Novel Stretchable Electrically Conductive Composites for Tunable RF Devices

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ABSTRACT — Stretchable, flexible and tunable RF devices that are fabricated with Polydimethylsiloxane (PDMS) Electrically Conductive Composites (ECC) are presented. Using this composite material allows mechanical modulation of the device dimensions resulting in tuning of its frequency response. A planar loop antenna and a 5th order stepped impedance low pass filter operating around 1.5 GHz with tunability greater than 15% are shown. The ECC can reach an electrical resistivity as low as 10^{-4} Ω. cm, which is close to a metal resistivity. The materials are also ultra-low cost for massive fabrication. This technology opens the door for tunable RF devices on flexible and curvilinear packages.

Index Terms — Flexible, Stretchable, Frequency tunable, Reconfigurable RF devices, Loop antenna, Stepped impedance low pass filter

I. INTRODUCTION

Flexible and stretchable electronic devices that are lightweight, tunable and biocompatible have recently attracted increasing interest from industry and academia [1]. A wide range of applications such as radio frequency identification (RFID) systems, antennas used for satellite communications, wireless body area networks (WBAN), and medical implantable systems require devices that are reconfigurable, nonplanar and wearable.

Recently, various methods to fabricate stretchable devices have been reported. Initially, wrinkled electrodes on prestretched elastic substrates were enabled for electroactive polymer actuators. Skin-like circuits have also been described [1]. Lacour et al. proposed a conceptual hardware architecture [2]-[3], where an elastomeric skin carried rigid islands on which active subcircuits were made. The subcircuit islands were interconnected by stretchable metallization. Kim et al. improved this technique to be adjusted in silicon integrated circuits (ICs) [4]-[5]. In continuation with this work, Rogers et al. fabricated stretchable devices by utilizing ultra-thin wavy interconnects of high-quality thin films, to minimize the compressive and tensile stresses [6].

Fabrication of stretchable electronic devices through out of plane geometric patterning requires complex and costly processing steps and designs, making it impractical for mass produced consumer electronic devices. Secondly, because out of plane geometry is required for stretchability of the device the aerial density is limited.

A different approach to stretchable electronic packages uses liquid metal filled microfluidic channels. This approach has been used for multiaxially stretchable antennas by Cheng et al. and Masahiro et al. [7]-[10]. The latter contain GaIn that is scarce, not biocompatible and it freezes at near ambient temperatures.

More recently, we presented the microwave characterization of transmission lines using silver flakes, silicone and other additives. Initial results proved the stretchability up to a strain [defined as the percentage change in length or (l-l0)/l0] of 60% and indicated the potential for RF devices and thermal interconnectors [11]-[12]. However, there was no analysis about the relationship between the RF performance and the stretchability. In this paper, we present for the first time low cost stretchable RF devices that can reconfigure their electric response based on a solid metal as the conductive material.

In this paper, the whole structure utilizes stretchable electrically conductive composites (ECC) embedded in stretchable substrates, which are inherently flexible and stretchable. The technology is tested for the first time in the form of a loop antenna and a stepped impedance filter. Using this structure we show tunability of up to 450MHz at a frequency band around 1.5 GHz which is useful for PCS applications.

II. STRETCHABLE MATERIAL TECHNOLOGY

The demonstrated stretchable loop antenna and filter were embedded in a polydimethylsiloxane (PDMS) elastomeric substrate. The antenna and filter were formed with stretchable electrically conductive composites (ECC) composed of Ag flakes (Ferro) with a filler loading of 81 wt. % in a Pt cured Poly (dimethylsiloxane) (PDMS) matrix. The ECC used is biocompatible and chemically and thermally stability. The manufacturing process steps consist of the following: stencil printing ECC, encapsulation with silica-reinforced PDMS and lift off from the substrate. The fabrication processes for the devices and SEM image of Ag flakes with additives are shown in Figure 1.

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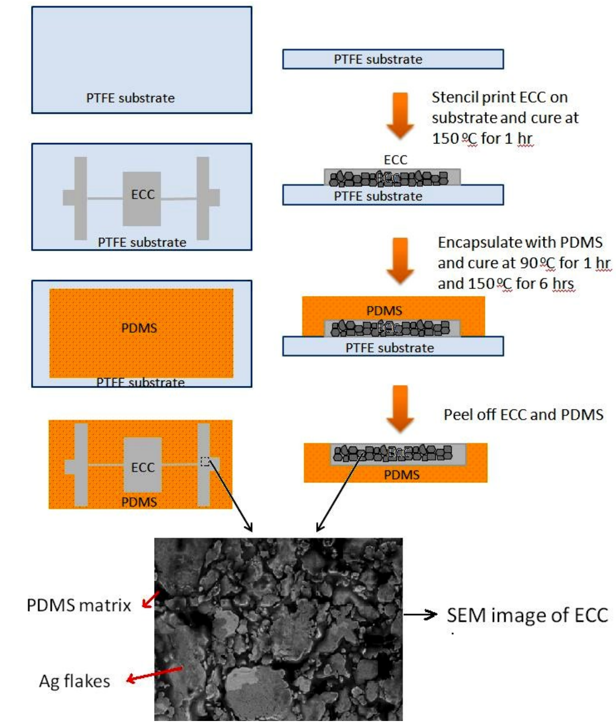


Fig. 1. Schematic drawing of fabrication process.

The ECC has resistivity as low as 10^{-4} Ω. cm, which is only a few orders of magnitude higher than bulk copper. In addition, since PDMS remains mechanically compliant at temperatures <-80 °C (glass transition temperature (Tg=-120°C), it is stretchable at extremely low temperatures.

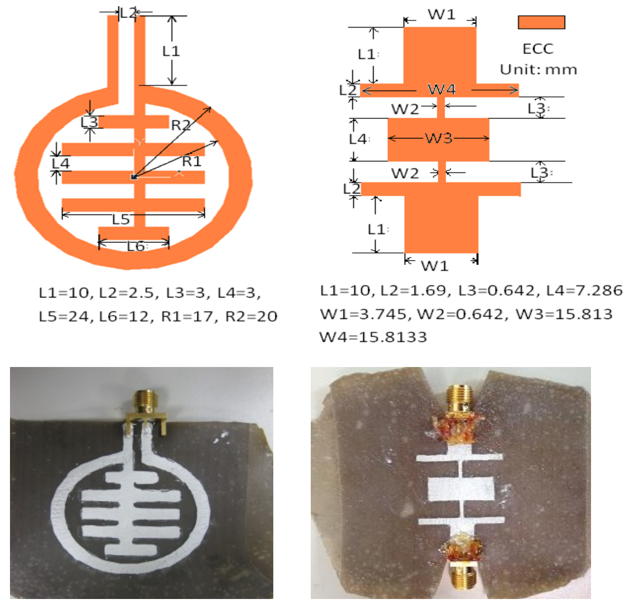
III. DESIGN METHODOLOGY OF THE TUNING FREQUENCY

Here a loop antenna and a low-pass filter are designed as examples to demonstrate that the center frequency is tuned by stretching this kind of ECC material.

III.1 Loop antenna

A loop antenna for the frequency range of 1-3GHz is designed with 500MHz of tuning capability. To get a more compact size and facilitate the integration of other electronic components, a fishbone like planar antenna is designed as shown in Figure 2 (a), similar to the loop antenna with square grid inside [10]. The resonant frequency f of this antenna is determined by the overall length of the loop. The fishbone like structure makes the actual resonant frequency lower than a circle antenna without the internal fishbone structure. Figure 2(a) depicts the dimensions of the stretchable loop antenna. The frequency can be approximately estimated using Eq. (1):

$$f = \frac{c}{2L_{loop}\sqrt{\varepsilon_{eff}}} \quad (1)$$



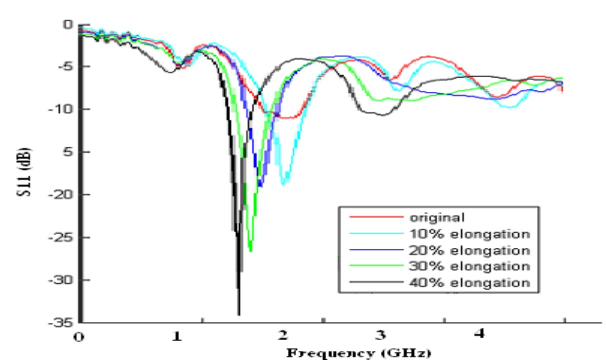
(a) (b)

Fig. 2. (a) The geometry and photograph of the stretchable loop antenna. (b) The geometry and photograph of the stretchable stepped impedance low pass filter

where c is the speed of light in free space and εeff is the effective dielectric constant (εr~1) due to the negligible effect of the thin PDMS membrane. The antenna was optimized using Ansoft's HFSS full-wave simulator. On the top of PDMS membrane, an SMA connector was attached to the two openings of the antenna. An ECC was used to secure the SMA connectors to the substrate.

III.2 Low-pass filter

A low-pass stepped-impedance filter with a cut-off frequency around 1.7 GHz for communication applications was also designed. Using Linecalc of Agilent ADS, the width and length of the microstrip lines of the stepped impedance low pass filter were calculated. A full-wave Method of Moments simulation was used as the final validation of the design and to generate the artwork as shown in Figure 2(b).



(a)

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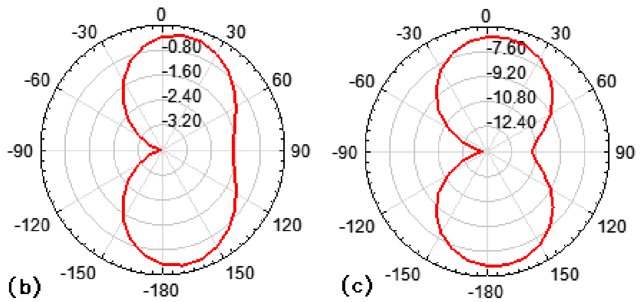

Fig. 3. (a) Measured resonant frequency of the loop antenna as a function of the tensile strain. (b) Simulated radiation patterns of nonstretched antenna. (c) Simulated radiation patterns of stretched antenna with a 40% elongation.

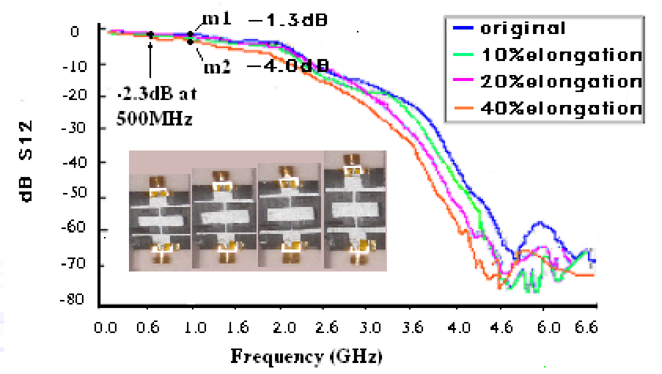

Fig. 4. Measured S21 of the filter as a function of the tensile strain.

IV. RESULTS

The S-parameters for the two devices were measured using an Agilent PNA (E8361C). An SOLT calibration was performed. Mechanical tests on stretching the antenna and the filter were also performed. The maximum stretching of the device reached up to 60% without any plastic deformation or damage to the device or the SMA connectors. But for a stable measurement, S-parameter measurements were taken up to a 40% stretching.

Regarding the antenna, within the range from 1 GHz to 3 GHz, the resonant frequency moves as expected while the radiation pattern shows an increase of the gain of the antenna (Fig. 3). As the analysis given from Eq. (1), when the length of the antenna is increased, the resonant frequency decreases accordingly. The resonant frequency of 1.75 GHz at its original dimension decreased to 1.3 GHz when the antenna was stretched in one direction by 40%. The radiation patterns of the antenna were simulated at 1.75GHz; the E-plane patterns simulated with original dimensions and with a 40% elongation are shown in Fig. 3 (b) and (c) respectively. After releasing the antenna, the same frequency response was obtained as in the "pre-stretched" state which demonstrates the robustness of the stretchable material. On the other hand, the measured S-parameters of the filter (Fig. 4) show that the cut-off frequency of the low-pass filter shifts from 1.4 GHz to 1.2 GHz with an elongation of up to 40%. The filter insertion loss was measured to be 2.3dB at 500MHz at the filter's original size. The loss remained practically unchanged when the filter was stretched up to 40%. Overall, a considerable frequency shift was observed during stretching for both the antenna and the filter.

V. CONCLUSIONS

A new method has been developed to build stretchable RF structures with tunable response. The frequency response can be controlled by changing the dimensions of the structure formed using, for the first time, highly conductive stretchable PDMS-ECC material as the conductor. The high performance and reliability of this technology was demonstrated with a reconfigurable loop antenna and a low-pass filter operating in the 1.5 GHz frequency range. This technology is promising for the development of low cost stretchable RF electronics with good tunability and relatively low loss.

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