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Stretchable Microfluidic Radio Frequency Antenna**

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Keywords: Antenna, Stretchability, Microfluidic, PDMS, Ecoflex

This paper describes a method for fabricating highly stretchable and robust antennas for radio-frequency signals. The antennas consist of liquid metal (eutectic gallium indium alloy, EGaIn) enclosed in elastomeric microfluidic channels. These antennas can be flexed, twisted, and stretched up to 2.2 times of their original length l_0, and exhibit little degradation (< 1 %) in radiation efficiency even after being stretched to $l = 1.50\ l_0$ more than 100 times. This stretchability allows the resonance frequency of the antennas, which depends on the antenna length l, to be tuned from 0.738 to 1.53 GHz. The stretchable and robust antennas may be useful in reconfigurable and conformal structures, wearable sensors and large-area electronics, and other devices that must undergo large mechanical deformation.

"Stretchability" in electronics has the potential to open new opportunities, particularly in the area of large-area devices and systems, and in systems that require the device to conform to a non-planar surface, or to reconfigure structurally in use.[1,2] Although large-area electronic devices on "flexible" substrates such as polymer or paper substrates have been demonstrated,[3,4] flexible electronics is limited to nearly flat substrates. In contrast, stretchable electronics can cover almost arbitrarily curved surfaces and movable parts, and this may significantly enhance the comfort of the user or simplify the integration for a wide range of applications.[1-5] Conventional electronic devices are usually made from rigid materials, which do not stretch or bend gracefully. For example, typical inorganic semiconductors fracture at tensile strain less than 1 %. New approaches to stretchable electronics are now being developed. In the recent significant advance, Rogers et al.[2,6] have described stretchable integrated circuits with elongation up to 100 % using wavy, thin silicon ribbons on pre-stretched elastic substrates. However, mechanical mismatch between the solid materials and elastomers in these approaches limits multiaxial stretchability.

Antennas offer new, attractive applications for stretchable electronics, such as reconfigurable antennas,[7] antennas for limited and non-planar spaces,[8] and wearable sensors. Two methods are commonly used to build antennas. The most common method for commercial applications 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. Furthermore, neither method works when large deformation in 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[9] and antennas.[10,11] Besides its ability to produce stretchable antennas, this method features several 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) the method can be adopted to incorporate other stretchable 2D and 3D devices with dimensions down to tens of microns; iv) it allows the antenna to be easily integrated with other fluidic components for tuning, sensing, and signal modulation. All the previous studies, however, show either limited stretchability (< 40 %)[10,11] or require additional processing steps (e.g., punching holes)[9] to obtain acceptable stretchability. This limitation arises from the fact that these approaches employed only one type of elastomer (PDMS) in the devices. PDMS itself has limited stretchability and would break if the strain exceeds 160 %. Furthermore, since only one type of elastomer was employed, the whole structure experienced a uniform strain when being stretched, and was likely to break at its weak points, such as the inlets and outlets of the microfluidic channels, and the interfaces between the elastic and rigid parts (e.g. external electrical connectors) of the devices, even under a strain much smaller than the maximal elongation (Figure S1B). For this reason, the devices suffered from poor mechanical durability.[10,11]

To improve the stretchability and the mechanical durability under strain, we have developed 'hybrid' structures that integrate silicone rubbers with different stiffness (Table 1) in building the microfluidic channels. We used a stiff silicone rubber (PDMS) where mechanical durability is required (e.g., around the external electrical connector) and soft elastomer (Ecoflex^{TM}, a soft, platinum-catalyzed silicone) where stretchability is necessary (e.g., around the electrically conductive lines). In an appropriate design of this type, when the conductive lines surrounded by soft elastomer are stretched by more than 100 %, the relatively stiff polymer around the rigid connector is not significantly strained; thus the hybrid structure, combined together with the liquid metal, provides mechanical durability under strain, and results in an extremely robust antenna structure that easily survives severe, repeated deformation.

Figure 1 shows a schematic of the stretchable antenna. As a proof of concept, we choose to fabricate a half-wave dipole antenna for its structural simplicity. The dipole antenna consists of two equal, linear branches separated by a small gap, and is 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 a dimension of 32.5 mm (L) × 3 mm (W) × 200 μm (thickness). 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 determined to yield reasonably low electrical resistance (< 1 Ω).

The antenna branches consist of a 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.[12] 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, self-passivating oxide skin, and acceptable cost (see Table S1 in the Supporting Information for a list of metals and their properties).[13]

We fabricated the microfluidic channels using PDMS, a relatively stiff silicone rubber, and Ecoflex, a very soft platinum-catalyzed silicone. A thick (~ 3 mm in this study) PDMS slab, although not sufficiently elastic to be the sole material used in the intended applications, was well suited and used 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 up to 10 times of its original length without breaking (Table 1); and thus it was used 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 at a temperature 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 made a contact between the 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. Detailed descriptions of fabricating antennas are given in the Supporting Information.

We compared the characteristics of two types of antennas: “all PDMS” structures (insulators made only of PDMS) and “PDMS/Ecoflex” structures (insulators surrounding the connector in PDMS, and the other parts in Ecoflex) under strain. We measured the three different properties of antennas to demonstrate the feasibility of a ‘stretchable’ antenna; i) radiation: the reflected *EM* power, 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 length $l = 1.50\ l_0$, where l_0 is the original length of the antenna.

The ratio between the reflected and incident *EM* power as a function of stretch ratio (l/l_0) was measured using a network analyzer (Figure 2). If the antenna radiates efficiently, most of the incident *EM* power is radiated into the free space, resulting in low reflected power. This value of reflected power, measured in $|S_{11}|$, is –30 dB, –20dB 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 unstretched antennas with original length l_0 exhibit $|S_{11}|$ value of ~ –33 dB. As the antenna is stretched to length l, $|S_{11}|$ values varies from ~ –30 dB (at $l = 1.26\ l_0$) to ~ –23 dB (at $l = 1.59\ l_0$) to ~ –16 dB (at $l = 1.90\ l_0$) to ~ –19 dB (at $l = 2.20\ l_0$); this progression demonstrates that the “PDMS/Ecoflex” structure exhibits good radiation efficiency, even when stretched up to 2.2 times of its original length (or under tensile 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 and break points 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 strains (Figure S1B).

Figure 3 illustrates the change in the resonance frequency of the antenna with different stretch ratios. The resonant frequency of a half-wave dipole antenna can be calculated by

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

where f is the resonance frequency (MHz), l is the length of antenna (m), and $\varepsilon_{\mathrm{eff}}$ is the effective dielectric constant of the medium [a combination of the dielectric constants of silicone rubbers ($\varepsilon \sim 2.5$) and air ($\varepsilon = 1$) in this study]. 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 l_0 to $l = 2.20\ l_0$. As shown in Figure 5, the good agreement between our measurement and Equation (1) indicated that the antenna has worked as intended. 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 from l_0 to $l = 1.50\ l_0$. (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 results in an antenna structure that repeatedly returns to its original shape, even after multiple deformations, without losing its electromagnetic properties. In addition, the antennas exhibit 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 comprises two types of silicone rubber with different stiffness to significantly improve the mechanical durability and stretchability. The structure of the antenna developed in this study has three advantages over existing stretchable antennas: 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 one type of silicone rubber (e.g. all PDMS). Antennas made using the hybrid PDMS/Ecoflex structure exhibit over 95 % efficiency in radiation at a tensile strain of 120 %. 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 to $l = 1.50\ l_0$.

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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.

Figure 1. Schematic 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.

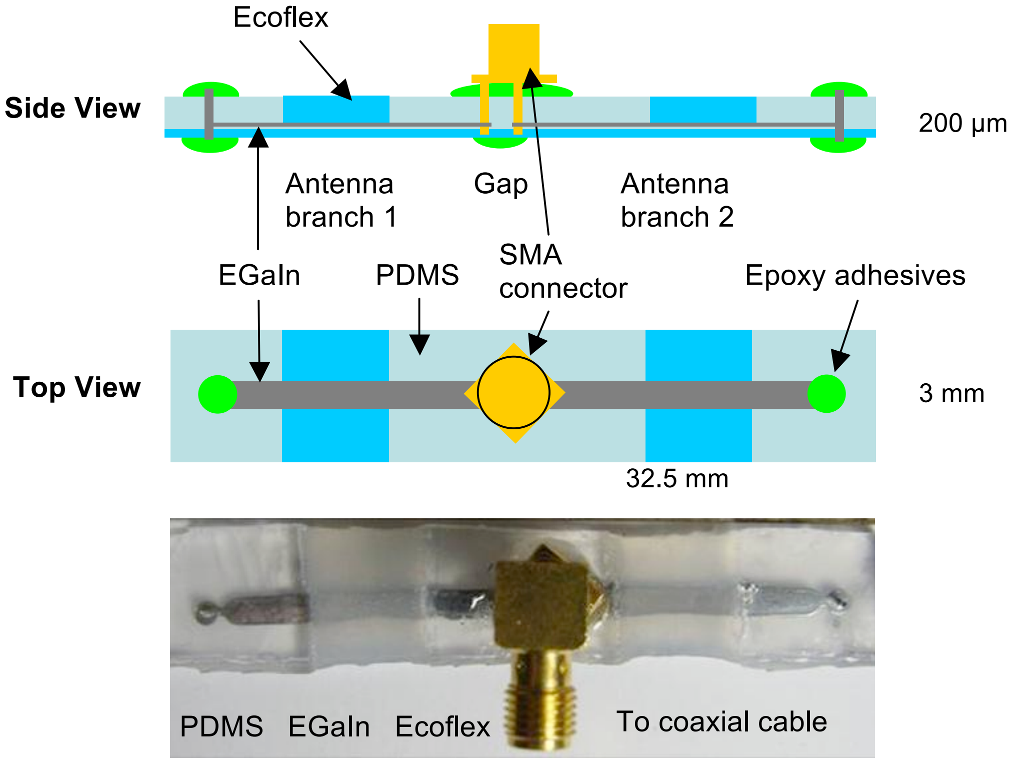


Figure 2. The reflected power (dB) from the antenna as a function of the stretch ratio (l/l_0). The symbols (◆) show the reflected power of "PDMS/Ecoflex" hybrid structure while the symbols (◇) show that of "all PDMS" structure at their resonance frequencies. Measurement under each stretch ratio was repeated five times. The "PDMS/Ecoflex" hybrid structure exhibited good radiation efficiency when stretched from l_0 up to $l = 2.20\ l_0$, while the "all PDMS" structure failed at a tensile strain greater than 20 %.

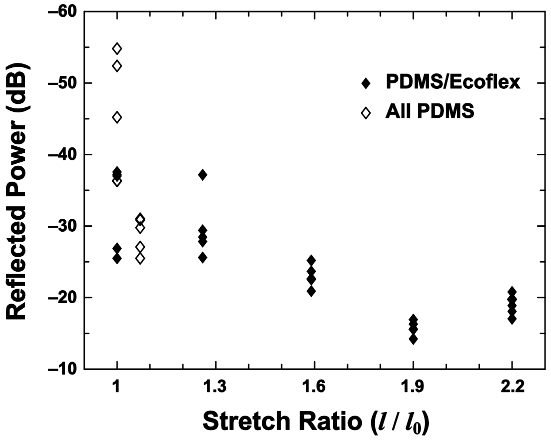


Figure 3. The resonance frequency (GHz) of the antenna as a function of the length of antenna (in unit of l_0). The resonance frequency of the antenna decreased from 1.53 GHz to 0.738 GHz as the antenna was stretched from l_0 to $l = 2.20\ l_0$. After releasing the strain, the resonant frequency returned from 0.738 GHz to 1.53 GHz: the tuning is thus reversible. Measurement under each stretch ratio was repeated five times. The fitted curve was calculated using Equation (1) with $\varepsilon_{\text{eff}} = 2.1$.

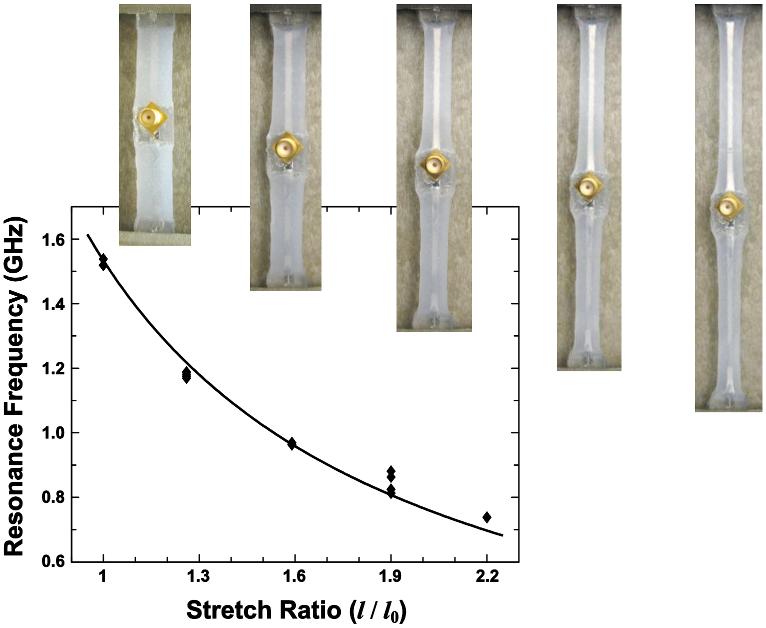
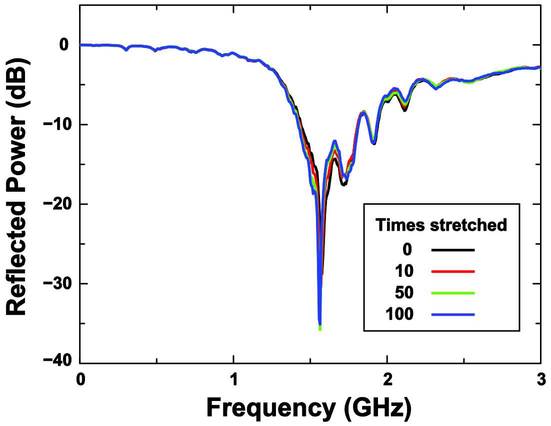


Figure 4. Frequency response of the reflected power from the antenna after repetitive stretching to $l = 1.50\ l_0$. Plots show the reflected power after the antenna had been stretched 10, 50, and 100 times. The results demonstrated that the resonance frequency and the radiation efficiency of the antenna were almost unchanged (within 1 %) after the antenna had been stretched 100 times.



Supporting Information for

Stretchable Microfluidic Radio Frequency Antenna

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Table S1. Properties of Representative Metals

Metal	**Melting Point (°C)**	**Electrical Conductivity**[a, b] **(10^6·S/m)**	**Bulk Price**[c] **(US$/kg)**	**Conductivity / Price (kS·kg/m·US$)**
EGaIn	15.5	3.4	420	8
Al	660.3	38.0	2	19,000
Cu	1084.6	59.6	7	8,800
Ag	961.8	63.0	650	97
Au	1064.2	45.0	40,000	1
Pt	1768.3	9.5	51,000	0.2
Hg	−38.8	1.0	16	63
Ga	29.8	3.7	410	9
$\mathbf{Ga^{68.5}In^{21.5}Sn^{10}}$	−19.0	3.5	380	9
$\mathbf{Ga^{61}In^{25}Sn^{13}\ Zn^{1}}$	7.6	2.8	370	8

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[c] Pure metal prices are quoted from international metal markets, including New York Mercantile Exchange (NYMEX), London Metal Exchange (LME), and warehouse in Rotterdam, Netherland. Alloy prices are calculated from pure metal prices according to the compositions of the alloys.

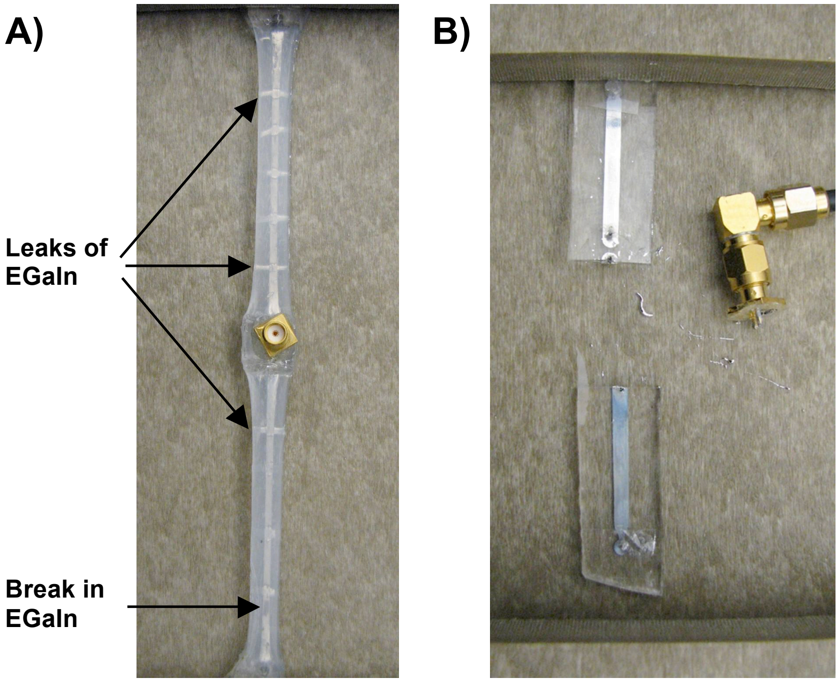

Figure S1. Photos of antennas that failed under tensile strain. A) “PDMS/Ecoflex” and B) “All PDMS” structure.

Experimental Details

Fabrication of Stretchable Antenna (using PDMS and Ecoflex as Insulator)

Figure S2 sketches the fabrication steps of the stretchable antenna. The antenna was constructed by filling EGaIn in microfluidic channels made of insulating silicone rubbers. The microfluidic channels were formed by sticking together two half-cured silicone rubber layers. The top layer contained the microfluidic channel features that were copied from a master; the bottom layer was featureless. They together formed the microfluidic channels, and were fabricated separately.

The master for the top layer was fabricated from SU-8 photoresist (MicroChem, Inc) on a 4-inch silicon wafer (Silicone Sense Corp.). Patterns of microfluidic channels were defined by photolithography; and the resulting SU-8 master was silanized by exposing it to a vapor of 1H,1H,2H,2H-perfluorooctyl trichlorosilane (Aldrich) overnight. On the SU-8 master, the areas that would eventually comprise Ecoflex were masked with polyimide tapes (Figure S2A). Poly(dimethylsiloxane) (PDMS) (Dow Corning Sylgard 184, 10:1) was poured onto this master and partially cured in an oven at 60 °C for 30 min (Figure S2A). To open the areas that would eventually comprise Ecoflex, the PDMS was cut by a razor blade along the edges of the polyimide tapes, which were then stripped away, removing the PDMS from these areas (Figure S2B). Freshly prepared Ecoflex (type 0030, Reynolds Advanced Materials, within 10 min after mixing the hardner and prepolymer at a ratio of 1:1) was then poured into these open areas, and partially cured at 60 °C for 10 min. This resulted in a hybrid structure that consisted of silicone rubbers of different stiffness (Figure S2C). This top layer of the microfluidic channels was cut by a razor blade along the circumference of the silicon wafer, and then peeled off the master (Figure S2D).

The bottom layer of the microfluidic channels was built on a bare, featureless silicon wafer. We first covered a 4-inch silicon wafer with polyimide tapes so that the bottom layer could later be easily peeled away from the silicon. Ecoflex was poured onto the taped wafer, and partially cured at 60 °C for 10 min (Figure S2E). Then a 50 µm-thick (as measured by SEM) PDMS was spin-coated (2000 rpm for 30s) onto the Ecoflex, and partially cured at 60 °C for 30 min (Figure S2F).

With both layers ready, the top layer was placed on top of the bottom layer to form the microfluidic channels (Figure S2G). Good adhesion was achieved as both layers were still very sticky from the partial curing. After completely cured by heating at 60 ℃ for 3 hr, the resulting structure was peeled away from the silicon wafer (Figure S2H). To create inlets and outlets for the microfluidic channels, through holes were punched by a needle (20 Gauge = 0.9 mm diameter) (Figure S2H), and the bottom openings of the holes was sealed by epoxy (Figure S2I). EGaIn (Aldrich) was injected by positive pressure into the inlet using a syringe (Figure S2J). The resulted EGaIn-filled microfluidic channels would act as the two branches of the dipole antenna. A 3 mm SMA connector (Digikey Inc.) was attached to the device by inserting its pins into the inlets/outlets of the microfluidic channels at the gap (Figure S2K); and the electrical connections formed naturally between the SMA connector and antenna branches as the EGaIn surrounded and wetted the pins of the connector. Finally, epoxy was applied to seal the microfluidic channels, and to fix the connector in place (Figure S2L).

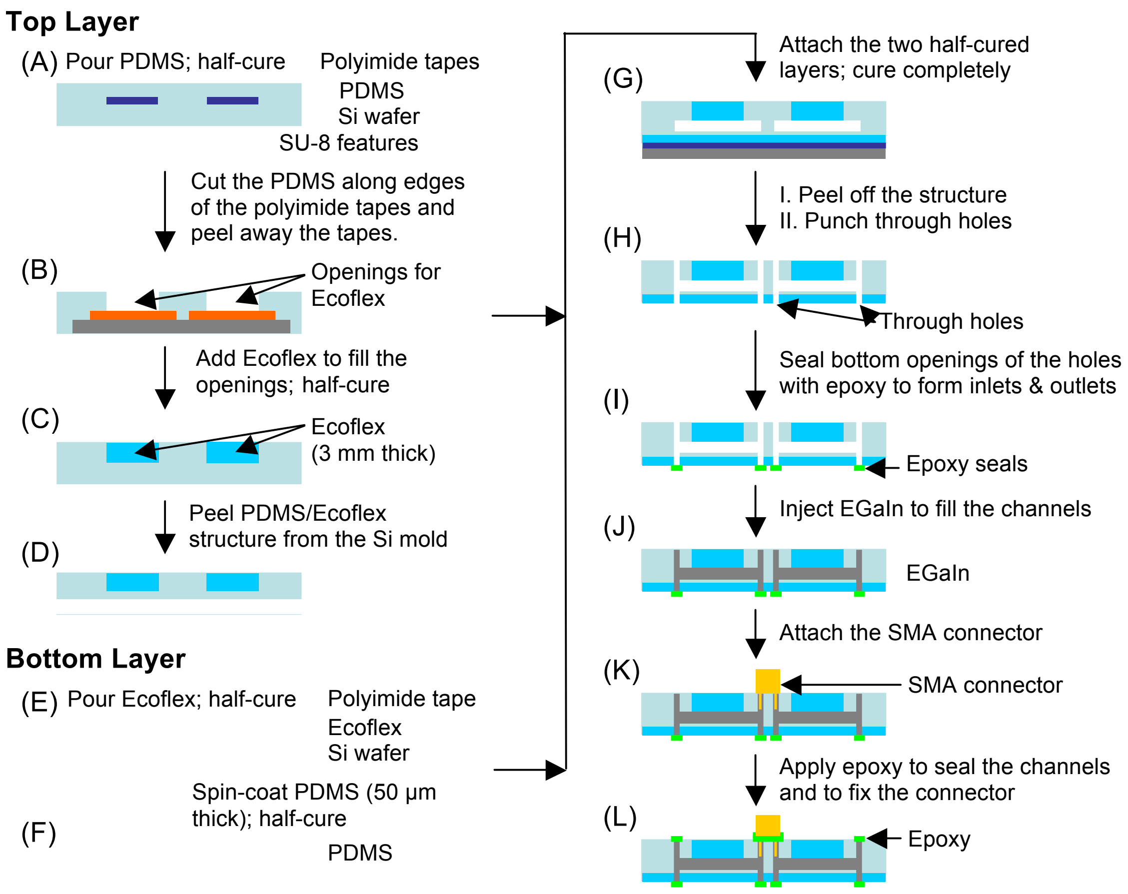

Figure S2. Steps of fabrication of the stretchable antenna.

Fabrication of Stetchable Antenna (using only PDMS as Insulator)

Antennas made in only PDMS were fabricated using a procedure similar to that we have described above. For the top layer, PDMS was poured onto the same SU-8 master and cured at 60 °C for 3 hr. The fully cured PDMS layer was cut by a razor blade along the circumference of silicon wafer, and peeled off the master. For the bottom layer, we prepared a 4-inch silicon wafer by silanizing it in a vapor of 1H,1H,2H,2H-perfluorooctyl trichlorosilane (Aldrich) overnight, so that the bottom layer could later be easily peeled away from the silicon wafer. PDMS was then spin-coated at 500 rpm for 30s, resulting in a 300-µm-thick film (as measured by SEM), and fully cured at 60 °C for 3 hr. The top layer was placed on top of the bottom layer to form the microfluidic channels. Both layers were treated with oxygen plasma for 60 s in order to improve the adhesion. The resulting structure was peeled away from silicon wafer. The rest steps followed the same description for the antenna using the PDMS/Ecoflex hybrid structure (Figure S2H – L).

Evaluation of the Performance of the Antenna

We measured the resonance frequency and radiation efficiency of the antenna, at its stretched and un-stretched states, using an Agilent 8358A 300 kHz ~ 9 GHz Network Analyzer (Figure S3). The antenna was put on a half-inch thick polyethylene board during evaluation, and was held in the stretched state using a pair of plastic clamps. The antenna was connected to the network analyzer directly through the rigid 50 Ω SMA connector and a 50 Ω coaxial cable without using a balun (balanced-unbalanced impedance transformer), because the purpose of this work is to demonstrate the stretchability and durability of our antenna, instead of characterizing a well-known dipole antenna. The network analyzer sent electromagnetic (*EM*) waves at frequency *f* to the antenna via the coaxial cable. When the *EM* wave reached the antenna, part of its energy was radiated by the antenna into free space; a small portion was lost as heat due to ohmic resistance of the antenna; and the rest was reflected back to, and measured by, the network analyzer (Figure S3). We repeated these measurements over a range of frequencies to obtain the frequency response of reflected power from the antenna.

Half-wave dipole antenna is known to have a radiation resistance (R_{rad}) close to 50 Ω at its resonance frequency. [1,2] Therefore, the incident power is maximally coupled to *EM* radiation at the resonance frequency, resulting in a sharp dip in the frequency response of the reflected power. Such dip was indeed observed in our measurement with magnitude greater than 15 dB (Figure 4), meaning that more than 95 % of the incident power was coupled to *EM* radiation; and we measured the resonance frequency and radiation efficiency of the antenna from the position and magnitude of the dip, respectively.

We directly inferred the power radiated into free space from the reflected power measured by the network analyzer. For example, a reflection ratio of–20 dB and –10 dB corresponded to a radiation efficiency of 99 % and 90 %, respectively. We ignored the ohmic loss inside the antenna. This is justified by the fact that the radiated power and ohmic loss are given by I^2R_{rad} and I^2R_{loss}, respectively, for an *ac* current *I* flowing in the antenna, and that the radiation resistance R_{rad} (~ 50 Ω) is much greater than the ohmic resistance R_{loss}, which is estimated to be less than 1 Ω based on the antenna geometry and the resistivity of EGaIn.

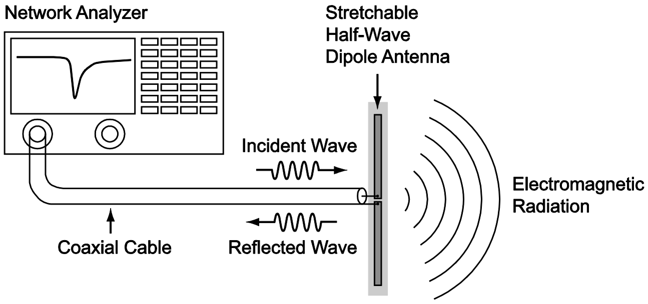

Figure S3. Measurement setup for antenna evaluation.

[1] For an ideal half-wave antenna in free space, its radiation resistance and reactance range from 50 Ω to 75 Ω and from –50 Ω to 50 Ω, respectively, around its resonance frequency ($f = 0.43 \sim 0.505\ c/l$, with c the speed of light in free space, and l the antenna length). The radiation resistance and reactance, as well as the resonance frequency, are expected to decrease when the antenna is embedded in a dielectric substrate like our stretchable antenna.

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