired structure. A second method uses chemical etching and plating to make small patterns of metal. This method can make flexible antennas by patterning metal on a flexible substrate. Neither of these methods can produce stretchable antennas. Further, neither method works when large deformations in the antenna structure, and thick metal sections (for high currents in high-power transmission), must be combined.

Microstructured channels fabricated in elastomeric polymers and filled with liquid metal have recently been employed for stretchable interconnects[11] and antennas.[12,13] Besides its ability to produce stretchable antennas, this method has four advantages over existing methods employed in commercial applications: i) the process is fairly simple and scalable; ii) it does not involve etching or plating, and thus does not produce hazardous waste; iii) it can be adopted to incorporate other stretchable 2D and 3D devices with dimensions down to tens of micrometers; and iv) it allows the antenna to be easily integrated with other fluidic components for tuning, sensing, and signal modulation.

Stretchable antennas fabricated based on PDMS and liquid metals have recently been demonstrated. For instance, Wu et al.[12] and Dickey et al.[13] reported an unbalanced loop antenna and a half-wave dipole antenna that were fabricated by injecting Galinstan (Ga 68.5 %, In 21.5 %, and Sn 10 %) and EGaIn (eutectic gallium indium alloy, Ga 75.5 % and In 24.5 %) into microfluidic channels in elastic PDMS substrates. These antennas can be stretched up to a strain of 40 %. This stretchability, however, is significantly less than the maximum strain of 160 % that PDMS can sustain. This limitation arises from the fact that these approaches employed only one type of elastomer (PDMS) in the devices. Since only one type of elastomer was employed, the whole structure experienced a uniform strain when being stretched, and was likely to break at the weak points—inlets and outlets of the microfluidic channels, and interfaces between the elastic and rigid parts (e.g., external electrical connectors) of the devices, even under a strain much smaller than the maximum strain that the elastomer can sustain (Figure S1B, Supporting Information). For this reason, the all-PDMS devices that have been designed to date have suffered from poor mechanical durability.[12,13]

To improve the stretchability and mechanical durability of siloxane/EGaIn-based antennas under strain, we have developed 'hybrid' structures that integrate silicone rubbers of different stiffness (**Table 1**) in building the microfluidic channels. We used a stiff silicone rubber (PDMS) where mechanical stability is required (e.g., around the rigid electrical connector) and a soft elastomer (Ecoflex, another silicone polymer softer than PDMS) where stretchability is necessary (e.g., around the stretchable antenna branches). In an appropriate design of this type, when the soft elastomer containing the liquid metal was stretched by more than 100 %, the relatively stiff polymer around the rigid electrical connector was not significantly strained. This hybrid structure showed good mechanical stability.

Figure 1 is a schematic diagram describing the stretchable antenna. As a proof of concept, we chose to fabricate a half-wave

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Table 1. Mechanical properties of PDMS and Ecoflex used as insulating material in stretchable antenna.

	Elongation at Break [a] (%)	Shore Hardness [b]	Tear Strength [c] (pli)
PMDS-184	160	A-48	15
Ecoflex-0030	900	00-30	38

[a] The strain on a sample when it breaks.
[b] A measure of the hardness of a material, typically used for polymers, elastomers and rubbers. Materials measured in Shore 00 scale are much softer than those measured in Shore A scale.
[c] The tensile force required to tear a pre-slit sample film of unit thickness, measured in pli or pounds per linear inch.

dipole antenna, because it is structurally simple. The dipole antenna consisted of two equal, linear branches separated by a small gap, and was fed by electrical signals at the gap via a 3-mm SMA connector and a coaxial cable. In this specific design, each antenna branch had dimensions of 32.5 mm (L) ×3 mm (W) ×200 μm (thickness) when unstrained. The antenna length was first chosen to give a resonance frequency (which is inversely proportional to the antenna length) around 1 GHz; and the width and thickness were then chosen to yield reasonably low electrical resistance (<1 Ω).

The antenna branches consist of eutectic alloy of 75.5 % gallium and 24.5 % indium (EGaIn), and are embedded in microfluidic channels composed of PDMS and Ecoflex. We chose EGaIn primarily because it is a liquid at room temperature, and thus can be injected into the microfluidic channel without heating; it can also self-heal after deformation.[2] It forms a thin Ga_2O_3 surface film upon exposure to air;[2] this film helps it to avoid fracture when elongated. Other favorable attributes of EGaIn include its low electrical resistivity (29.4×10^{-6} Ω-cm), high thermal conductivity, low toxicity, low vapor pressure, light weight, and acceptable cost (see Table S1 in the Supporting Information for a list of metals and their properties).[1,2]

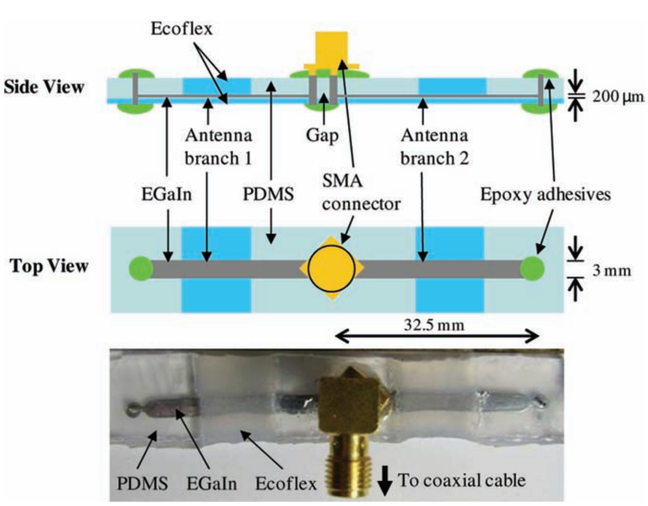

Figure 1. Schematic illustrations and optical micrograph of the stretchable antenna. The half-wave dipole antenna is made of EGaIn embedded in microfluidic channels composed of PDMS and Ecoflex. EGaIn is injected by positive pressure into the inlet, and the EGaIn-filled microfluidic channels are sealed with epoxy resin.

A thick (~3 mm in this study) PDMS slab, although not sufficiently elastic to be the sole material used in the intended applications, was suited for regions of low strain; we used it in regions where we needed a stiff material (for example, around the rigid SMA connector).[14] Compared to PDMS (which breaks when the strain exceeds 160 %), the soft Ecoflex is highly stretchable, and can be elongated to up to 10 times its original length without breaking (Table 1); we used Ecoflex for the elastic insulating channels that held the antenna branches. Ecoflex peels away from a master in a manner similar to PDMS, so soft lithography can be used in its fabrication.[15] It is also cured using a procedure and at a temperature (T ~ 60 °C) similar to that used to cure PDMS, and can easily be processed and co-processed with PDMS. Ecoflex does not adhere well to fully cured PDMS; we therefore contacted half-cured Ecoflex and half-cured PDMS, and cured the composite structure, to ensure good bonding at the boundary between these two types of silicone rubber. The Supporting Information gives detailed descriptions of procedures used to fabricate antennas.

We compared the characteristics of two types of antennas under strain: "all PDMS" structures and "PDMS/Ecoflex" composite structures (in which insulators surrounding the connector are PDMS, and the other parts are Ecoflex). We measured three different properties of antennas to demonstrate the feasibility of a 'stretchable' antenna. i) Radiation: the reflected *EM* power, and hence the efficiency of radiation of the antenna under strain. ii) Tunability: the resonance frequency of the antenna under strain. iii) Reliability: the frequency response of reflected *EM* power after repetitively stretching the antenna up to a strain of 50 %.

We used a network analyzer to measure the ratio between the reflected and incident *EM* power as a function of tensile strain (**Figure 2**). If the antenna radiates efficiently, most of the incident *EM* power is radiated into free space, and there is little reflected power. This value of reflected power, measured in $|S_{11}|$, is –30 dB, –20 dB and –10 dB when 99.9 %, 99 % and 90 % of the input power is radiated from antenna, respectively (smaller values of $|S_{11}|$ indicate higher efficiency of radiation for an antenna). For the "PDMS/Ecoflex" structure, the unstrained antennas exhibited $|S_{11}|$ value of ~ –33 dB. As the antenna was stretched, $|S_{11}|$ values varied from ~ –30 dB (at strain of 26 %) to ~ –23 dB (at strain of 59 %) to ~ –16 dB (at strain of 90 %) to ~ –19 dB (at strain of 120 %); this progression demonstrates that the "PDMS/Ecoflex" structure exhibits good radiation efficiency, even when stretched up to a strain of 120 %. When stretched further, silicon rubbers (PDMS and/or Ecoflex) employed in the antennas lost adhesion (although the structure did not break), often causing leaks of EGaIn (Figure S1A). On the other hand, for the "all PDMS" structure, unstretched antennas exhibit $|S_{11}|$ value of ~ –45 dB, while antennas stretched by 7 % in length exhibit $|S_{11}|$ value of ~ –29 dB. These antennas broke under tensile strain greater than 20 %, and were thus unreliable at even moderate values of strain (Figure S1B).

Figure 3 illustrates the change in the resonance frequency of the antenna under different values of strain. The resonant frequency of a half-wave dipole antenna can be calculated by Equation (1), where f is the resonance frequency (MHz), l is the length of antenna (m), and ε_{eff} is the effective dielectric constant of the medium (a combination of the dielectric constants of silicone rubbers (ε ~ 2.5) and air (ε = 1) in this study).

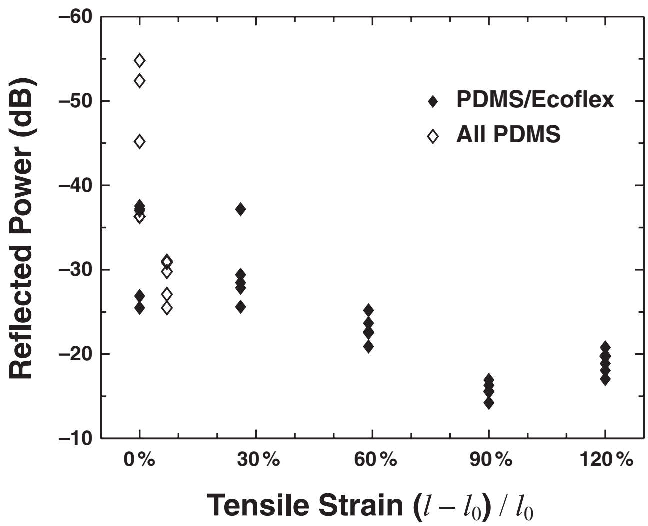

Figure 2. The reflected power (dB) from the antenna as a function of the tensile strain. The filled diamonds show the reflected power of "PDMS/Ecoflex" hybrid structure while the open diamonds show that of "all PDMS" structure at their resonance frequencies. Measurement under each value of strain was repeated five times. The "PDMS/Ecoflex" hybrid structure exhibited good radiation efficiency when stretched up to a strain of 120 %, while the "all PDMS" structure failed at a strain greater than 20 %.

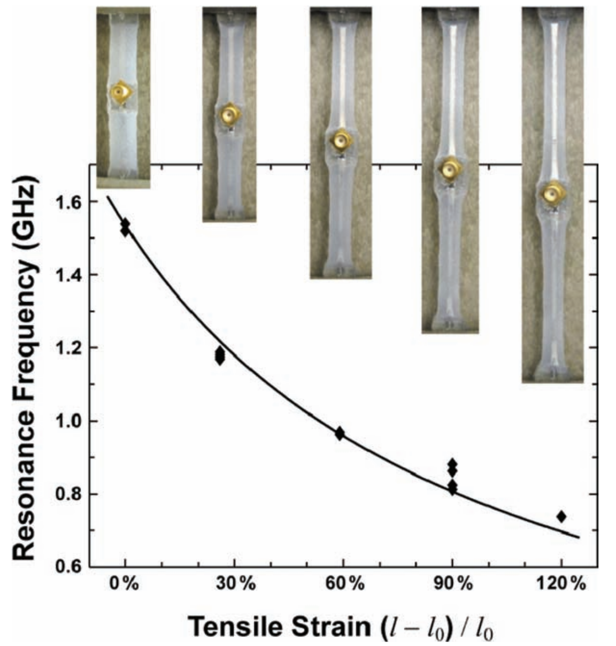

Figure 3. The resonance frequency (GHz) of the antenna as a function of the tensile strain. The resonance frequency of the antenna decreased from 1.53 GHz to 0.738 GHz as the antenna was stretched from l_0 to $l = 2.20\ l_0$. After releasing the strain, the resonant frequency returned from 0.738 GHz to 1.53 GHz: the tuning is thus reversible. Measurement under each value of strain was repeated five times; and the data points are shown as individual diamonds (♦) in the plot. The fitted curve was calculated using Equation (1) with $\varepsilon_{\mathrm{eff}} = 2.1$.

$$f = \frac{143}{l} \times \frac{1}{\sqrt{\varepsilon_{\mathrm{eff}}}} \tag{1}$$

When the length of the antenna increases, the resonant frequency decreases accordingly. In our experiment, the resonance frequency of the antenna decreased from 1.53 GHz to 0.738 GHz as it was stretched from its original length l_0 to $l = 2.20\ l_0$. As shown in Figure 3, the good agreement between our measurement and Equation (1) indicated that the antenna worked as predicted. After releasing the strain, the resonant frequency returned from 0.738 GHz to 1.53 GHz. This reversible tuning demonstrated the robustness of our stretchable antenna.

We investigated the reliability of the antenna by repeatedly stretching it up to a strain of 50 %. (**Figure 4**). Even after being stretched over 100 times, the antenna exhibited a resonance frequency nearly the same (within 1 %) as the initial measurement. Thus, the combination of a liquid metal antenna with a highly elastic insulating material resulted in an antenna structure that repeatedly returns to its original shape, even after multiple deformations, without losing its electromagnetic properties. In addition, the antennas exhibited little change (within 1 %) in their properties over 4 months of storage under ambient conditions.

In conclusion, we have developed a new method to build stretchable antennas with tunable resonance frequencies, by injecting liquid metal into a microfluidic channel in an elastomeric structural matrix. This microfluidic channel uses the combination of two types of silicone rubber with different stiffness to improve the stretchability of the antennas. The structure of the antenna developed in this study has three advantages over existing stretchable antennas:[12,13] i) This antenna is highly stretchable, and thus has a wide tuning range. By stretching the antenna, the resonance frequency can be tuned from 0.738 to 1.53 GHz. ii) This antenna is more durable than the one fabricated in a single type of stiff silicone rubber (PDMS). Antennas made using the hybrid PDMS/Ecoflex structure exhibit over

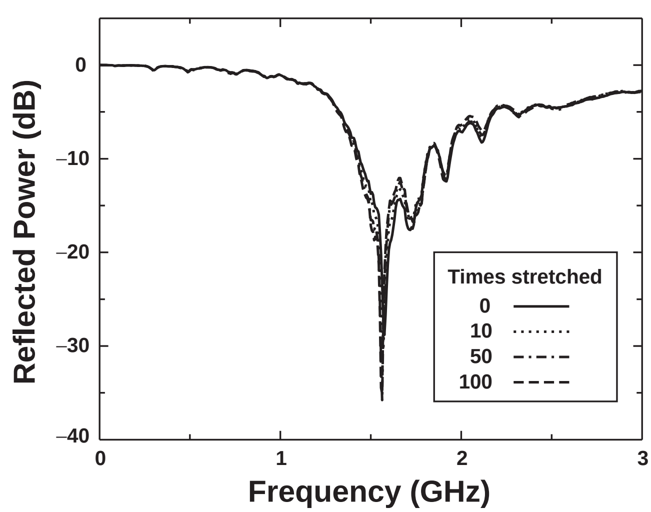

Figure 4. Frequency response of the reflected power from the antenna after repeated stretching up to a strain of 50 %. Plots show the reflected power after the antenna had been stretched 10, 50, and 100 times. The results demonstrated that the resonance frequency and the radiation efficiency of the antenna were almost unchanged (within 1 %) after the antenna had been stretched 100 times.

95 % efficiency in radiation at a tensile strain of 120 %, while those reported in[12] and[13] break under a strain greater than 40 %. iii) This antenna is more reliable to repeated cyclic strain than those comprising only PDMS. The antenna preserves its electromagnetic properties after being stretched 100 times up to a strain of 50 %. To the best of our knowledge, this is the first reliability test reported for stretchable antennas.

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Supporting Information

Supporting Information is available online from Wiley InterScience or from the author.

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