Supporting Information for

Stretchable Microfluidic Radio Frequency Antenna

Masahiro Kubo[1 †], Xiaofeng Li[2 †], Choongik Kim[1], Michinao Hashimoto[1],

Benjamin J. Wiley[1], Donhee Ham[2] and George M. Whitesides[1*]

[1] Prof. G. M. Whitesides, Dr. M. Kubo, Dr. C. Kim, Dr. M. Hashimoto, Dr. B. J. Wiley

Department of Chemistry and Chemical Biology, Harvard University

12 Oxford St., Cambridge, MA, 02138 U.S.A.

[*] E-mail: gwhitesides@gmwgroup.harvard.edu

[2] Prof. D. Ham, X. Li

School of Engineering and Applied Sciences, Harvard University

29 Oxford St., Cambridge, MA, U.S.A.

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
$Ga^{68.5}In^{21.5}Sn^{10}$	−19.0	3.5	380	9
$Ga^{61}In^{25}Sn^{13}$ Zn^{1}	7.6	2.8	370	8

[a] *CRC handbook of Chemistry and Physics*, CRC Press, **2009**

[b] N. B. Morley, J. Burris, L. C. Cadwallader, M. D. Nornberg, *Rev. Sci. Instrum.* **2008**, *79*, 056107.

[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.

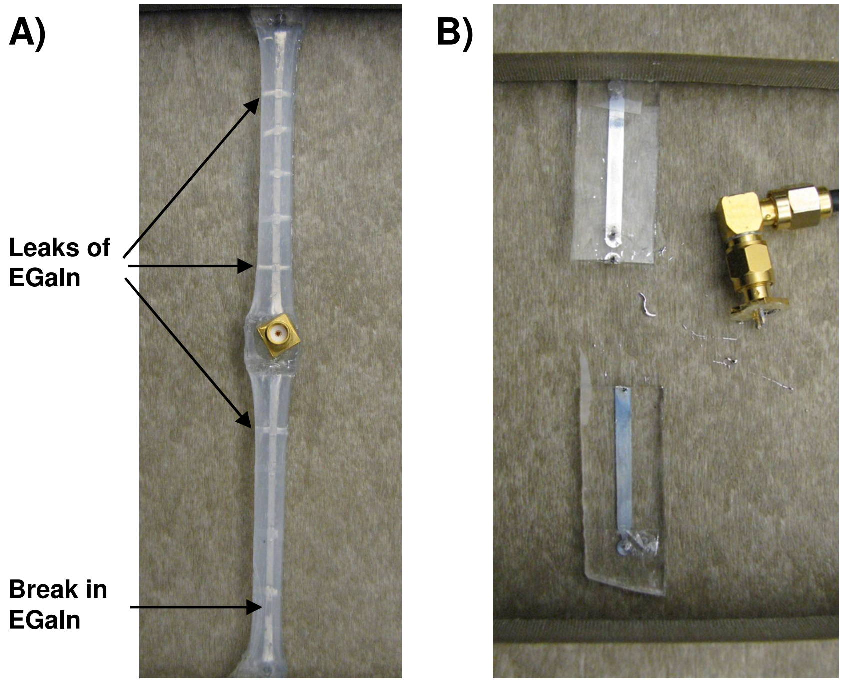

Figure S1. Photos of antennas that failed under tensile strain. A) “PDMS/Ecoflex” and B) “All PDMS” structure.

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).

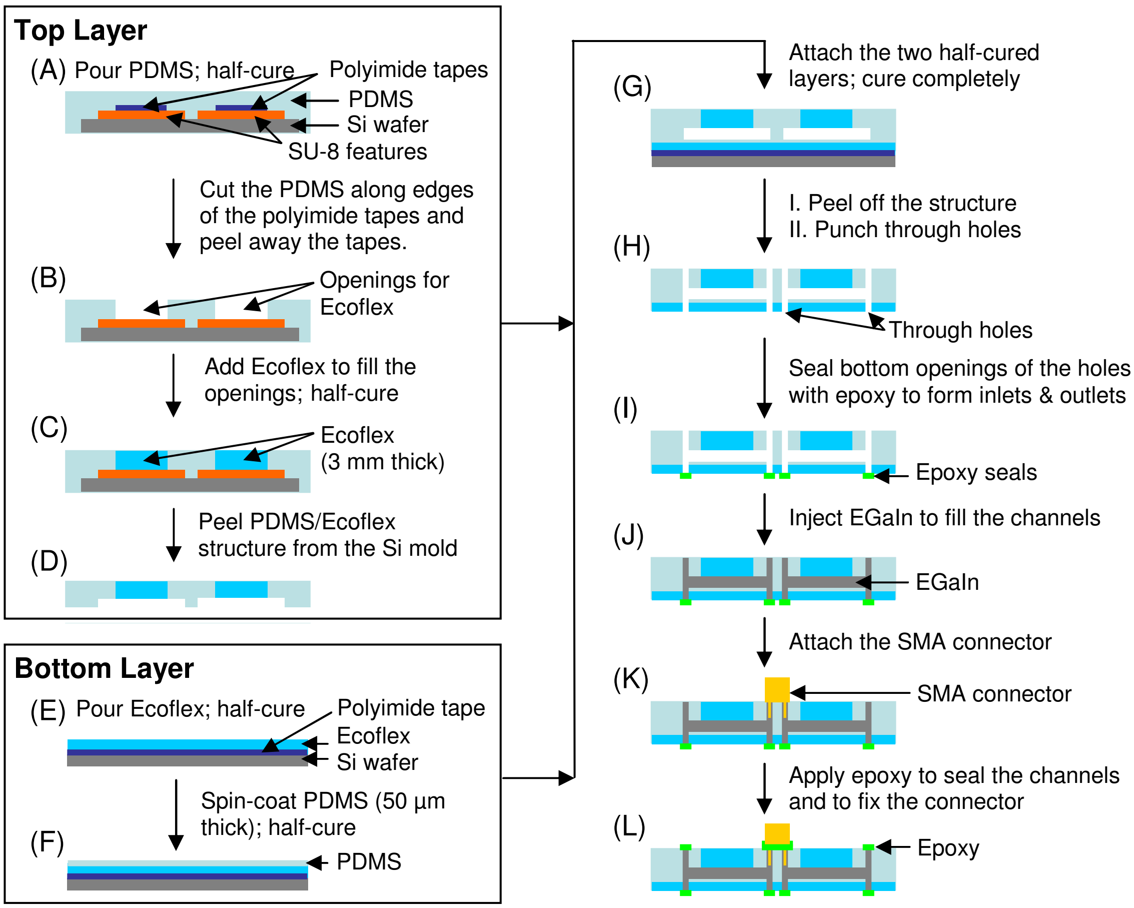

Figure S2. Steps of fabrication of the stretchable antenna.

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.

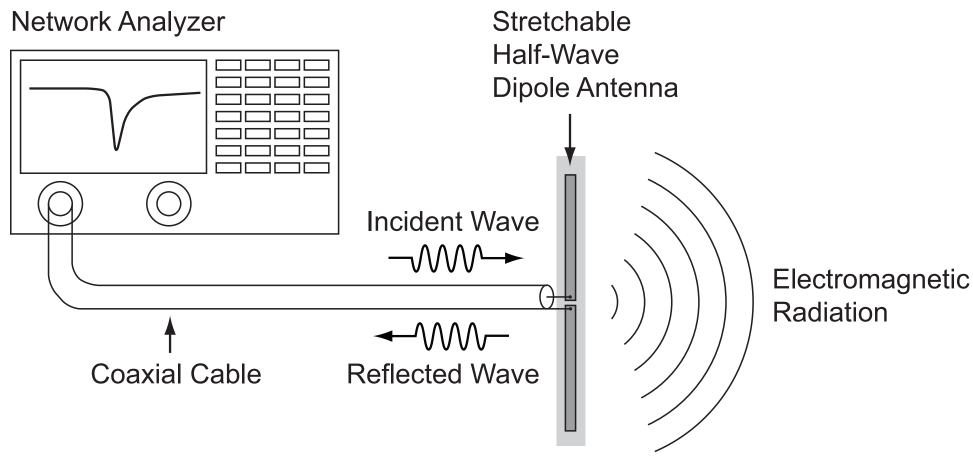

Figure S3. Measurement setup for antenna evaluation.

[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.

[2] *Antenna Engineering Handbook* (2nd ed.), ed. by R. C. Johnson, H. Jasik, **1984**, McGraw-Hill.