a. PRF#: 59021-DNI7

b. Project Title: Controlled Mechanical Buckling: A Perfect Platform for Designing Multifunctional 3D Surface Structures

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Overview: The structural design of our research program is supported by this ACS PRF DNI grant for creating two stretchable microstrip antennas: "meshed microstrip antenna" and "arched microstrip antenna". The former exploits initially wavy structures from patterning and the latter also uses the deformed wavy structures created from the pre-strain strategy. In comparison to their solid microstrip antenna counterpart, the radiation properties of the resulting stretchable microstrip antennas do not change much. Meanwhile, the resonance frequency decreases with the externally applied tensile strain along the feeding direction in the design of the "meshed microstrip antenna", but increases with the increasing strain in the design of the "arched microstrip antenna". The change in the resonance frequency with the externally applied tensile strain in the latter design has a high sensitivity, manifesting a 3.35 and a 1.49 fold increase of the sensitivity when compared with previous reports that used silver nanowires- or liquid metals-based stretchable microstrip antennas. Considering the high sensitivity and compliant characteristic of the stretchable microstrip antenna, we have demonstrated an "arched microstrip antenna" based strain sensor that is capable of detecting the motion of human wrists with high sensitivity, little hysteresis, and possible wireless communication.

Progress: A typical microstrip patch antenna consists of the conductive patch and ground plane separated by a rigid dielectric substrate layer. The first step in the design of flexible and stretchable antennas started by replacing the conventional rigid substrate with a flexible and stretchable layer such as elastomeric polymers. Due to their low Young's modulus, hyperelastic property, and decent dielectric properties (dielectric constant of 3.125 and loss of 0.01 in the frequency range from 2.5 GHz to 3.5 GHz), Ecoflex and Solaris (Smooth-on) as representative silicone elastomers were chosen as the stretchable substrate. Without using any structural design in the conductive elements (i.e., patch and ground plane), a Solaris substrate with a thickness of 1.5 mm sandwiched between a solid copper patch and a solid ground plane formed a microstrip antenna with a resonance frequency at 3.50 GHz and a bandwidth of 0.11 GHz. Consistent with the previous reports,[1-2] this result implies that the use of silicone elastomer as the dielectric substrates does not compromise the performance of microstrip antennas.

Next, we have explored two representative stretchable structures in designing and fabricating the stretchable, mechanically reversible microstrip antennas from

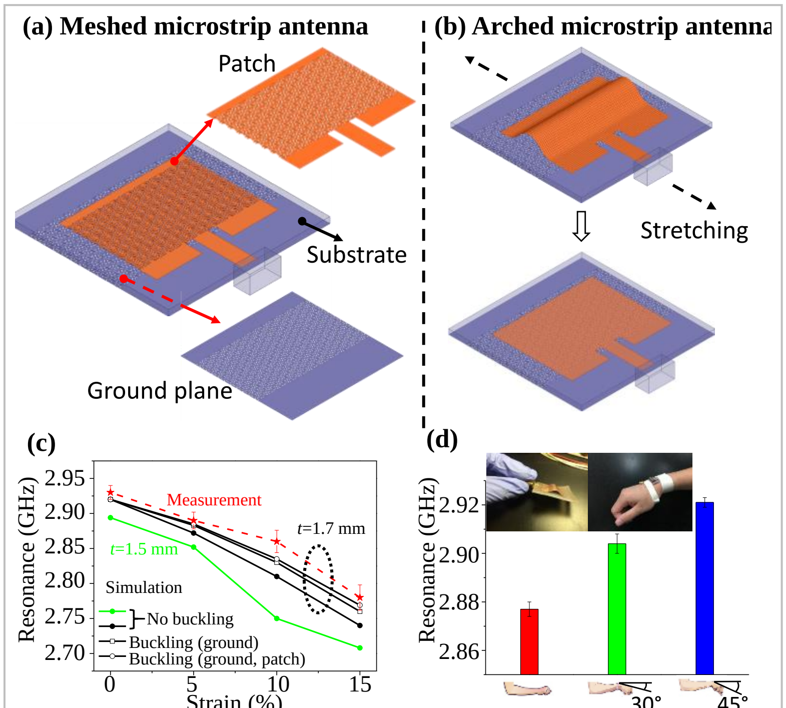

Figure 1: (**a**) "Meshed" and (**b**) "Arched" microstrip antennas. (**c**) S_{11} parameter of the antenna in (**a**) upon stretching. (**d**) Demonstration of the antenna in (**b**) as strain sensor for motion detection.

conventional metals: deformed wavy structure created from the use of the pre-strain strategy and the initially wavy structure from patterning. In addition to the simple arc demonstrated here, the former could easily be extended to various 3D structures when combined with the mechanically guided assembly process. The latter could be combined with the optimization strategy to create a strain-limiting, mechanically invisible device, which is particularly suitable for the application of bio-integrated electronics.[3] Using these stretchable structures yielded two structural designs for the stretchable microstrip antenna: "meshed microstrip antenna" (**Fig. 1a**) and "arched microstrip antenna" (**Fig. 1b**). The former exploits the serpentine network for a meshed patch and meshed ground plane, whereas the latter explores a meshed ground plane and an arched shape for the patch. Taken together the set of non-dimensional parameters in the unit element of the horseshoe shapes (i.e., normalized thickness, normalized width, and arc angle) with the different patterns that can be created with the unit element, the stretchability of the resulting structure can be easily tuned to several tens of percent. The demonstrations presented in this preliminary study are obtained by a simple cutting method, but the designed patterns could easily be created by the other advanced manufacturing methods such as porous LIG. The prediction of the radiation properties of both designs from the simulation is verified by the experiment (**Fig. 1c**). Due to the tunable dependence of the resonance frequency shift on the tensile strain, the resulting stretchable microstrip antenna is also demonstrated as a class of novel strain sensors (**Fig. 1d**) that could enable wireless communication by using the technique of wireless interrogation.[4]

Significance and Impact: The practical application of flexible and stretchable electronics has been hindered by ineffective communication of the large volume of data from sensors and the resulting requirement of high power to process them. The wireless technology that includes Bluetooth, near field communication (NFC), and inductive coupling could bypass these limitations to wirelessly transmit data and power in real-time because of their compactness and high processing capacity with minimal power consumption. Compared with batteries and supercapacitors, these wireless transmission modules eliminate the need for the replacement and, thus, are durable. In addition to wireless data and power transmission, wireless technology has also been used to remotely interrogate strain, chemical signal, crack propagation, among many others. As a critical component for long-range operation, the class of radio frequency antennas has attracted increasing attention, especially for flexible and stretchable sensors. Because of the availability of commercial radio frequency chips in the miniaturized form, the long-range operation with radiofrequency components results in an increasing interest in both research labs and future commercialization.

Career development: The ACS PRF has supported the stipend of one graduate student on this project. The graduate student presented a poster on his early efforts on this project at several meetings at Penn State. The PI also presented this work as part of his seminar talks at several places. In addition to one paper published in *ACS Applied Materials & Interfaces*, a manuscript describing our early efforts of a stretchable wideband antenna that is almost unchanged to the uniaxial tensile strain of 15 %, is in advanced stages. Support from the ACS PRF has also enabled us to submit one NSF grant application in 2019 in order to continue our areas of investigation into stretchable and reconfigurable antennas.

References:

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