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STRETCHABLE ANTENNAS AND RECTENNAS FOR WIRELESS COMMUNICATION AND AMBIENT RF ENERGY HARVESTING

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by
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ABSTRACT

Bio-integrated electronic devices can pliably conform to the textured skin surface to continuously monitor the physiologically relevant parameters or biomarkers, with a huge impact on human health from preventative monitoring and early diagnostic confirmation to non-invasive and convenient therapeutic options. The ultimate application of this class of emerging electronics hinges on the indispensable modules of stretchable wireless transmission and power supplies. While near field communication (NFC) allows for wireless powering and communication with a working distance of ~ 3 cm, radio frequency (RF) antennas enable wireless transmission of data and energy in the far-field. Materials engineering (i.e., using novel materials with combined superior electrical and mechanical properties, such as nanomaterials and composites) and structural engineering on conventional rigid materials (i.e., employing serpentine, wavy and 3D structures) have been widely used in the design and fabrication of stretchable antennas. Compared to the approaches that exploit stretchable conducting materials such as liquid metal or elastomers with conductive fillers, designing conventional metals in a serpentine or meshed geometry is still of high interest because of their high radiation efficiency. Although this structural design concept has resulted in various stretchable dipole and patch antennas, the limited bandwidth still limits their applications in wireless communication and energy harvesting because of the frequency detuning from mechanical deformations. In this work, we proposed various stretchable structures in the design of stretchable antennas, including patch and dipole, based on conventional materials and found a way to effectively tune the resonance frequency response to external deformations. A large resonance frequency shift to mechanical deformations enables the application in wireless strain sensing, while robust resonance frequency upon stretching promises stable and reliable communication performance. Then, we introduced a stretchable wideband dipole antenna consisting of serpentine units for both main and parasitic arms created by exploiting the laser-
induced graphene (LIG) pattern and maskless metal coating. The compensation for the frequency detuning upon deformations helps to further improve the robust electromagnetic properties. Additionally, combining the stretchable dipole antenna with a high-efficiency impedance matching network and rectifying circuit leads to a stretchable rectifying antenna (i.e., stretchable rectenna) that can continuously harvest electromagnetic radiation energies from various widely available RF sources (e.g., WI-FI, 4G, and upcoming 5G). As an added component into the clean energy portfolio for future energy supply, the ambient RF energy-harvesting solution could also contribute to integrated energy systems and enable self-powered systems and remote monitoring of the environment.
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Chapter 1

Introduction

1.1 Background

According to Maxwell’s equations, radiated fields are produced when a charge accelerates or decelerates [1]. Serving as an interface between radio waves propagating through space and electric currents moving in metal conductors, the antenna is the essential element of all radio equipment to convert between electric and electromagnetic energies. Chief performance measures of antennas are the directional characteristics as depicted in the radiation pattern and the resulting gain that accounts for the efficiency. The other important parameters also include the resonance frequency and bandwidth. These properties are affected by the types of antennas, as well as the geometric and material parameters in each type. Though there are various antennas, the most widely studied ones are the monopole, dipole, and patch antennas, among others, due to their simple structure and ease of fabrication.

As wireless technology plays a critical role in remote communication, non-contact charging (or powering), and identification, it is highly desirable to develop wearable antennas for the fast-developing flexible and stretchable electronic devices that have broad applications in health monitoring and clinic therapeutics [2-4]. As a representative example, radio-frequency identification (RFID) could wirelessly detect a fracture in a structure or the health condition of individuals from a relatively long distance without the need for an external power source [5, 6]. In order to integrate electronics onto the human body, that is typically associated with curvilinear surfaces and dynamically changing motions, the bio-integrated devices must be conformal and physically flexible or even stretchable. As the key component in wireless technology, the
representative patch antenna that consists of a rigid dielectric substrate and metal radiation parts in the traditional design is neither flexible nor stretchable. Because the bending stiffness of a thin film structure that characterizes its resistance against bending deformation roughly scales with the cubic of its thickness [7], thinning down the thickness of the structure represents an effective means to enable flexible/bendable antennas [8-10]. Due to the dictated thickness in the dielectric substrate, the rigid dielectric substrate is typically replaced by a flexible textile or elastomeric substrate in the design of the flexible antenna [11, 12]. When the stretchable property is of concern for the antenna, approaches based on stretchable materials and/or stretchable structures have been explored. After replacing the rigid dielectric substrate with a flexible or stretchable substrate, the radiation parts of antennas can then be replaced by stretchable materials or be engineered into a stretchable layout. In either approach, a tradeoff between the stretchable mechanical property and the microwave performance of the system is observed [13, 14]. In order to address this challenge, different strategies have been proposed and extensively studied. The radiation property of the flexible and stretchable antennas under mechanical deformation will be specifically discussed in this mini-review.

As the conductive component is the key for the radiation parts, the widely used methods to construct a conductive component over stretching have been studied for the stretchable antenna. In this mini-review, we will first discuss the considerations and implementations of flexible and stretchable antennas that are based on textiles. Next, we will introduce the composite elastomer with an interpenetrating network of liquid metal for the stretchable antenna. Composite elastomer embedding conductive fillers for the stretchable antenna will then be reviewed. Finally, we will briefly discuss the effort to explore stretchable structures from conventional metals for the stretchable antenna. Bearing these similar design principles as the patch antenna, the transmission lines that are essential to the input and output of electromagnetic signals will also be briefly
discussed. Moreover, we will highlight the challenges and opportunities in the burgeoning field of flexible and stretchable antennas for future development.

1.2 Insulating and Conducting Fabrics for Textile Antennas

Due to the ease of integration on the clothes, flexible antennas that are based on textiles have attracted significant attention. In the textile antenna, the conventional dielectric substrate such as Rogers (dielectric constant of 3–10 and dielectric loss tangent of 0.001–0.005) is replaced by fabrics to enable flexibility. Depending on the properties of the fiber components and the structure of the yarns in the textile substrate, their dielectric constants and loss tangents are measured to be in the ranges of [1.5, 2] and [0.005, 0.05], respectively [15, 16]. In comparison to the conventional substrate such as Rogers, the relatively low dielectric constant of textiles could provide a slightly large impedance bandwidth and a high radiation efficiency in the resulting antenna, but the small value makes it difficult to miniaturize certain types of wearable and stretchable antennas such as the microstrip antenna and planar inverted-F antenna [16]. The performance of fabric materials such as cotton and polyester as the dielectric substrate in a microstrip patch antenna with conventional copper for patch and ground plane has been evaluated and the returned loss of the antenna at resonance is ~ −15 to −20 dB, indicating a good radiation efficiency [17]. Replacing the dielectric substrate with a textile substrate while keeping the conventional metals for the radiation components evaluates the effect of the textile substrate on the antenna performance [14-18]. Even with the non-uniform thickness in the textile substrate, the measured resonance frequency agrees reasonably well (an error of ~6.1%) with the results obtained from the simulation that takes the assumption of a uniform thickness.

In order to provide an all-textile antenna, the radiation components need to be replaced by conductive fabrics as well. Various methods have been explored to obtain conductive fabrics,
including chemical modification and physical mixing the fabric with conductive components. In one attempt to chemically modify the fabric surfaces, polyaniline (PANI) is covalently grafted onto a fabric substrate to yield a conductive fabric (Figure 1-1 Ai) [19]. Post-treatment in bath solutions of different pH values can further tune the conductivity of the fabric, which provides a switch between conductive (sheet resistance of \( \sim 2.5 \times 10^5 \Omega/\square \) at pH of 0) and insulating (sheet resistance of \( \sim 4 \times 10^{10} \Omega/\square \) at pH of 14) behaviors (Figure 1-1 Aii). The decrease in the pH of the reactant solutions results in an increase in the degree of protonation (H\(^+\) doping), leading to a decrease in the sheet resistance of the fabric. In contrast, OH\(^-\) deprotonation of PANI chains in the reactant solution with high pH levels leads to an increased sheet resistance. The electrically conductive property of the resulting fabric is also shown to be highly stable. As demonstrated in the simulated dry-wash test, the conductivity of the conductive fabrics with different degrees of grafting (DG) of PANI shows negligible changes after 40 times of dry-wash cycles. Even though the conducting fabric has the merit of softness and washability, the relatively high sheet resistance would lead to a poor antenna performance such as a radiation efficiency of less than 10%[20, 21].

The physical mixing involves the use of several conductive materials. As a widely used organic conductive material, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) can be mixed with the solution of polyurethane (PU) to modify its conductivity in the spinning process (Figure 1-1 B) [22]. For instance, mixing the PU solution with PEDOT:PSS 13.0% (weight ratio) yields a conductive composite fiber with an electrical conductivity of 940 S/m and a stretchability of 345%. Mixing carbon nanotubes (CNTs) with the polymer has attracted great attention because of the reinforced mechanical and electrical properties [23-29]. In order to explore CNTs in the conductive fabric, coating textile with a mixed solution of aqueous CNT dispersion and a water-based polyacrylate dispersion binder can lead CNT particles to form a honeycomb structured conductive network in the coating [24], which results in sheet resistance of \( \sim 60 \ \Omega/\square \). These
Conductive fabric materials with improved conductivity have great potentials in the application of wearable antenna [30, 31].

In order to improve the electrical conductivity, metal plating, and especially the electroless plating on fabric has been explored [32-34]. Among a variety of metals (e.g., nickel, silver, and copper) that have been explored, the silver-plated fabric is found to have the best electrical conductivity due to the ultrahigh conductivity of silver [32]. With a comparable conductivity but at a much lower cost, the copper plating is widely used. In a typical process of the copper-plated fabric, cotton fibers are firstly modified with poly(4-vinyl pyridine) (P4VP) to serve as an adhesive layer for silver ions (Figure 1-1 C) [35]. Next, Ag obtained after the reduction of silver ions acts as a catalyst for the subsequent Cu deposition in the electroless coating bath. The conductivity of the resulting textile initially increases with the increase of the P4VP concentration and then saturates because of a poor fluidity and non-uniform coating, yielding a maximized sheet resistance of ~0.04 Ω/□. It is of significant interest to precisely control the size of radiation parts in the textile antenna. Among the different approaches, laser cutting, programmable knitting or embroidery, and printing are widely adopted. In the programmable embroidery, an embroidery design program first generates digitalized patterns for the sewing machine. Precisely embroidering flexible silver-coated fibers in a double-layer manner onto a regular fabric, assembled onto the polymer substrate, yields basic RF prototypes such as transmission lines, patch antennas, and antenna arrays with comparable performance with their copper counterparts [36]. The precision of embroidery can reach ~0.1 mm, promising great potential in the industrial application [37]. In another study, weaving copper yarns (conductivity of 10⁷ S/m) as a radiating patch and the ground layer with E-glass fibers of five layers as the substrate in the 3D fabric antenna is achieved by a 3D orthogonal weaving machine (Figure 1-1 D) [38]. When the antenna is bent with the curvature along with the feeding direction, the effective resonant length decreases, leading to an increase in resonance frequency. In comparison, the antenna with a bending curvature perpendicular to the feeding direction shows a relatively sTbale
resonance frequency. Printing technique represents an alternative to precisely control the size of the pattern. As shown in Figure 1-1 E, copper sulfate (CuSO₄) and sodium borohydride (NaBH₄) solutions can be sequentially dispensed through two syringes [39]. After oxidation and reduction, a uniform conductive copper layer forms on the textile surface. However, the wettability of textiles could pose a potential issue for a uniform coating of copper.

The sheet resistance of the textile also depends on the design and process of knitting or weaving. As shown in Figure 1-1 F, the conductive fabric in the single pique structure (orange dot in the bottom one) with more conductive pathways has a smaller contact resistance than the plain knit structure (red dot in the top one) [40]. As the pliability of the conductive fabric is of critical importance to the textile antenna in the practical applications, the mechanical properties of the base fabric need to be closely examined as well. Due to the knitting structure in the fabric, its mechanical properties are intrinsically anisotropic. The Young’s modulus of fabrics ranges from tens of kPa to several MPa and the Poisson ratio is in the range of [0.1, 0.4] [41]. The specific techniques to assemble the antenna with a fabric substrate and conductive fabric radiation part also need to be carefully chosen, as the electrical short or additional loss may occur [16]. The widely used methods include a connection with a seam, a thermal adhesive layer, and silicone encapsulation.

Due to the soft mechanical properties of the fabric, textile antennas can easily be bent without the loss of function, as demonstrated in the operation of microstrip [42] and dipole [43] antennas. Likely due to the negligible change in the length of radiation parts, the resonance frequency of the textile antennas remains almost unchanged during the bending. Though flexible, the textile is not intrinsically stretchable. Thus, structural design has been explored to enable its stretchable properties. In the cases of monopole and dipole antennas that are most widely used because of their simple structure and ease of fabrication, the arm can be designed into serpentine structures embedded in an elastomer matrix [44, 45]. With a negligible elongation in the length of the antenna arm upon a tensile strain, a relatively stable resonance frequency can be expected. When embedded
into a tire, a stretchable dipole antenna with silver-coated fabrics as the two serpentine arms and PDMS for the encapsulation layer has a longer operation range (2.8 m) than a commercial antenna (1.2 m). Combining such an antenna with the sensor, RF chip, and microcontroller would present the promising potential for precise and stable tire monitoring (e.g., tire revolutions and pressure) [44].

**Figure 1-1. Textile antennas.** (Ai) Preparation of the conductive textile by chemical grafting of polyaniline (PANI) onto cotton fabrics. PANI is linked to cotton fibers through two chemical modifications of the side chain of fibers. (Aii) The sheet resistance of the conductive fabric after immersing in bath solutions with different pH values. The inset schematic shows the transformation
between emeraldine base (insulating form) and emeraldine salt (conductive form) by H+ protonation and OH- deprotonation of PANI chains. Reproduced with permission from [19]; Copyright 2015, Nature Publishing Group. (B) The schematic illustration shows the preparation of polyurethane (PU)-based conductive fibers after mixing the solution of PU with the poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) fillers followed by a spinning process. Reproduced with permission from [22]; Copyright 2015, American Chemical Society. (C) Schematic illustration of the electroless deposition of copper on cotton fabrics. Step 1: poly(4-vinyl pyridine) (P4VP) is first attached to cotton fabrics by dip coating. Step 2: silver ions are absorbed due to the strong affinity of pyridyl groups to metals. Step 3: silver ions are reduced to silver particles, which will act as the catalyst for the copper deposition. Reproduced with permission from [35]; Copyright 2016, Royal Society of Chemistry. (Di) Schematic and (Dii) weaving process of the 3D fabric antenna. (Diii) Optical images show the bending of 3D fabric patch antennas with the curvature along with or perpendicular to the feeding direction. Reproduced with permission from [39]; Copyright 2016, SAGE Publications. (E) Patternning of conductive traces on textile substrates with an automatic dispensing system by sequent dispensing of copper sulfate (CuSO4) and sodium borohydride (NaBH4). A conductive copper film forms after the redox reaction. Reproduced with permission from [40]; Copyright 2014, SAGE Publications. (F) Micro-computed cosmography images of conductive fabrics with different knitted structures. The contact resistance of the top (plain knit, the interlock of the knit stitches) is contributed by the overlap of two conductive yarns, whereas that of the bottom (single pique with 50% tuck stitch, the interlock of the knit stitch and the tuck stitch) is from three conductive yarns. The latter one with more conductive pathways has a smaller contact resistance. Reproduced with permission from [40]; Copyright 2018, SAGE Publications.

1.3 Composite Elastomer with an Interpenetrating Network of Liquid Metal Antennas

It represents an interesting direction to fill the microfluidic channel created from elastomeric polymers with room-temperature liquid alloys. The ability to flow liquid metal in the microfluidic channel ensures electrical continuity even under various loading conditions. The fairly simple and scalable process does not involve etching or plating that produces hazardous waste. It can also be easily integrated with other 2D/3D devices and especially fluidic components for sensing and actuation [46, 47]. Compared with mercury, gallium alloy is more widely used due to its nontoxicity and good conductivity (3.46 × 106 S/m) [48]. In addition to being used for stretchable interconnection [49-51], the design has attracted increasing attention in stretchable antennas [52] and metamaterials [53]. The demonstrated examples include a stretchable unbalanced loop antenna [54, 55], a half-wave dipole antenna [56, 57], a patch antenna [58, 59], and a planar inverted cone antenna [60].
The unbalanced loop antenna with a resonance frequency of 2.4 GHz exhibits a stretchability up to 40% along two orthogonal orientations, with a radiation efficiency of over 80% [54]. The resonance frequency of the half-wave dipole antenna can be tuned in a linear way by mechanically stretching the antenna without hysteresis upon relaxation, useful for the wireless strain sensing (Figure 1-2 A) [57]. The antenna also self-heals in response to sharp cuts such as those induced by a razor blade and returns to its original conducting state, which is possibly due to the elasticity of the PDMS. In the case of a microstrip patch antenna, a complete, evenly filled liquid metal is required in the co-planar sheet-like geometries (in both patch and ground plane). In order to shape the liquid metal in such requisite geometry, a serpentine pathway of posts with constant height has been designed (Figure 1-2 Bi) [59]. Following the Young-Laplace equation that governs the minimal pressure to induce the flow, a careful design in the spacing between adjacent posts in the array can guide the liquid metal to flow in the desired serpentine pathway. An appropriate height of the posts can also prevent the channel collapse. Taken together with the fact that a thin oxide skin spontaneously and rapidly forms on the surface of the liquid metal, the idea of periodic posts also allows the creation of microelectrodes of liquid metals to have direct contact with the fluid in the adjacent microfluidic channels for many microfluidic applications such as electrophoresis (Figure 1-2 Bii) [61].

An alternative to the use of periodic posts, a meshed structure is also explored to shape the plane geometry [58, 62]. The resonance frequency of the resulting stretchable antenna decreases with stretching up to 15% before mechanical failure due to the mechanical mismatch. Due to the shift of resonance frequency of the stretchable antenna under stretching, it presents a mismatch in the resonance frequency to the receiving horn antenna, consequently leading to the decrease of the received power (or output voltage) by the horn antenna (Figure 1-2 C). This stretchable antenna based on a liquid metal mesh network can work as strain detectors in a wireless mode with very low power consumption. A mechanically flexible planar inverted cone antenna (PICA) has also
been demonstrated for ultra-wideband (UWB) applications [60]. The presented antenna has a radiation efficiency of over 70% in the range of 3–10 GHz (a return loss better than 10 dB within 3–11 GHz) and it also allows a tensile strain up to 40% along either x- or y-direction.

The stretchability of these demonstrated systems is significantly less than the maximum strain that the elastomer can sustain. The reason is possibly arising from the fact that the uniform stretching in a single type of elastomer would lead to breaking at weak points: (1) inlets and outlets of the microfluidic channels, and (2) interfaces between the elastic and rigid parts such as the external electrical connectors of the devices. To address this challenge, a hybrid design integrates silicone polymers with different stiffness to build the microfluidic channel, where a stiff elastomer such as PDMS is used in the regions with weak points and a softer elastomer such as Ecoflex is used to enhance the stretchability in the other regions (Figure 1-3 A) [56]. The demonstrated half-wave dipole antenna is highly stretchable (i.e., functional over a tensile strain of 120%) with a wide tuning range that follows an inversely proportional relationship between the resonance frequency ($f$ in MHz) and the length of the antenna ($l$ in m): $f = \frac{143}{(l \sqrt{\varepsilon_{\text{eff}}})}$ where $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the medium. The radiation efficiency of the antenna is over 95% even at a tensile strain of 120% and a reliability test also demonstrates negligible changes (i.e., within 1%) in the resonance frequency and radiation efficiency with the antenna being stretched 100 times for a tensile strain of 50%. Another technique to address the issue of a mechanical mismatch for improving the stretchability is to use the slot-aperture-coupled feeding technique, where the rigid feed line is separate from the stretchable patch [62].

While it is useful to have a wide tuning of the resonance frequency in the designed stretchable antenna, it is also highly desirable for the stretchable antennas to have unaltered resonance frequency upon stretching, which may open up opportunities for easy transmission of data or energy in bio-integrated electronics. Because the conductive element of the antenna is the fluidic liquid metal, the shape and mechanical properties of the antenna are defined by the elastomeric channels.
As the resonance frequency of a half-wave dipole antenna upon stretching primarily depends on the deformed length of the antenna, a rational design of the antenna would give the same deformed length as the initial length.

Figure 1-2. Stretchable microfluidic antennas filled with the liquid metal. (Ai) Schematic illustration of the molding and injection process to fabricate the liquid metal-based stretchable dipole antennas. (Aii) Demonstration of the deformability and self-healing capability. (Aiii) The measured resonance frequency of the dipole antenna with stretching. The experimental measurements show an approximately linear relationship.
Reproduced with permission from [57]; Copyright 2009, John Wiley and Sons. (Bi) Schematic illustration of the patch composed of serpentine microfluidic channels defined by an array of posts. (Bii) Separated by two parallel rows of PDMS posts, liquid metal microelectrodes are created to be in direct contact with the central fluidic channel for applications such as electrohydrodynamic mixing and dielectrophoresis. Reproduced with permission from [61]; Copyright 2011, Royal Society of Chemistry. (C) The stretchable patch antenna with the meshed ground plane and patch of the liquid metal (Ci) before and (Cii) after stretching. (Ciii) shows a wireless strain detector based on the stretchable patch antenna. The output voltage of a receiving horn antenna changes with the stretching state of the transmitting antenna because of the resonance frequency shift. Periodic stretching and releasing lead to a periodic change of the output voltage in the receiving antenna. Reproduced with permission from [58]; Copyright 2011, John Wiley and Sons.
Figure 1-3. Structural design of the microfluidic antenna filled with the liquid metal. (Ai) Schematic and optical image of the structural design used to improve the stretchability of the dipole antenna that is based on the liquid metal. (Aii) Resonance change as a function of a tensile strain. (Aiii) Comparison of the radiation efficiency of the antenna with (i.e., PDMS/Ecoflex) or without (i.e., all PDMS) structural engineering under various levels of tensile strain. Notably, failure of the “all-PDMS” structure occurs for a tensile strain of 20%. Reproduced with permission from [56]; Copyright 2010, John Wiley and Sons. (Bi) Optical images of the microfluidic dipole antenna filled with the liquid metal with two serpentine arms in an undeformed state, and being twisted, bent, and...
The resonance frequency change as a function of the tensile strain. Depending on the specific aspect ratio (i.e., the ratio of nominal height $h_{antenna}$ to width $W_{antenna}$), the microfluidic antenna can be designed to be strain-dependent or independent. Reproduced with permission from [63]; Copyright 2014, Royal Society of Chemistry.

One design shapes the dipole antenna in a serpentine geometry with a specific aspect ratio (i.e., the ratio of nominal height $h_{antenna}$ to width $W_{antenna}$) to provide an almost unaltered resonance frequency for a tensile strain up to 50% (Figure 1-3 B) [63]. Depending on the aspect ratio, the resonance frequency can also increase or decrease in a tunable manner, but the design with an increasing resonance frequency requires a large aspect ratio in the antenna that is associated with a weak electrical signal for the measurement. The almost unaltered resonance frequency with the tensile strain is currently limited to the stretching in one direction; thus, it is desirable to have a design for omnidirectional unaltered resonance frequency.

1.4 Composite Elastomer Embedding Conductive Fillers

Although the relationship between the antenna performance and the conductivity especially during stretching for a stretchable antenna is not explicitly studied, it is believed that a high conductivity during stretching is of critical importance. A significant reduction in conductivity is commonly observed in polymer composites loaded with conductive fillers under tensile strain [64]. The phenomenon (i.e., piezoresistive effect) is a result of filler displacement or rotation within the matrix. The resistive response to the strain of composites determines their practical applications. Composites with a large piezoresistance have been widely studied in strain sensing [65-68]. Analytical models of the piezoresistance of polymer composites with conductive fillers such as carbon black [69, 70], CNTs [28, 71], and metal spheres [72] indicate that the conductivity $\sigma_{\text{stretched}}$ upon stretching is related to its initial conductivity $\sigma_{\text{initial}}$ as:

\[ \sigma_{\text{stretched}} = \sigma_{\text{initial}} \]
\[
\sigma_{\text{stretched}} \approx \sigma_{\text{initial}} \exp \left[ \frac{4\pi \sqrt{2m\phi}}{h} (s_{\text{initial}} - s_{\text{stretched}}) \right],
\]

where \( m \) is the mass of an electron, \( \phi \) is the height of the tunneling potential barrier, \( h \) is Planck’s constant, and \( s_{\text{initial}} \) (or \( s_{\text{stretched}} \)) are the average interparticle distance between fillers before (or after) stretching. In order to maintain a high conductivity during stretching, it is highly desirable to reduce the tunneling potential barrier \( \phi \) or to minimize the interparticle distance \( s_{\text{stretched}} \) during stretching. The strategy toward the former could include removal of the insulating lubricant on the surface of the fillers. The desired properties toward the latter could be enabled by the careful design of the shape and morphology of the fillers such as a high aspect ratio. Mixing silver nanoparticles with PDMS shows a relatively high conductivity of 1000 S/cm and the value is observed to increase slightly upon a tensile strain of 30% [73]. Though a high silver volume fraction in the composite yields a high conductivity and a stable conductivity change over a tensile strain, its high viscosity also makes it difficult to print. The dipole antenna prepared by a standard stencil printing of the Ag-PDMS composite is demonstrated to have a low loss and long-distance communication capability in the on-body scenario. When compared with nanoparticles, the nanowires with a high aspect ratio show more stable performance in the conductivity over a tensile strain. For the highly aligned fillers, the high conductivity is only maintained for stretching along the aligned direction [74, 75]. Although randomly dispersed 1D fillers can provide better omnidirectionally high conductivity under a small tensile strain, they begin to align along the stretching direction and lose the conductive path in the other two directions, resulting in a decrease in the overall conductivity [76].

Silver nanowires (AgNWs) are a class of representative 1D fillers used in many stretchable electronic devices. AgNWs synthesized via a copper (II) chloride (CuCl\(_2\))-mediated polyol process is first deposited and etched into a patterned geometry. Casting and curing of a PDMS layer result
in a composite layer with AgNW on the top surface of PDMS. The patch and the ground plane prepared with the same process are then bonded to form a patch antenna [77]. When subject to a pressure applied on the top surface of the patch antenna, its resonant frequency decreases from 2.37 GHz to 2.27 GHz as the force (or pressure) increases from 0 to 10 N. A transmission line fabricated with the same process also only shows a slight change in the S-parameters upon bending over a bending radius of 10 mm. Although a direct tensile test is not conducted in this study, the resulting antenna is expected to deform for an applied tensile strain. In a similar study, casting and curing a liquid PDMS on top of the screen printed AgNWs conductive film result in the conductive AgNW film embedded as a surface layer in the PDMS substrate (Figure 1-4 A). Bonding the patch layer with a ground plane layer yields a 3-GHz microstrip patch antenna and a 6-GHz 2-element patch array that are mechanically tunable and reversibly deformable. The resonance frequency approximately shows a linear change with the applied tensile strain, so it could be envisioned for applications such as wireless strain sensing [78].

Beside nanowires, a conductive composite mat of silver nanoparticles and rubber fibers has been exploited to achieve a high conductivity during stretching because of the formation of the conductive silver network in the rubber fiber (Figure 1-4 B) [79]. Reducing the silver nanoparticle precursor absorbed in the electrospun poly (styrene-block-butadiene-block-styrene) (SBS) rubber fibers yields a mat with percolated silver nanoparticles inside the fiber. The fiber mat shows a high bulk conductivity even at large deformations and the conductivity decreases from ~5000 S/cm from the initial state to ~2200 S/cm at a tensile strain of 100%. Although the upper surface of the fiber mat from electrospinning on a silicon wafer is porous with pores of a few micrometers, its surface roughness can be greatly reduced by sandwiching the fiber mat between two silicon wafers followed by thermal annealing at 90 °C for a short time of 10 min. With a slight decrease from 150 μm to 120 μm in the thickness, the average surface roughness of 134 nm is obtained, allowing direct printing of the precursor solution through conventional techniques such as nozzle printing or inkjet
printing. Direct chemical reduction of the precursor solution results in electrical conduction with applications in the stretchable radiofrequency antenna, strain sensors, and other circuit components. The stretchability of the prepared half-wave dipole antenna allows tunability over a wide range of frequencies with a similar level of high-quality radiation efficiency.

In another effort to achieve high conductivity in the highly deformed state, the iodine treated silver flake is mixed with the silicone mixture matrix in a weight ratio of 80:20 to result in a silicone-based electrically conductive adhesive (silo-ECA) (Figure 1-4 C) [80]. Two surface modification methods have been used to form a strong conductive network: (1) reduction of the coordinated silver salt in the commercial silver flakes by using long-chain hydride-terminated polydimethylsiloxane (H-PDMS) and (2) exposure of fresh silver at the flake surface by iodination treatment. After the modification, the electrically insulating lubricant layer on silver flakes is removed and the silver flake develops into a spike-like shape due to the chemical reduction. The combined surface modification method helps reduce the tunneling potential barrier \( \Phi \) between the silver flakes and the inter-tunneling distance to yield a high conductivity before and after stretching (e.g., the initial conductivity of \( 1.51 \times 10^4 \) S/cm and a conductivity above \( 1.11 \times 10^3 \) S/cm upon a tensile strain of 240%). In addition, the shear force during the printing process allows the silver flakes to stack parallel to one another, which ensures that the distance between flakes is almost unaltered during stretching in a certain range. By using the stretchable silo-ECA as the conductive pattern and the pure silicone polymer as the substrate, stretchable circuits can be fabricated through the soft-lithography process or stencil printing. The resulting quarter-wavelength bowtie antenna shows a tunable resonant frequency with high-quality radiation efficiency and almost a linear dependence on the tensile strain. It should be noted that the antenna could be stretched over the demonstrated 60%, but the weak connection with the SMA connector likely causes the mismatch for damage. It should also be noted that besides the examples discussed above, the recent studies on the highly stretchable, conductive composite elastomers also show great potential in stretchable
antennas. The representative examples include an all-polymer stretchable conductor by doping ionic additive–assisted enhancers in PEDOT:PSS [81], printable elastic conductors formed in situ by mixing Ag nanoparticles with micrometer-sized Ag flakes [82], the biocompatible Ag-Au core-sheath nanowire [83], among others.
Figure 1-4. Stretchable antenna based on composite elastomers embedding conductive fillers. 

(Ai) The fabrication process of the stretchable patch antenna with the AgNW-PDMS composite. AgNW: silver nanowire. (Aii) The stretchable patch antenna in the undeformed and various deformed states such as bending and twisting. (Aiii) The measured and simulated resonance frequency of the antenna as a function of the tensile strain. Upon stretching and releasing, no obvious hysteresis is observed. Reproduced with permission from [78]; Copyright 2014, American
Chemical Society. (Bi) Schematic illustration of electrospun poly (styrene-block-butadiene-block-styrene) (SBS) rubber fibers with interconnected silver particles inside the fibers and on the surface to act as conductive pathways. The composite of the SBS and silver particle is highly conductive even at a tensile strain of 100%. SEM images of the composite at a tensile strain of (Bii) 5% and (Biii) 20%. Even with silver debris at a tensile strain of 20%, only a slight decrease in the conductivity is observed. (Biv) Change in the resonance frequency of a dipole antenna that uses the conductive composite as the two radiation arms (inset). Reproduced with permission from [79]; Copyright 2012, Nature Publishing Group. (Ci) Schematic illustration of a conductive composite consisting of silicone polymer and silver flakes. (Cii) SEM images and schematic illustrations that show the roughening process of the silver flakes by using long-chain hydride-terminated polydimethylsiloxane (H-PDMS), leading to a decrease in the interparticle distance between neighboring flakes. (Ciii) When compared with various previous studies, the silicone-based electrically conductive adhesive (silo-ECA) only shows a slight decrease in the conductivity for a tensile strain of 100%. (Civ) Change in the resonance frequency of a bow-tie antenna that uses the conductive composite as radiation components as a function of tensile strain. Reproduced with permission from [80]; Copyright 2015, John Wiley and Sons.

1.5 Stretchable Structures from Conventional Metals

By avoiding localized plastic deformation such as local thinning or forming shear bands [84], thin films of gold evaporated onto elastomeric membranes of polydimethylsiloxane (PDMS) allow the system to be stretched over tens of percent that far beyond the fracture strain of a freestanding gold film [85-88]. Applying the concept of stretchable metals as conductive elements in the design of antennas yields stretchable antennas with conventional metals. The stretchable planar inverted-F antenna (PIFA) can operate under a tensile strain up to 10% with a reversible performance when relaxed to 0%, but it shows a relatively poor efficiency with an extra 10 dB loss compared with a standard one, likely due to the thin geometry and low conductivity in the evaporated Au film [89]. Therefore, ink-jet printing has been used to produce thick (200–400 nm) silver films on a patterned PDMS substrate for a dipole antenna. Comparing with a standard dipole antenna, the stretchable dipole antenna shows an extra loss of 1.7 dB and its performance is not reversible.

As stretchable structures have been widely exploited to enable stretchable properties to conventional brittle materials toward stretchable electronics, it occurs naturally to apply such concepts in the design of the stretchable antenna, where conventional metals can be used as
conductive elements. As briefly discussed in the stretchable textile antenna, antennas with simple geometries (e.g., monopole and dipole antennas) can be easily designed into a stretchable form by replacing the straight lines with serpentine lines. As an alternative to the stretchable material, meandered structures provide stretchable properties to enable a stretchable antenna. A meandered dipole with a parasitic arm made of copper on the silicone and polyurethane (TPU) substrate has demonstrated a wideband match in stretched conditions, with a reflection coefficient lower than $-10$ dB up to stretching of 20% at the designed 2.4 GHz working range [90]. On-body measurement with physical phantoms also shows the practical values of the reflection coefficient and radiation efficiency when there is a separation of a few millimeters between the antenna and the human body. Photo-lithographic processes also allow the creation of patterned copper foils for fractal antennas and a demonstrated example shows a Vicsek curve loop antenna with a fundamental mode near 1.7 GHz and an impedance of 42 ohms (Figure 1-5 A) [91]. When mounted on stretchable substrates, the fractal antenna offers not only a compact nature (total length of $\lambda_0/6$ at resonance with $\lambda_0$ of the free space length) but also stretchable characteristics (almost unchanged resonance frequency and radiation patterns upon a tensile strain of 30%).

When the geometry becomes complicated, strategies have been explored to convert a rigid metal section with a curvilinear layout to a mesh with rectangular and trapezoidal unit cells, and then to a serpentine mesh layout [13]. Implementing the strategy to a microstrip transmission line shows the change of effective electrical lengths in the design with different arc angles in the serpentine mesh. The attenuation constant and phase constant are also shown to depend on the arc angle. Based on serpentine mesh layouts, a natural tradeoff between the stretching mechanics and microwave performance of the system is observed. Changes of effective wavelength and power attenuation in microstrip transmission lines with a serpentine layout are also observed in other metallic structures. In the case of a far-field dipole antenna, these two changes correspond to the changes in resonance frequency and antenna gain (or radiation efficiency), respectively (Figure 1-
A complicated geometry such as a midfield phased surface with concentric metal rings has also been demonstrated to focus microwave energy for powering implanted biomedical devices (e.g., light-emitting microdevice) inside the human body (through water that mimics biological tissue). Because a thicker trace is used in the midfield phased surface, the stretchability is limited to 10% and the efficiency only decreases by 2.2 dB under the maximal stretching. A similar serpentine geometry but with a freestanding design has also been applied to a copper/polymer thin film bilayer for a monopole antenna [92]. Even after a tensile strain of up to 30% and for 2000 cycles, the antenna still retains the essential properties, including resonance frequency and bandwidth, gain, radiation pattern, and directionality. In addition, the transmitter board integrated with the stretchable antenna has shown the capability for the far-field communication. With the stretchable antenna mounted on a stretchable fabric and worn by a human subject, the RF power of 1 dBm (1.25 mW) from the transmitter reduces to −100 dBm over a distance of 80 m in an open area on the university campus [92]. When combining the optogenetics with the stretchable antenna that harvests near or far-field RF power between adjacent serpentine traces [93-96], the integrated system achieves optogenetic modulation of the spinal cord and peripheral nervous system (Figure 1-5 C) [95]. This device would facilitate the long-period experimental study on neuronal circuitry.

The concept of deformable structure can also be used for the design of reconfigurable and deployable antennas [97-99]. For instance, the resonant frequency of the antenna can be tuned over a wide range of distinct and discrete frequencies with robotic growth (i.e., tip-extending) that is controlled by a closed-loop system [97]. The demonstrated examples include monopole, Yagi-Uda, and helical antennas. In a similar idea, rotating the top substrate mechanically reconfigures a dual-band antenna from a patch state (with an omnidirectional radiation pattern) to a monopole state (with a directional pattern) (Figure 1-5 D) [100]. Combining such a concept with smart materials such as those responding to external triggers could further enhance the performance of the system.
those that are capable of delivering microwave signals (beyond the previously reported direct current or low-frequency signals). A twisted-pair transmission line integrated into thin-film serpentine microstructure minimizes electromagnetic interference to allow its use in bioelectronics (Figure 1-5 E) [101]. The twisted-pair structures also demonstrate their use as passive components such as stretchable microwave low-pass filter and band-stop filter. From the measured $S_{11}$ curves, it can be concluded that stretching up to 35% does not lead to their performance degradation. With the potential use for high-speed digital circuits, this type of high-performance transmission lines could be integrated with active devices to provide high-speed wireless communication systems for remote monitoring of patients in the clinical applications.

Overall, the antenna based on the structural design on conventional metal has the advantage of high efficiency due to better conductivity. Also, it can be easily soldered with other electrical components and thus has more potential in practical applications. Previous research in this field is mostly focused on the design of dipole antennas because of the easy transformation, and not too much attention was paid to the patch antennas. Despite the demonstrated stretchability, the mechanical-sensitive radiation properties can only be used in strain sensing with the need for stable communication performance unaddressed. In this work, we address this challenge by two different ways, depending on the antenna type (the dipole or patch antenna). For the patch antenna, a 3D arched structure was introduced to the meshed serpentine patch to compensate for the frequency shift upon deformation, leading to a quite stable resonance frequency in a large stretching range. We proposed a wideband dipole antenna by adding a pair of parasitic arms to afford for the frequency detuning effect in the antenna with a single pair of arms. The stretchable wideband dipole antenna was able to harvest the RF energy with high efficiency even under deformations (stretching, bending and twisting) or being attached to a jacket for wearable applications.
Figure 1-5. Stretchable antennas that exploit stretchable structures of conventional metals.
(Ai) Return loss parameters of a fractal Vicsek curve loop antenna under different levels of tensile strain. The inset shows an optical image of an unstrained antenna fully bonded onto an elastomeric substrate. Scale bar, 4 mm. (Aii) Far-field profiles of the loop antenna only show a slight change in the radiation patterns at 30% tensile strain. Reproduced with permission from [91]; Copyright 2014, Nature Publishing Group. (Bi) Stretchable dipole antenna by converting solid radiation parts to serpentine mesh layouts. (Bii) The corresponding reflection curve with an increasing tensile strain. (Biii) Transformation of a midfield phased surface from a solid structure to a meshed stretchable layout. (Biv) Demonstration of powering an LED with the stretchable midfield phased surface at different levels of tensile strain. Reproduced with permission from [13]; Copyright 2017, John Wiley and Sons. (Ci) Anatomy and location of the peripheral and epidural devices relative to the sciatic nerve. (Cii) Exploded view schematic illustrating the energy harvester component that includes the stretchable antenna, AC/DC converter, and an integrated LED toward wireless optogenetics. Reproduced with permission from [95]; Copyright 2015, Nature Publishing Group. (D) Photograph of fabricated antenna that can be mechanically reconfigured from a patch state to a monopole state. Reproduced from [100]; Copyright 2017, John Wiley and Sons. (Ei) Stretchable twisted-pair transmission line inspired by twisted-pair cables. (Eii) Scattering (S-) parameter of a stretchable low-pass filter (left) and band-stop filter (right) at a tensile strain of 0%, 20%, 25%, and 35%. The inset shows the corresponding optical image of the two filters. Reproduced with permission from [101]; Copyright 2016, John Wiley and Sons.
Chapter 2

Stretchable Wideband Dipole Antennas and Rectennas for Wireless Communication and RF Energy Harvesting

2.1 Introduction

Dipole antennas are widely used in wireless communication due to the omnidirectional radiation and easy fabrication process. Previous research has a great interest in designing flexible/stretchable dipole antennas as the communication module in the flexible/stretchable electronics. It is straightforward to replace the conventional metal with stretchable materials (such as liquid metals and conductive filler/elastomer composites) as radiation arms. Alternatively, it is also easy to enable the stretchability by structural engineering (i.e., replacing the straight arm with serpentine arm and using stretchable silicone polymers) which makes it a good start point for the desire of flexible/stretchable antennas. However, the resonance frequency shift upon mechanical deformations still restricts its application as the communication module in flexible electronics. We designed and fabricated a stretchable wideband dipole antenna by adding an additional pair of parasitic arms to address this issue. Due to the coupling effect, the two resonances from the driven and parasitic arm leads to the “dual-resonance” phenomenon and the consequent wideband characteristic.

Leveraging the recently developed laser-induced graphene (LIG)[102] with high conductivity, we designed and fabricated a stretchable wideband dipole antenna. As the conductivity of the LIG (~700 S/m) is not sufficient to minimize the loss for RF applications, we exploited the maskless coating of metallic nanomaterials such as silver (Ag) on the LIG followed by a photonic sintering process to significantly reduce its sheet resistance. Following the design,
stretchable wideband dipole antennas consisting of serpentine units for both main and parasitic arms were experimentally demonstrated. The deformation-dependent radiation properties (e.g., bandwidth and resonance) were extensively investigated. Next, connecting the stretchable wideband dipole antenna with a rectifying circuit resulted in a high-efficiency stretchable rectifying antenna (i.e., rectenna) to continuously harvest the ambient RF energy from various widely available RF sources (e.g., WI-FI, Bluetooth, 4G, and upcoming 5G). The direct current (DC) power continuously generated from ambient RF energy harvesting can be used by external loads[103, 104] or to charge energy storage devices (e.g., batteries and supercapacitors). By providing an always-on energy-harvesting solution for wearable electronics[105], this technology can help address the challenges in the intermittent energy harvesting from human activities (e.g., breathing and walking) through piezoelectric[106] or triboelectric[107] effect. The ambient RF energy harvesting could also be exploited for implantable electronics[108] to monitor real-time physiological conditions, deliver drugs[109] or medical treatment[110], promising the possible integration with the recent development of transient electronics[111]. As an added component into the clean energy portfolio for future energy supply, the ambient RF energy-harvesting solution could also contribute to integrated energy systems and enable self-powered systems and remote monitoring of the environment. Integrating the wireless transmission and energy harvesting modules with various LIG[112] sensors could also enable the all-LIG stretchable electronics to open up a new frontier for diagnostic monitoring and therapeutic options.

2.2 Stretchable Wideband Dipole Antennas for RF Energy Harvesting

Fabrication of stretchable metal antennas was achieved by selective metal surface coating on porous LIG patterns. In brief, a CO$_2$ laser (wavelength of 10.6 μm) in the raster mode was first used to transform commercially available polyimide (PI) thin films into conductive LIG patterns with a thickness of ~20 um in a programmable manner (Figure 2-1 A). Employing the same laser
in a vector (cut) mode cut through the outlines of the LIG pattern, creating a PI mask (i.e., self-mask) for selective metal surface coating. After spraying another layer of metallic ink such as Ag nanoparticle (Ag NP) ink, peeling off the PI self-mask left Ag only on the LIG patterns to form Ag/LIG/PI composite. Following exposure of a pulsed xenon light, the sintering of Ag NPs yielded highly conductive patterns on the Ecoflex substrate. The strong bonding between the PI and Ecoflex substrate was achieved by coating PI with a (3-Aminopropyl)triethoxysilane (APTES) and UV/ozone treatment of the interface. The remaining PI layer underneath the Ag/LIG pattern naturally served as a stiffener to help reduce the local strain in the conductive pattern upon mechanical deformations (e.g., stretching, bending, or twisting) because of strain isolation[113, 114].

The simple fabrication process with selective metal surface coating on LIG patterns eliminates the need for photolithographic processes to significantly reduce the fabrication complexity while retaining a reasonably good spatial resolution in the created patterns. In comparison to the metal patterning technique provided by a programmable cutting machine[115-117], a greatly improved spatial resolution with well-defined features and fewer defects in the pattern could be easily achieved. Consistent with the literature reports of the porous LIG[112, 118], the Raman spectrum exhibited three characteristic peaks, i.e., the D peak at ~1350 cm\(^{-1}\), the G peak at ~1580 cm\(^{-1}\), and the 2D peak at ~2700 cm\(^{-1}\) (Figure 2-1 B). The small intensity ratio (~0.5) of the D to G peak implies a relatively high quality of the 3D porous graphene. The ratio of the 2D to G peak of ca. 0.48 also confirmed the multi-layered structure of the 3D porous LIG[119].

The conductivity of 3D multi-layered porous LIG is already very high compared to the 3D graphene prepared from many other methods[113], which enables its use in various sensing applications. However, insufficient conductivity would still result in a high loss when used in RF applications such as antennas. Considering the excellent conductivity and solderability required for electromagnetic devices, the Ag NP ink was selected in this study. Applying the Ag NP ink in a 0.6 mm × 50 mm rectangular ribbon pattern reduced its sheet resistance from ~52 Ω/□ to ~1.9 Ω/□, helping reduce the radiation loss in the resulting stretchable dipole antennas. The selective surface coating of metal could be easily extended to electroplating of the other conductive metal materials (e.g., Cu or Au ink) or electroless plating such as nickel. Note that it is also possible to increase the spatial resolution of the LIG patterns using the UV laser [120] to a linewidth of 40 μm or a femtosecond laser to a linewidth of ~ 10 μm. Besides the stretchable dipole antennas, the other LIG based sensors can also be integrated into the same system during the fabrication process, which will be discussed in-depth in the later sections.
By using the simple PI self-mask, a reasonably good pattern accuracy was achieved. As the PI self-mask outlines from laser carving were designed to be slightly larger than that of the LIG pattern, the linewidth of the Ag/LIG/LIG composite uniformly increased from 400 to 410 µm by only 2.5%. After the coating of the Ag NP layer, the thickness of the conductive pattern increased from ~20 µm (in porous LIG) to ~30 µm (in Ag/LIG), as indicated by the scanning electron microscopy (SEM) images (Figure 2-1C). The coating of the conductive Ag layer formed excellent adhesion to the LIG layer as it filled in the porous LIG layer. By contrast, the silver layer is easily delaminated during the soldering process without the LIG layer. Mechanical tensile tests revealed the effective moduli of the PI, LIG/PI, and Ag/LIG/PI composites to be 2.1 GPa, 0.92 GPa, and 1.4 GPa, respectively. Considering the definition of the effective modulus in the composite[117] as $E_{eff} = \Sigma E_i h_i / \Sigma h_i$, where $E_i$ and $h_i$ are the Young’s modulus and thickness of each layer in the composite, the Young’s moduli of the LIG and Ag/LIG composite were calculated to be 0.13 GPa and 0.93 GPa. Electromechanical measurements of the conductive LIG/Ag patterns indicated that the resistance of the serpentine pattern was only increased by ~5.5% upon a tensile strain of 15% while the resistance of the straight line pattern increased by >200% even upon a tensile strain of 3%. The negligible change in the conductivity of LIG/Ag serpentine patterns under stretching ensured a low loss and a high efficiency when used in RF applications such as antennas.
Mechanical measurements of the Ecoflex and polydimethylsiloxane (PDMS, monomer: curing agent = 10:1) substrates also revealed their Young’s moduli to be 0.04 and 1.4 MPa, respectively.

Figure 2-1 Energy harvesting and wireless communication through stretchable wideband antennas in batteryless flexible electronics and the fabrication process of high-performance wideband dipole antennas based on laser-induced graphene (LIG) patterns with a surface metal coating. (A) Schematic illustration of the fabrication process to prepare a patterned composite metal/LIG film as a wideband dipole antenna for radiofrequency (RF) applications. (i) Thin polyimide (PI) film was first treated with (3-Aminopropyl)triethoxysilane (APTES) diluted by ethanol (2% v/v) and then laminated onto a UV/ozone treated Ecoflex substrate. The CO2 laser in a raster and then a vector mode was used to create and crave the desirable LIG patterns. After (ii) spray coating of a metallic ink layer such as silver nanoparticle (Ag NP), peeling off the excessive PI film with tweezers left the Ag NP ink only on the LIG pattern. (iii) Photonic sintering of Ag NP ink resulted in a conductive Ag conductive layer on the LIG pattern. Annealing the sample at 80 °C accelerated the bonding process between the PI and Ecoflex substrate to yield a completed sample. (B) Raman spectrum of the LIG pattern, exhibiting characteristic D, G, and 2D peaks. (C) Optical and SEM images of the LIG pattern on PI bonded to the Ecoflex substrate before and after the coating of the Ag layer. Scale bar in the microscopic images in the red and blue dashed box is 0.4 mm.
Because of the excellent electromechanical properties, the Ag/LIG serpentine patterns were utilized as radiation arms (or driven arms) of stretchable dipole antennas. Considering the coupling effect, placing a pair of parasitic arms next to the driven arms yielded a stretchable wideband dipole antenna (Figure 2-2), which would enable stable and robust communication of data and energy under various mechanical deformations. Both of the driven and parasitic arms were shaped into serpentine layouts composed of two different building blocks of circular arcs of 60°. In the proof-of-concept demonstration, the inner radii of arcs were chosen as 2.7 mm and 1.5 mm, respectively. With a line width of 0.4 mm for both arcs, the gap between the main and parasitic arms was determined to be 0.8 mm. As the bandwidth of the wideband dipole antenna resulted from the capacitive coupling between the driven and parasitic arms, the dependence of the bandwidth on the coupling effect was investigated. When separately used, each pair of arms (i.e., driven and parasitic) was associated with one resonance. The difference between the two resonant frequencies affected the coupling. In order to study such a coupling effect, the length of the lower long arm was fixed while the length of the upper short arms was reduced to result in another two different configurations (i.e., “Cut-I” and “Cut-II” as indicated by the position of the scissor in Figure 2-2 A). The apparent length of the short arms (i.e., the “Cut-0” configuration) of 25.7 mm decreased to 22.3 and 20.8 mm for the “Cut-I” and “Cut-II” configurations, respectively. The influence of feed location on the radiation properties of antennas was investigated by feeding either the long arms (i.e., “FL”) or short arms (i.e., “FS”). By connecting the pair of parasitic arms, the effect of optional connection on the radiation properties was further investigated. Detailed geometric parameters of stretchable dipole antennas with parasitic arms and their corresponding structures can be found in Figure 2-2 B and C.
Figure 2-2 Geometrical parameters of the dipole antenna with different configurations and the corresponding notation. (A) Geometric parameters in the design of stretchable wideband dipole antennas that consist of two pairs of arms (i.e., upper and lower) both with a width of w (0.4 mm) as radiation elements. Each pair of arms is built from one representative unit with two arcs of the same arc angle (i.e., θ) but different radii (i.e., r and R) as in between the two dotted lines. The pair of driven arms are displaced by a distance of d from the pair of parasitic arms. The geometric relationship gives $R - r = w + d$. The coordinate systems to measure the actual and apparent lengths of each arm are defined by the dashed blue and black lines (s and x coordinate systems), respectively. Additional arcs are applied at the end of five representative units in each
arm to tune the resonance frequency close to 2.4 GHz. As the length of the lower pair of arms is longer than that of the upper, the design with the feed applied to the upper (or lower) as driven arms is designated as Feed Short, FS (or Feed Long, FL). The optional connection on the pair of parasitic arms indicates two parasitic arms could either be connected or unconnected. The cut is also applied to the upper pair of arms at the locations indicated by the scissor to change the relative length in between driven and parasitic arms for investigating the coupling effect. The actual length of one upper arm is 45.1, 39.2, and 37.0 mm for the cut-0 (uncut), I, and II configurations, respectively. (B) Geometrical parameters of stretchable dipole antennas with parasitic arms. The long arm is fixed in all designs. The short arm has three different lengths: “Cut-0”, “Cut-I” and “Cut-II”. (C) A dipole antenna composed of straight arms for comparison.

In order to address the challenge of directly connecting the dipole antennas with a SubMiniature version A (SMA) connector, coaxial cables with 50 Ω characteristic impedance (CAB.011, Taoglas Limited Inc.) were split at the one end and soldered with dipole antennas by using a low temperature soldering paste for the easy manual soldering. Including this additional coaxial cable should not change the antenna characteristics such as the $S_{11}$ curve, resonant frequency, and corresponding radiation patterns[13]. The split coaxial cables at one end, however, introduced exposed wires, which may affect the measured radiation properties of antennas. The negligible effect of exposed wires on the antenna performance of microstrip patch antennas was confirmed by a direct comparison of the $S_{11}$ curves between the experimental measurements with (using coaxial cables) or without exposed wires (using SMA). The negligible effect of the exposed wire resulted from its physical location away from the radiation part of the patch. However, the exposed wire of coaxial cables increased the effective length of the radiation arm in dipole antennas, leading to a decrease (i.e., redshift) in the resonant frequency[121].

The resonant frequency decreases with the increasing length of radiation arms for dipole antennas with straight arms, which can be approximately expressed as $c/(2L\sqrt{\varepsilon_r})$, where $c$ is the speed of light in vacuum, $L$ is the half-length of dipole antennas, and $\varepsilon_r$ is the effective dielectric constant depending on surrounding materials. However, this expression does not hold true for dipole antennas with serpentine arms. Numerical simulation based on finite-difference time-domain method (FDTD) or finite element analysis served as a useful tool for the design of
stretchable dipole antennas. The radiation properties (e.g., resonant frequency and bandwidth) of stretchable dipole antennas without parasitic arms were first investigated. Dipole antennas consisting of a single pair of arms with different lengths were designed, fabricated, and measured (see the geometric parameters in Table 2-1). Compared to the dipole antenna with straight arms, the stretchable dipole antenna with serpentine arms of the same apparent length \( L_{\text{apparent}} = 47.2 \text{ mm} \) resonated at a lower frequency because of its longer actual length \( L_{\text{actual}} = 56.2 \text{ mm} \) (Figure 2-3). However, this serpentine dipole antenna still had a higher resonant frequency than that of the straight dipole antenna with a length of \( L_{\text{actual}} \), likely attributed to the geometric effect. As the same building block was used to construct the serpentine dipole antennas with different actual (or apparent) lengths, the resonant frequency of the serpentine dipole antenna increases from 2.21 GHz to 2.86 GHz as the actual length decreases from 56.2 mm to 43.6 mm (Figure 2-4). The same trend was also observed in the experimental measurements, though the values of the resonant frequency were measured to be lower than those of simulation because of the exposed wire in the experiment. When the exposed wire was considered in the simulation, an improved agreement in the resonant frequency was obtained between the simulation and experimental measurement. While including the exposed wire in the simulation yielded a better agreement, the simulation without the exposed wire of a small length still captured the trend and provided physical insights with a relatively good agreement.

Table 2-1. Radiation properties of the stretchable antenna with a single pair of serpentine arms having the same building block with different lengths. The fractional bandwidth (in the unit of \%) is also shown in the bracket.

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<tr>
<td><strong>Long</strong></td>
<td>47.2</td>
<td>56.2</td>
<td>2.16</td>
<td>2.20</td>
<td>0.22 (10.2)</td>
<td>0.23 (10.5)</td>
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<td></td>
<td>S11 (dB)</td>
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<tr>
<td>Short (Cut-0)</td>
<td>45.1</td>
<td>53.8</td>
<td>2.31</td>
<td>2.33</td>
<td>0.24 (10.4)</td>
<td>0.24 (10.3)</td>
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<tr>
<td>Cut-I</td>
<td>39.2</td>
<td>46.6</td>
<td>2.63</td>
<td>2.67</td>
<td>0.28 (10.6)</td>
<td>0.27 (10.1)</td>
</tr>
<tr>
<td>Cut-II</td>
<td>37.0</td>
<td>43.6</td>
<td>2.82</td>
<td>2.86</td>
<td>0.29 (10.3)</td>
<td>0.28 (9.8)</td>
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**Figure 2-3.** Simulated $S_{11}$ curves of the antenna with serpentine arms ("Long") or straight arms with a length of the apparent (39.2 mm) or actual (46.6 mm) length of the serpentine arms.

**Figure 2-4.** Simulated $S_{11}$ curves of dipole Stretchable antennas composed of a single pair of serpentine arms with different lengths. The actual length for the four serpentine dipole antennas is 47.2, 45.1, 39.2, and 37.0 mm, respectively.
Next, the influence of unconnected parasitic arms on the radiation properties of the serpentine dipole antennas was investigated, by using unconnected parasitic arms in the “Cut-I” or “Cut-II” configurations. The simulations indicated that two serpentine dipole antennas (“FL-Unconnected-I” and “FL-Unconnected-II”) resonated at 2.17 and 2.15 GHz (Figure 2-5), which is very close to that of stretchable dipole antennas without parasitic arms (2.21 GHz). Defining the bandwidth as the frequency range with $S_{11}$ values less than -10 dB (indicated by the dotted line), the bandwidths of two serpentine dipole antennas were measured to be 0.21 and 0.26 GHz. These values were close to that of the serpentine dipole antenna without parasitic arms (0.22 GHz). These results suggested that feeding the long arms with unconnected short arms as parasitic loading does not lead to much improvement in the bandwidth. However, changing the feed location from the long to short arms resulted in two serpentine dipole antennas (i.e., “FS-Unconnected-I” and “FS-Unconnected-II”) with increased bandwidth to 0.30 and 0.36 GHz, respectively. The corresponding fractional bandwidth, which is calculated by bandwidth over resonance, also increases to 12.1 and 14.1, respectively, compared with 10 % for the dipole antenna without parasitic arms. As can be seen from the simulated electric field and surface current distribution (Figure 2-6), the parasitic arms in the “FS-Unconnected-I” antenna demonstrated a larger induced electric field and a higher peak surface current ($4.0 \times 10^2$ A/m) than those in the “FL-Unconnected-
I” antenna (peak surface current of $3.0 \times 10^2$ A/m), implying a stronger coupling effect.

**Figure 2-5.** $S_{11}$ of stretchable dipole antennas with unconnected parasitic arms. $S_{11}$ curves of dipole antennas with “Cut-I” (A) or “Cut-II” (B) as the short arm. Feed location was chosen at either the long (FL) or short (FS) arms. The influence of exposed wires of coaxial cable on $S_{11}$ curves was considered in the simulation of “Cut-I”. The bandwidth is defined at the $S_{11}$ value lower than -10 dB.

**Figure 2-6.** Simulated electric field (E_field) and surface current (J_surf) distribution of stretchable dipole antennas with unconnected parasitic arms. Left (A) and right (B) panel correspond to dipole antennas with the “FL-Unconnected-I” and “FS-Unconnected-I” configuration, respectively. In the surface current distribution, both the color and size of arrows indicate the magnitude of surface current. The current flow is indicated by the arrow direction.

In contrast to the dipole antennas with unconnected parasitic arms or even without parasitic arms, the dipole antennas with connected parasitic arms exhibited a strong coupling effect with a clear “double-peak” characteristic in the $S_{11}$ curve, consistent with the literature reports[122-124].
As the indicators of the coupling effect[125], the peak and inflection points were observed in the real and imaginary parts of the impedance of the “FS-Connected-I” antenna in the simulation (see the arrows in Figure 2-7). The experimental measurements also demonstrated two resonances at 1.91 and 2.25 GHz for the “FS-Connected-I” antenna (Figure 2-8 A), which was validated by the simulation considering the exposed wire (2.06 and 2.29 GHz). Because of the capacitive coupling between the driven and parasitic arms, these two resonance states were slightly different from the original resonance of the two separately used dipole antennas (i.e., with a single pair of arms in the “Long” and “Cut-I” configurations). The simulated electric field and surface current distribution also revealed the resonance characteristic at the two frequencies (Figure 2-9). The parasitic arm was indirectly excited due to the coupling effect with a large peak electric field ($1.05 \times 10^5$ V/m) and surface current ($5.6 \times 10^2$ A/m) at its resonance state of 2.06 GHz. At the resonance state of the driven arms (i.e., 2.29 GHz), the electric field in the parasitic arm was observed to be much smaller with no obvious current flow, indicating excitation only in the driven arms. Compared to the “FS-Unconnected-I” antenna, the stronger coupling effect in the “FS-Connected-I” antenna led to a much larger fractional bandwidth (~ 26 %) and a more obvious shift of the $S_{11}$ curve.

![Image](image.png)

**Figure 2-7.** Real (solid) and imaginary (dashed) part of the simulated impedance of dipole antennas with a single pair of short (“Cut-0”) arms (black curve), the “FS-Connected-I” (red curve), or “FS-Unconnected-I” (blue curve) configuration.
Figure 2-8. Design of the stretchable wideband antenna and its mechanical-electromagnetic properties. (A) Influence of the relative length difference between driven and parasitic arms on the S11 curve of the antenna. The apparent length of driven arms (L_{app}) varies (i.e., 37.0, 39.2, and 45.1 mm), whereas the parasitic arms are fixed at a length of 47.2 mm. Bandwidth is defined as the frequency range with S11 values lower than -10 dB (corresponding to a standing wave ratio of ~2), as indicated by the dotted lines. (B) Influence of the uniform gap between the driven and parasitic arms as it reduces from 0.8 to 0.6 mm (while fixing the inner radius at 1.2 mm and changing the outer radius from 2.7 to 2.5 mm). (C) Measured S_{11} curves of the stretchable wideband antenna under a tensile strain up to 15%. The two arrows indicate the two resonance states. (D) Measured and simulated bandwidth of the stretchable antenna with connected or unconnected parasitic arms and without parasitic arms.
Figure 2.9. Simulated electric field (E_field) and surface current (J_surf) distribution of the “FS-Connected-I” (stretchable wideband) antenna at resonance. (A) and (B) panels correspond to dipole antennas with the “FS-Connected-I” configuration at two resonance frequency 2.06 and 2.29 GHz, respectively. Both the size and color of arrows in the surface current distribution indicates the magnitude of the current flow.

As the coupling of two resonance states in the “double-peak” characteristic induced the large bandwidth, changing the relative lengths of driven and parasitic arms represented an easy way to tune the bandwidth. Compared to the “FS-Connected-0” antenna with a narrow bandwidth because of two merged resonance states, the “FS-Connected-II” antenna with reduced length in the
driven arm exhibited a clear “double-peak” characteristic (Figure 2-8 A). The bandwidth of the antenna, however, does not monotonically increase with the relative length difference between driven and parasitic arms. In fact, the degraded impedance matching resulted in significantly increased reflection loss in the “FS-Connected-II” antenna that did not even have a bandwidth because its entire $S_{11}$ curve was above -10 dB. The “FS-Connected-I” antenna was associated with the largest bandwidth because of the split of two resonance states and good overall impedance matching to 50 Ω ports.

Besides the relative lengths of driven and parasitic arms, the capacitive coupling also depends on the spacing, $d$, between the two pairs of arms. The simulation of the capacitive-coupled dipole antenna with straight arms demonstrated a weaker coupling effect and ultimately the disappearance of the double-peak characteristic as the spacing increased. Although the spacing in the capacitive-coupled dipole antenna with straight arms can be easily controlled, it is challenging to only change this spacing without changing the other geometrical parameters in the stretchable wideband dipole antennas. Simply bringing the driven arms closer to the parasitic arms would yield a non-uniform spacing between the two. In this case, even though the coupling effect still existed, the two resonances tended to merge as the two pairs of radiation arms were brought closer. While reducing the radius of outer arcs ($R$) leads to a uniform decrease in the spacing, the length in the driven arms is also reduced. For instance, uniformly reducing the space from 0.8 to 0.6 mm led to a slight shift in the frequency to the higher value in the $S_{11}$ (Figure 2-8 B). The shift of the lower resonant frequency is directly related to the shortening of the long (parasitic) arm. Even though the length of the short (parasitic) arm remains unchanged, the coupling effect ultimately leads to the shift of the higher resonant frequency. Other than the shift in the frequency, the resulted bandwidth only decreased slightly from 0.45 GHz to 0.42 GHz by 6.7%. The negligible change in the bandwidth implies the possibility to shrink the size of stretchable dipole antennas.
The change in the conductivity could also tune the radiation performance of the antennas. The simulated $S_{11}$ curves indicated that the bandwidth increased from 0.30 to 0.61 GHz as the conductivity of Ag/LIG patterns decreased from $1.3 \times 10^7$ to $1.3 \times 10^5$ S/m. While the large bandwidth of the low conductive antennas was desirable, their radiation efficiency and total efficiency (defined as a product of radiation efficiency and reflection efficiency) are compromised due to the ohmic loss. The radiation efficiency rapidly decreased from 92% down to 61% at 2.39 GHz as the conductivity decreased from $1.3 \times 10^7$ to $1.3 \times 10^5$ S/m. Considering the reflection efficiency of 88% in the antenna, the total efficiency of the low conductive antenna (with a conductivity of $1.3 \times 10^5$ S/m) was only 54%. The conductivity of the Ag/LIG pattern was measured to be $\sim 1.3 \times 10^6$ S/m with a variation of 10%. Because of the excellent conductivity, the radiation efficiency of 81% was considerably higher than the previously reported values (e.g., 70% for flexible textile antennas[126] or 70 - 80% for liquid metal antennas[127, 128]). Although there were location- or sample-dependent variations in the measured conductivity of radiation elements in the antenna, the same conductivity value was used for the Ag/LIG patterns in the simulation for simplicity, partially helping explain the difference between the simulation and measurement. Besides the conductivity variation, the varying thickness in the Ecoflex substrate may also lead to the deviation of $S_{11}$ curves for determining resonant frequency and bandwidth.

The radiation performance of the stretchable dipole antenna upon tensile strain was evaluated by using a custom-built stretcher. When a uniform substrate layer was used, stretching frequently led to the damage at the feed location because of the localized high strain. Methods to address this challenge include the strain isolation that explores the substrate or encapsulation with location-dependent stiffness such as a stiff material in the feed location and soft material in the other places[56]. In a representative demonstration, the soldered feed location was encapsulated by a thin PDMS layer with Young’s modulus of 1.4 MPa, whereas the soft Ecoflex encapsulation with Young’s modulus of 0.05 MPa in the other regions ensures the large stretchability of the dipole
antenna (Figure 2-10 A). Strain at the feed location was negligibly small (i.e., close to 0%), confirming the effectiveness of this strain-isolation design. Although the strain in Ecoflex reached 37.2% upon a tensile strain of 15%, the maximal principal strain was only ~ 3.14% over ¼ cross-sectional area in the Ag/LIG layer, by only considering in-plane bending of the serpentine units (Figure 2-10 B). Consideration of the out-of-plane buckling with bending/twisting in the serpentine units further reduced the local strain to 2.02% in the Ag/LIG layer (Figure 2-10 C). After introducing the pair of parasitic arms, the maximal strain in the Ag/LIG patterns was almost unchanged (3.02% for unconnected or 3.07% for connected) for an applied tensile strain of 15%. However, the strain in Ecoflex increased to 102% for unconnected (or 98.5% for connected) because of the additional constraint from the parasitic arms.

Figure 2-10. (A) Optical image of the “Long” antenna under 15% stretching. The corresponding simulated strain distribution of the Ecoflex substrate and Ag/LIG layer (B) without or (C) with consideration of the out-of-plane buckling in the Ag/LIG layer.
Upon stretching, the serpentine arms unfolded to increase the apparent length of the antenna along the direction of the tensile strain, leading to a decrease in frequency (Figure 2-8 C), consistent with the literature reports[129]. The frequency shift was more apparent in the stretchable dipole antennas with unconnected parasitic arms (e.g., 0.08 GHz) than that without (0.05 GHz) for an applied tensile strain of 15%. Interestingly, the frequency shift for the “FS-Connected- I” was only ~ 0.01 GHz. In addition to the frequency shift, the simulated bandwidth was also observed to decrease as the applied tensile strain increased, which was validated by the experimental measurements (Figure 2-8 D). For all these three stretchable antennas (“FS”, “FS-Unconnected- I” and “FS-Connected- I”), the measured bandwidth in the stretchable dipole antenna with connected parasitic arms decreased by 0.02 GHz for an applied tensile strain of 15%. The slight difference in resonance frequency and bandwidth between the measurement and simulation with exposed wires could attribute to the variations in the substrate thickness and conductivity of the radiation elements. Nevertheless, a reasonably good agreement was still observed, which captured the important trends. Because of the negligible influence on the $S_{11}$ curves from the out-of-plane buckling, it is not taken into consideration in the following simulation analysis for computational efficiency. Considering the frequency shift and the decrease of the bandwidth with the applied tensile strain, the overlapping bandwidth over the range of the applied tensile strain (i.e., the operating bandwidth of stretchable antennas (defined as the frequency range with the $S_{11}$ value always less than -10 dB under 0 - 15% stretching), the shaded areas in Figure 2-8 C) became smaller than the bandwidth without stretching. Compared to the operating bandwidth of 0.14 GHz in the “Single-Long” stretchable antenna for an applied tensile strain of 15%, the stretchable dipole antenna with unconnected parasitic arms exhibited a wider operating band (0.23 GHz). Owing to the small changes in the frequency shift and bandwidth upon stretching, the operating bandwidth of the stretchable dipole antenna with the connected parasitic arms further demonstrated a significant increase in the operating bandwidth (i.e., 0.47 GHz). Additionally, the “double-peak”
(or “dual-resonance”) characteristic in $S_{11}$ curves was not affected by the stretching, indicating a robust radiation performance against stretching. Although the resistance of the Ag/LIG serpentine patterns increased by 5% with the applied tensile strain of 15%, it only led to a change of less than 1% in the resonant frequency and bandwidth. Therefore, the structural deformation (i.e., unfolding of the serpentes) was believed to be the main driving factor. To further investigate the deformation-dependent radiation, we simulated and compared the radiation patterns of the stretchable dipole antennas with and without parasitic arms at resonance. The introduction of the serpentine design was first shown to have a negligible change to the omnidirectional radiation pattern of dipole antennas even upon stretching (see the “Single-Long” antenna in Figure 2-11). Including an additional pair of connected parasitic arms also exhibited a negligibly small change the radiation pattern even upon stretching, highlighting a stable performance in this stretchable wideband dipole antenna.

**Figure 2-11.** Simulated radiation patterns of the (A) “Long” or (B) “FS-Connected-I” (stretchable wideband) antenna under 0 and 15% stretching.

Besides stretching, the robust performance of the stretchable wideband dipole antenna was also confirmed against the other deformation modes such as bending and twisting (Figure 2-12 A). The “double-peak” characteristic in $S_{11}$ curves for the stretchable wideband dipole antenna (i.e., “FS-Connected-I”) was well maintained even with large bending and twisting deformations.
(Figure 2-12 B). Compared to stretching, bending and twisting resulted in little change in the lengths of driven and parasitic arms and the spacing between them. The nearly unaffected coupling between driven and parasitic arms led to a negligibly small change in the $S_{11}$ curve. Owing due to the high dielectric constant and loss of human tissues, directly attaching the stretchable wideband dipole antenna on the human wrist resulted in the disappearance of the “double-peak” characteristic in the measures and simulated $S_{11}$ curve (Figure 2-12 C). However, the wideband and “double-peak” characteristic were gradually recovered as the distance between the antenna and human wrist increased (Figure 2-12 D). Because of the reduced dielectric constant and loss in the surrounding environment introduced by the air gap, the resonant frequency also shifted to a larger value from 2.20 to 2.30 GHz as the distance increased from 1 to 5 mm. The frequency shift of the stretchable dipole antenna with connected parasitic arms was much smaller than that without parasitic arms (i.e., from 2.00 to 2.25 GHz in the “Single-Long” antenna), which also indicated a more robust performance against the dielectric change of the environment or misposition. The use of the additional parasitic arm also helped reduce the specific absorption rate (SAR) when the stretchable wideband dipole antenna was used in wearable applications. The input power to antennas was set as 0.1 W and the corresponding SAR value (averaged over 10 g tissue) at the resonance for the “Single-Ling” and “FS-Connected-Ⅰ” antenna was shown in (Figure 2-13 A and B). The maximum SAR value of the stretchable dipole antenna only slightly reduced from 2.08 to 1.98 W/kg, which was just below the European safety limit of 2 W/kg, as the distance increased from 1 to 5 mm. In contrast, the stretchable dipole antenna with connected parasitic arms exhibited a decrease in the maximum SAR from 1.59 to 1.35 W/kg.
Figure 2-12. Characterization of the stretchable wideband antenna under large deformations or attached to human bodies. (A) Optical images of the stretchable wideband dipole antenna upon deformation (i.e., stretching, bending, and twisting). (B) Measured $S_{11}$ curves of the stretchable dipole antenna upon bending or twisting. (C) Measured and simulated $S_{11}$ curve of the stretchable dipole antenna on human wrists. Inset shows the optical image of the antenna on human wrists. When attached to human bodies, the “double-peak” characteristic of the stretchable dipole antenna disappears due to a high dielectric constant of human bodies. (D) Simulated $S_{11}$ curves of the stretchable wideband antenna attached above human wrists at various distances from 1 to 5 mm. The double resonance gradually recovers at a distance of 4 mm.

Figure 2-13. Simulated specific absorption rate (SAR) of human bodies at the resonance frequency of the (A) “Long” (without parasitic arms) and (B) “FS-Connected-I” (with parasitic arms) antennas.
when attached above the wrist with different distance (from 0 to 5 mm). The input power is set as 0.1 W and SAR is averaged over 10g of tissue.

The energy harvesting performance of rectennas based on the proposed “FS-Connected-I” Connecting the stretchable wideband dipole antenna with a rectifying circuit yield a stretchable rectenna (Figure 2-14). The Schottky diode SMS7630 (Skyworks Solutions Inc.) was configured in a full-wave Greinacher rectifying circuit with a two-branch impedance matching circuit (inset in Figure 2-14 A) for improved sensitivity and efficiency over a broad frequency range (1.75 to 2.45 GHz)[103]. Using a microwave oven as a convenient radiation source, the bias voltage output $V_{\text{out}}$ over a load with a resistance of $R=15\, \text{k}\Omega$ was measured by a digital multimeter. The output power of the harvested energy from the stretchable rectenna calculated by $P_{\text{out}} = \frac{V_{\text{out}}^2}{R}$ was measured at locations with an increasing distance from the radiation source. As measured by a portable spectrum analyzer, the input power from the microwave oven radiation decreased with the increasing of distance, leading to a decrease in the output power from the stretchable rectenna (Figure 2-14 B). Though the Schottky diodes only require a low biasing voltage for a weak input signal (forward bias voltage: 60–120 mV @ 0.1 mA for SMS7630), their RF-DC conversion efficiency is significantly reduced for W operation to become around 0.1% [130]. The reduced RF-DC conversion efficiency of the Schottky diode with the decreasing input power mainly accounted for the decrease in the effective efficiency that was calculated as the ratio of the output power from the stretchable rectenna to the peak input power (Figure 2-14 B). Considering the fact that the efficiency of the rectenna consists of RF-DC conversion efficiency, the efficiency of the antenna, and input power, it is indeed impressive to achieve an effective efficiency of ~ 1.0% at a peak input power of 1 μW. This effective efficiency of ~ 1.0% is significantly larger than the theoretical limit of the RF-DC conversion efficiency of ~ 0.1% for the Schottky diode in W operation. This is because our stretchable wideband rectenna has combined received power over its band into DC power. For an input of -20 dBm, the demonstrated rectenna has a comparable
efficiency (13.5 %) than the previous dipole antenna based rectenna fabricated on conditional stiff boards (14 %) [103], owing to the use of wideband dipole antennas. The reported value is much large than that of MoS$_2$-based rectennas with printed dipole antennas on PI substrates[105]. The combination of wideband antennas and full-wave Greinacher rectifying circuit contributes to the impressive improvement. Patch antennas were featured by the narrow bandwidth, thus rectennas based on patch antennas in previous research showed a lower efficiency[131], compared with the proposed rectennas in this work. The energy harvesting efficiency was found to increase with input power by reducing the distance between the rectenna and transmitter due to the conversion characteristic of diodes, which is consistent with previous research[103, 132]. The stretchable wideband rectenna was also able to harvest the RF energy from cell phone hotspots, implying its possibility to provide an always-on energy-harvesting solution. The energy harvesting capability of the stretchable wideband rectenna was also reliable and robust against various deformation modes such as stretching or twisting, with the output power to be close to that without the deformation. This excellent energy harvesting performance against deformation is directly attributed to the stable bandwidth of the stretchable wideband dipole antenna. By attaching the stretchable wideband rectenna on the human arm, its on-body performance was also investigated (Figure 2-14 C). The ambient RF energy was still successfully harvested, though a reduction of 50% was observed in the harvested output power compared to that of the off-body because of the performance change in the antenna as discussed above. Note that the on-body energy harvesting performance of the stretchable wideband rectenna could be significantly improved by exploiting the metasurface ground[133] or stretchable patch antennas[116, 134], both of which reduce the absorption in the lossy body tissues. While the increase in the input power can improve energy harvesting efficiency[103, 105], the ambient RF energy is often limited to a low input power level (Figure 2-15). The methods to further improve the effective efficiency in the stretchable rectenna include the exploitations of the spin diode rectifiers to significantly enhance RF-DC conversion
efficiency [135] or of dual-polarized stretchable wideband dipole antennas to combine the randomly polarized electromagnetic field in the ambient environment[103, 136]. Nevertheless, different from the previously demonstrated flexible rectennas (e.g., PI rectennas[105], paper rectennas[137, 138], or textiles rectennas[131]), the result from this study is the first demonstration of the stretchable rectenna that is capable of harvesting ambient RF energies even against various deformation modes. Our demonstrated stretchable wideband rectenna has the smallest minimal input power (-50 dBm) and relatively high energy harvesting efficiency (13.5% at an input power of -20 dBm), which is even comparable to their rigid counterparts[103]. We also aimed to introduced stretchable metasurfaces underneath the stretchable dipole antenna to improve the on-body energy harvesting efficiency by reducing the absorption of human tissues.
Figure 2-14. Energy harvesting performance of the stretchable wideband rectenna. (A) Experimental setup to measure the energy harvesting performance of rectennas. A rectifier is designed to match 50 Ω input over the frequency from 2.0 to 2.5 GHz. A portable digital spectrum analyzer and a digital multimeter are used to measure the input RF power and the bias voltage over the resistance load. (B) Measured output power and effective efficiency as a function of the peak input power. (C) Optical images of the stretchable rectenna operated by the radiation of microwaves or cellphone hotspots under various deformations or on-body.
Figure 2-15. Screenshots of the measured RF spectrum in (A) an ambient environment, or (B) close to a working microwave oven or (C) cellphone hotspot using a portable spectrum analyzer. The outline is the maximal sampled value during one-second measurement and the shaded area indicates the real-time RF spectrum.

The demonstrated stretchable wideband dipole antenna for wireless transmission and stretchable wideband rectenna for energy harvesting can also be combined with various LIG sensors to yield the all-LIG stretchable electronics. In a representative demonstration, the all-LIG-based flexible integrated device was fabricated on a single PI film through laser scribing in ~ 30 mins (Figure 2-16 A). The all-LIG-based flexible device consisted of sensors (e.g., temperature, humidity, and ECG sensors), wireless transmission and energy harvesting modules, and the pins to connect with the off-the-shelf (COTS) chips such as a microcontroller. Pins and interconnects for connection can be surface coated with a silver nanoparticle ink, as described for the stretchable wideband antennas/rectennas. After the metal surface coating and removal of the PI self-mask, transfer the device onto an elastomeric substrate yielded the all-LIG-based stretchable electronics.
(Figure 2-16 B). The LIG temperature sensor patterned in a serpentine trace demonstrated relatively good linearity in the temperature range from 0 to 100 °C (Figure 2-16 C). Linear fitting of the measured resistance change to the temperature yielded a temperature coefficient of resistance (TCR) of -0.18%/°C, as expected from a p-type LIG. A humid sensor designed in the Archimedean spiral showed an exponential increase in the measured capacitance as the relative humidity (RH) increased, and the response decreased with the increasing frequency (Figure 2-16 D), consistent with previous studies [139]. Owing to its highly porous structure, the LIG humidity sensor exhibited a high sensitivity close to those based on the porous ceramics [140] and higher than those based on metal [141]. The two small LIG electrodes with a size of 3 mm × 3 mm were also able to capture high-fidelity electrophysiological signals such as the electrocardiogram (ECG) or electromyogram (EMG) (Figure 2-16 E).
Figure 2-16. Integrated stretchable LIG-based electronics and the sensing performance of individual components. (A) Leveraging the above fabrication process, various LIG-based sensors can also be fabricated. Depending on the need in each sensor, the metallic ink could be selectively applied at desirable locations with a mask to create location-dependent conductivity. Optical image shows a proof-of-concept demonstration of a flexible LIG-based electronic system that includes near-field communication (NFC) coil for short-range communication, wideband dipole antenna for RF long-range communication, sensing units (i.e., temperature sensor, hydration sensor, and electrodes for electrophysiological signal monitoring), connecting circuits for commercially available off-the-shelf (COTS) chips (COTS chips such as microcontroller were removed for clarity. (B) Photograph of LIG-based stretchable integrated electronics with temperature, hydration and ECG sensing functions by peeling off the excessive PI in the flexible LIG-based electronic system. (C) Measured resistive response of a LIG-based temperature sensor under stretching. Dashed line is the linear fitting of the measured curve with a slope of -0.18% °C⁻¹. (D) Measured capacitive response of a hydration sensor featured with an Archimedean spiral configuration in different relative humidity (RH) under different frequencies. (E) Electrocardiogram (ECG) signal measured by two LIG-based electrodes with a size of 3 mm × 3 mm.
2.3 Conclusion

The concepts reported here combine the coupled mechanical-electromagnetic design approach with a simple laser-based fabrication to enable the stretchable wideband rectenna with high efficiency and compliant mechanical properties. Integrating this rectenna to harvest ambient RF energies with various low-power LIG sensors yields a new class of stretchable all-LIG electronics for future wearable electronics, implantable devices, and remote sensors. To further reduce the absorption in the lossy tissues and improve the on-body energy harvesting performance, the metasurface ground [133, 142] or stretchable patch antennas [116] with wideband designs [143, 144] can be combined or exploited in the stretchable wideband rectenna. The methods for further improvement in the effective efficiency of the stretchable rectenna include the exploitations of the spin diode rectifiers to significantly enhance RF-DC conversion efficiency [135] or of stretchable wideband antennas with dual-polarization [104] (or circular-polarization [145]) to combine the randomly polarized electromagnetic field in the ambient environment.
Chapter 3

Structural Engineering on Stretchable Microstrip Antennas for Wireless Strain Sensing

3.1 Introduction

As an alternative to the stretchable materials, the structural design could also endow flexibility/stretchability to the intrinsically rigid, stiff materials [146, 147]. Early findings indicate that thin films of gold evaporated on the elastomeric substrate can be stretched over tens of percent [87], which is far beyond its fracture strain because of local thinning or forming shear bands [148]. Using this concept of stretchable metal yields the stretchable planar inverted-F antenna (PIFA) that can undergo reversible deformation up to 10 %, but the resulting antenna shows poor efficiency with an extra 10 dB loss in comparison to a conventional one, possibly from the thin film and low conductivity of the Au film [149]. In order to address this challenge, thick silver films of 200-400 nm have been ink-jet printed on a patterned PDMS substrate[149]. The stretchable dipole antenna created from this technique only shows an extra loss of 1.7 dB, but its performance is not reversible. The stretchable structures explored in the aforementioned stretchable sensors and devices provide inspiration for the structural design of the stretchable antenna based on conventional metals. For instance, a 2.4 GHz dipole antenna with meandered copper arm on the silicone and polyurethane substrate still shows a reflection coefficient < -10 dB up to a tensile strain of 20 %[150]. Based on the similar serpentine geometry, the monopole antenna integrated with the transmitter board that is worn on a human subject has even shown the far-field communication capability, where the RF power of 1 dBm (1.25 mW) from the transmitter reduces to −100 dBm over a distance of 80 m in an open area on the university campus[151]. Exploiting a strategy to convert rigid metal sections
to a serpentine mesh layout through rectangular and trapezoidal unit cells provides designs for a stretchable microstrip transmission line, a far-field dipole antenna, and midfield phased surface with concentric metal rings[152]. However, the use of photolithographic processes complicates the fabrication process though they are high-resolution and versatile to create complex patterns.

In this part, we will demonstrate the exploration of two representative stretchable structures in designing and fabricating the stretchable, mechanically reversible microstrip antennas from conventional metallic materials: deformed wavy structure created from the use of the pre-strain strategy[153] and the initially wavy structure from patterning[154]. In addition to the simple arc, the former could easily be extended to various 3D structures as demonstrated in several recent studies[155-157]. 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[158][159]. Taken together the set of non-dimensional parameters in the wavy serpentine (i.e. normalized thickness, normalized width, and arc angle) with the different patterns that can be created with the unit element of the wavy serpentine, the stretchability of the resulting structure can be easily tuned to several tens of percent, as demonstrated in our previous studies[158][159]. The demonstrations presented in this study are obtained by a simple cutting method, but the designs could easily be applied to the other advanced manufacturing methods such as laser patterned porous graphene[160, 161]. The prediction of the radiation properties of both designs from the simulation is verified by the experiment with reasonably well agreement. 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 that could enable wireless communication by using the technique of wireless interrogation[162].
3.2 Structural Engineering of Stretchable Microstrip Antennas with High Strain-sensitivity

A typical microstrip antenna consists of the conductive patch and ground plane separated by a stiff dielectric substrate layer. The first step in the design of flexible and stretchable antennas starts by replacing the conventional rigid substrate with a flexible and stretchable layer such as elastomeric polymers. Due to its 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. By using deformable wavy structures created from the use of the pre-strain strategy and the initially wavy structure from patterning, two structural designs have been investigated for the stretchable microstrip antenna: “meshed microstrip antenna” (Figure 3-1 A) and “arched microstrip antenna” (Figure 3-1 B). 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 formed by the pre-stretching strategy for the patch. Without any structural design, a Solaris substrate with a thickness of 1.5 mm sandwiched between a solid copper patch and a solid ground plane forms a microstrip antenna with a resonance frequency at 3.50 GHz and a bandwidth of 0.11 GHz. Consistent with the previous reports[56, 163], this result implies that the use of silicone elastomer as the dielectric substrates doesn’t compromise the performance of microstrip antennas.
Figure 3-1. Schematic illustrations of two representative designs of stretchable patch antennas through structural engineering of solid metal components. (A) “Meshed microstrip antenna” is obtained by replacing the solid patch and ground plane with serpentine networks. (B) “Arched microstrip antenna” is obtained by replacing the solid ground plane with a serpentine network and generating an arched patch by the use of the pre-strain strategy (i.e. selective bonding a solid, flat patch on a pre-stretched elastomeric substrate such as silicone polymers followed by the release of the pre-strain, which induces a compressive force to lift up the weakly bonded region).

Because of the in-plane bending and/or out-of-plane buckling upon the externally applied deformation such as stretching, the serpentine element can deform up to an applied tensile strain far beyond its fracture strain. The stretchability of the resulting microstrip antenna based on serpentine networks depends on the geometrical parameter of the representative serpentine element such as its line width, radius of curvature, and arc angle, as extensively studied in our previous work[158, 159]. Moreover, the change of these geometric parameters also leads to the change in the pattern and filling ratio (i.e. the ratio of the serpentine network over the apparent area in the meshed region) of the conductive components (i.e. the patch and ground plane). As the pattern and filling ratio alter the electric current flow in the antenna, the radiation property (e.g., the resonance frequency, gain, and efficiency) of the antenna will be affected accordingly. In the current study, we first investigated the antenna with the same pattern but different filling ratios. For the microstrip antenna with a solid patch and a meshed ground plane, the increase in the filling ratio of the ground
plane from 52.3 % to 74.2 % (Figure 3-2 A) results in the increase of resonance frequency from 2.67 GHz to 3.20 GHz (Figure 3-2 B), approaching that of an antenna with a solid ground plane (i.e. 3.5 GHz). The use of serpentine interconnects in either the patch or ground plane changes the current pathway and increases the propagation distance to result in an increase in the effective wavelength and a decrease in the resonance frequency. As the filling ratio increases, the increased current pathway leads to a shorter effective wavelength and a higher resonance frequency. On the other hand, the bandwidth of the antenna with a filling ratio from 54.4 % to 74.2 % slightly increases in comparison with their solid counterpart. Because of the deviation of the characteristic impedance from 50 ohms in the design with a sparsely meshed ground plane (i.e. small filling ratio), the magnitude of the reflection coefficient S$_{11}$ at resonance (-9.6 dB) is below the desired level of -10 dB in the design of meshed ground plane with a filling ratio of 52.3 %. The predicted results from the numerical simulation were verified by the experimental measurements (Figure 3-2 C) with a reasonably well agreement (Figure 3-2 D), consistent with the reported literature studies[164, 165]. The effect of the filling ratio on the meshed patch is similar to that on the meshed ground plane. Increasing the filling ratio from 64.7 % to 74.2 % in the meshed patch leads to the increase in the resonance frequency from 2.71 GHz to 3.08 GHz, consistent with the effect of the filling ratio on the resonance frequency and bandwidth reported in the previous studies[165, 166].
Figure 3-2. Effect of the filling ratio in the meshed ground plane. (A) Schematic illustrations of the meshed ground plane with an increasing filling ratio: 52.3%, 54.4%, 64.7%, and 74.2%. (B) Measured and (C) simulated S11 curves of the antenna that has a solid patch and a meshed ground plane with increasing filling ratio: 52.3%, 54.4%, 64.7%, and 74.2%. (D) The comparison of resonance frequency between the simulation (black) and measurement (red) as a function of filling ratio from 52.3% to 74.2%.

It should be noted that according to the transmission line model[167], the radiation of microstrip antennas occurs at the edge of the patch. Therefore, the feed line and the edges of the ground plane are not patterned to ensure a proper feed and to avoid the strong distortion in the radiation property. In order to select a proper value for the solid edge in the current study, we have verified the effect of the width of the solid edge on the reflection coefficient $S_{11}$ of the meshed
patch (Figure 3-3 A). As the width of the solid edge showed a negligible effect on the resonance frequency and bandwidth in both simulations (Figure 3-3 B) and experiments (Figure 3-3 C), a narrow edge width of 3 mm was selected throughout the remaining of the study unless otherwise specified. In contrast to the solid patch, the use of serpentine network structures with a filling ratio of 64.7 % for the patch showed a decrease in resonance frequency from 3.50 GHz to 2.71 GHz and a reduction in bandwidth from 0.1 GHz to 0.07 GHz (Figure 3-3 B). We also would like to point out that the upper limit of the filling ratio is currently limited by the smallest line width that can be achieved with the commercial cutter, but a denser network (i.e. a larger filling ratio) could be possible with other techniques such as laser patterning/cutting[160, 168] or high-resolution 3D printing[169]. This implies that the working frequency of proposed stretchable patch antennas can be further extended to a much larger range.

Figure 3-3. Effect of the solid edge width. (A) Schematic illustrations of the meshed ground plane with a filling ratio of 64.7 %, but an increasing edge width: 1 mm, 3 mm, and 5 mm. (B) Measured and (C) simulated S11 curves of the antenna that has a solid patch and a meshed ground plane with an increasing edge width: 1 mm, 3 mm, and 5 mm.

As shown in Figure 3-4 A, the meshed microstrip antenna with a filling ratio of 74.2 % in both the patch and ground plane was constructed by using the same representative serpentine
Prior to the externally applied tensile strain, the resonance frequency and bandwidth of the antenna decreased from 3.5 GHz to 2.92 GHz and from 0.11 GHz to 0.80 GHz, respectively (Figure 3-4 B). The resonance frequency further decreases monotonously to 2.74 GHz as the tensile strain increases to 15 %. Assuming in-plane bending without out-of-plane buckling in the serpentine network, the peak strain in the patch and ground plane is ~ 1.7 % for an applied tensile strain of 15 % (Figure 3-4 A), which is much smaller than the fracture strain of copper. It should also be noted that the out-of-plane buckling in the actual microstrip antenna could further reduce the peak strain in the serpentine network (as to be shown in Figure 3-6). The resonance frequency obtained from the simulation decreases from 2.92 GHz to 2.77 GHz as the tensile strain increases from 0 to 15 %, which agrees reasonably well with the experimental measurements (from 2.93 GHz to 2.78 GHz, Figure 3-4 C). The slight difference between the simulation and the experimental measurement is likely attributed to the inaccurate strain measurement in the homemade stretcher. The thickness of the dielectric substrate was measured to be 1.7 mm in the experiment, which was used in the simulation (Figure 3-4 B). In order to reveal the effect of the out-of-plane buckling of the meshed structure on the radiation properties of the resulting antenna, the simulation results that did not consider buckling (with a dielectric substrate of 1.7 mm and 1.5 mm) and the one that only considered buckling in the meshed ground plane were also included in Figure 3-4 D for comparison. The thickness of the dielectric substrate clearly showed a large effect on the resonance frequency, where the role of the buckling in the meshed patch and ground plane was relatively small. Based on the comparison of this set of results, it can be safely concluded that the out-of-plane buckling in the meshed patch and ground plane may be neglected if the computational resources are limited. For the sake of simplicity and consideration of computational resources, the out-of-buckling is not be considered in the design with a small line width such as the one with a filling ratio of 74.2 % unless otherwise specified in the following mechanical and electromagnetic simulation.
Figure 3-4. Design and performance of the meshed microstrip antenna. (A) Strain distribution in the meshed microstrip antenna with a filling ratio of 74.2 % for both the meshed patch and meshed ground plane before and after a tensile strain of 15 %. (B) Simulated and (C) measured $S_{11}$ curve of the meshed microstrip antenna. The thickness of the dielectric substrate was measured to be 1.7 mm, which was used in the simulation in (B). The out-of-plane buckling of the serpentine network in both the meshed patch and ground plane was also considered in the simulation. (D) The comparison of resonance frequency between the simulation (solid lines) and measurement (dashed line) for a tensile strain from 0 % to 15 %. The simulation results that do not consider buckling (with a dielectric substrate of 1.7 mm and 1.5 mm) and the one that only considers buckling in the meshed ground plane were also plotted for comparison. The thickness of the dielectric substrate was shown to have a large effect on the resonance frequency, where the role of the buckling in the meshed patch and ground plane was relatively small.

Reducing the filling ratio from 74.2 % to 64.7 % in the ground plane while keeping the filling ratio unchanged in the patch (Figure 3-5 A) leads to a decreased resonance frequency (from 2.92 GHz to 2.70 GHz) without tensile strain. Similar to the trend observed in a filling ratio of
74.2 %, the resonance frequency also decreases monotonically from 2.70 GHz to 2.52 GHz as the tensile strain increases from 0 to 15 % (Figure 3-5 B). The resonance frequency obtained from the experiment (Figure 3-5 C) agrees reasonably well with the prediction from the simulation (Figure 3-5 D). It should be noted that the peak strain in the ground plane obtained from the simulation reaches 8 % when the out-of-plane buckling is not considered. Three-dimensional mechanical simulation in ABAQUS indicates that the out-of-plane buckling occurs to reduce the peak strain by ten times to 0.8 %, due to its relatively large line width of serpentine connections (Figure 3-6). Similarly, including the out-of-plane buckling of the ground plane in the electromagnetic simulation leads to a slight increase in the resonance frequency, which provides a better agreement to the experimental measurements (Figure 3-5 D).

![Figure 3-5. Design and performance of the arched microstrip antenna that has a meshed ground plane with a filling ratio of 64.7 %. (A) Strain distribution in the resulting arched](image-url)
microstrip antenna before and after a tensile strain of 15 %. (B) Simulated and (C) measured $S_{11}$ curves of the arched microstrip antenna. The thickness of the dielectric substrate was measured to be 1.7 mm, which was used in the simulation that also considered the out-of-plane buckling of the serpentine network in the meshed ground plane. (D) The comparison of resonance frequency between the simulation (solid lines) and measurement (dashed line) for a tensile strain from 0 % to 15 %. The simulation results that do not consider buckling (with a dielectric substrate of 1.7 mm and 1.5 mm) were also plotted for comparison. The thickness of the dielectric substrate was shown to have a large effect on the resonance frequency, where the role of the buckling in the meshed ground plane was relatively small.

Figure 3-6. Strain distribution of a meshed ground plane with a filling ratio of 64.7 % under a tensile strain of 15 % stretching when the out-of-plane buckling was considered.

In addition to the shift in resonance frequency and bandwidth, the serpentine networks in the patch or ground plane slightly affect the directionality of radiation (Figure 3-7). Overall, the 3D radiation pattern of microstrip antennas is well conserved with the use of meshed structures, except for an increased radiation leakage along the –z-direction. The serpentine network structure with a filling ratio of 74.2 % in the ground plane shows a 0.18 dB increases for the radiation along the +z direction, when compared with that with the filling ratio of 64.7 %, as shown in the three-dimensional (3D) radiation pattern (Figure 3-7 A) and the normalized radiation pattern in both the E-plane and H-planes (Figure 3-7 B). The increase of backward radiation is also verified by the experiment, implying the inverse relation between the backward radiation and the filling ratio of
the ground plane. For an applied tensile strain of 15 %, the radiation along the +z-direction further increases for antennas with a filling ratio of both 74.2 % and 64.7 % (Figure 3-7 A). The enhancement of radiation along the +z direction likely originates from the increased filling ratio in the ground plane upon stretching. Because of a small resistive loss, the radiation efficiency of the meshed microstrip antenna also shows a significant enhancement when compared to those designed with the conductive textile, liquid metal, or conductive composite (Table 3-1). Upon an externally applied tensile strain of 15 %, the radiation efficiency of the meshed microstrip antenna with a filling ratio of 74.2 % and 64.7 % only slightly decreases by ~ 3.0 %. It is also noteworthy to mention that meshed microstrip antenna with a reduced filling ratio (64.7 % as opposed to 74.2 %) in the ground plane further shows an improvement in the radiation efficiency (78.4 % as opposed to 64.0 %), which is possibly due to the suppression of surface waves[170].

<table>
<thead>
<tr>
<th>Type of Microstrip Antennas</th>
<th>Radiation Efficiency (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile</td>
<td>48.0</td>
<td>[171]</td>
</tr>
<tr>
<td>Liquid Metal</td>
<td>58.0</td>
<td>[172]</td>
</tr>
<tr>
<td>Conductive Composite</td>
<td>41.5</td>
<td>[78]</td>
</tr>
<tr>
<td></td>
<td>40.0</td>
<td>[173]</td>
</tr>
<tr>
<td>Meshed, filling ratio of 64.7 %</td>
<td>78.2 (75.3)</td>
<td>This work</td>
</tr>
<tr>
<td>Meshed, filling ratio of 74.2 %</td>
<td>64.0 (61.2)</td>
<td></td>
</tr>
<tr>
<td>Arched, filling ratio of</td>
<td>87.0 (84.5)</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
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<td></td>
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<tr>
<td>64.7 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arched, filling ratio of</td>
<td>82.4 (74.6)</td>
<td></td>
</tr>
<tr>
<td>74.2 %</td>
<td></td>
<td></td>
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Note: The radiation efficiencies of the meshed and arched microstrip antenna after an applied tensile strain of 15 % are provided in the parenthesis, whereas those in the literature studies are not available.
Figure 3-7. Radiation pattern of the meshed microstrip antenna. (A) 3D radiation patterns of the stretchable meshed microstrip antenna with a meshed ground plane that has a filling ratio of (left) 64.7% and (right) 74.2%, simulated (top) before and (bottom) after the tensile strain of 15%. The meshed patch has a filling ratio of 74.2% in all four cases. (B) The comparison of the normalized radiation pattern in the (top) E-plane and (bottom) H-plane between the (left) simulated
and (right) measured results. While the filling ratio of the meshed patch was kept as 74.2 %, the filling ratios of the meshed ground plane are (black) 64.7 % and (red) 74.2 %, respectively.

In order to understand the role of the serpentine network structure from both the patch and ground plane on the resonance frequency upon stretching, the meshed microstrip antenna with either a stretched patch or a stretched ground plane was investigated (Figure 3-8). In the simulation, the meshed microstrip antenna has a filling ratio of 74.2 % in the meshed patch and a filling ratio of 64.7 % in the meshed ground plane. Compared with the antenna without stretching (black solid line in Figure 3-8), the tensile strain of 10 % applied on the patch (ground plane unstretched, the blue dashed line in Figure 3-8) leads to a decrease in resonance frequency from 2.64 GHz to 2.50 GHz. The observation is consistent with the empirical-analytic equation from the previous study[78, 172] that the resonance frequency scales inversely proportional to the electrical length along the direction of the current flow (the feeding direction)[56, 78], i.e.

\[ f = \frac{c}{2L\varepsilon_{\text{eff}}} \]

where \( L \) is the length of microstrip antenna, \( \varepsilon_{\text{eff}} \) is the effective dielectric constant of the substrate, and \( c \) is the speed of light in the vacuum. On the other hand, the tensile strain of 10 % applied to the ground plane (patch unstretched, the magenta dotted line in Figure 3-8) leads to an increase in the resonance frequency from 2.64 GHz to 2.71 GHz possibly due to the increased filling ratio upon stretching. The positive correlation between the resonance frequency and filling ratio is also revealed in other studies[165]. As the effect from the patch is more prominent, the combined effect from these two competing factors leads to the decrease of resonance frequency from 2.64 GHz to 2.55 GHz for a tensile strain of 10 % (the red dash-dotted line in Figure 3-8).
Figure 3-8. Simulated S11 curves of the meshed microstrip antennas with a meshed patch (filling ratio of 74.2 %) and a ground plane (filling ratio of 64.7 %) that are separately stretched to demonstrate the influence of each on the resonance frequency. Black solid line: 0 % strain on both the meshed patch and meshed ground plane. Blue dashed line: a tensile strain of 10 % on the meshed patch and 0% on the meshed ground plane. Magenta dashed line: a tensile strain of 10 % on the meshed patches and 10% on the ground plane. Red dashed line: a tensile strain of 10 % on both the meshed patch and the meshed ground plane.

Using an arched patch formed from the pre-strain strategy and a serpentine meshed ground plane, the “arched microstrip antenna” provides an alternative approach for the stretchable microstrip antenna (Figure 3-9 A). In order to reveal the role of the arched patch, a filling ratio of 74.2 % was chosen for the ground plane to ensure that the stretchability of the system is not limited by the ground plane. As the stretchability of the arched patch is approximately the level of the pre-stretch, a maximum pre-stretch of 15 % was used in the design for the proof-of-concept demonstration. The results from both the experiment and simulation reveal that further increase of the pre-stretch degenerates the performance of antennas due to the impedance mismatch. Prior to the application of the external tensile strain, the stretchable microstrip antenna shows a resonance frequency of 2.88 GHz with a bandwidth of 0.12 GHz in the simulation (Figure 3-9 B). When compared with the antenna with a solid patch and a solid ground plane, the resonance frequency decreased by 0.62 GHz. It is likely due to the increased dielectric layer thickness from the introduction of an air gap between the patch and ground plane, as well as the effect from the meshed ground plane. However, the influence of these two factors on the resonant frequency couple with each other and a straight explanation from the transmission line model doesn’t directly follow.
Surprisingly, the simulated resonance frequency increases monotonically from 2.88 GHz to 3.21 GHz as the tensile strain increases from 0 to 15 %, which is just opposite to the trend from the design of the “meshed microstrip antenna”. Tensile strain applied on the arched patch relaxes it to its initial, planar shape, which does not actually change the electrical length. As the tensile strain applied on the meshed ground plane would lead to an increase in the resonance frequency (Figure 3-8), the increase in the resonance frequency of the arched microstrip antenna could be explained. The observed monotonic dependence of resonance frequency on stretching was also verified by the experimental measurements that showed an increase from 2.92 GHz to 3.28 GHz (Figure 3-9 C), which agreed reasonably well with the predictions from the simulation (Figure 3-9 D). In comparison to the design of “meshed microstrip antenna”, the resonance frequency changes more dramatically upon tensile strain in the arched microstrip antenna. The bandwidth of the arched microstrip antenna does not vary with the tensile strain and remains ~ 0.12 GHz in the simulation (Figure 3-9 D).
Figure 3-9. Design and performance of the arched microstrip antenna. (A) Strain distribution in the arched microstrip antenna with a filling ratio of 74.2 % for the meshed ground plane before and after a tensile strain of 15 %. (B) Simulated and (C) measured $S_{11}$ curves of the arched microstrip antenna. The thickness of the dielectric substrate was measured to be 1.7 mm, which was used in the simulation that also considered the out-of-plane buckling of the serpentine network in the meshed ground plane. (D) The comparison of resonance frequency between the simulation (solid lines) and measurement (dashed line) for a tensile strain from 0 % to 15 %. The simulation results that do not consider buckling (with a dielectric substrate of 1.7 mm and 1.5 mm) were also plotted for comparison. The thickness of the dielectric substrate was shown to have a large effect on the resonance frequency, where the role of the buckling in the meshed ground plane was relatively small.

In addition, the radiation efficiency of the arched microstrip antenna decreases from 87.0 % to 84.5 % when an applied tensile strain of 15 % (Table 3-1) unfolds the arc into its initial, flat
shape (Figure 3-10). Compared to the meshed microstrip antennas, the radiation efficiency of the arched microstrip antennas is higher because of the use of a solid patch. As shown in Figure 3-11 A, reducing the filling ratio of the ground plane from 74.2 % to 64.7 % leads to the decrease of the resonance frequency from 2.88 GHz to 2.68 GHz in the simulation (Figure 3-11 B), which is similar to the results from the meshed microstrip antenna. Following stretching leads to the shift of resonance frequency from 2.68 GHz to 2.90 GHz, which also agreed reasonably well with the experimental measurements (Figure 3-11 C and D). Overall, the arched microstrip antenna has better radiation performance in the +z direction than that of the meshed microstrip antenna. For the meshed ground plane with a filling ratio of 64.7 %, its radiation in the +z direction is above 4.1 dB (Figure 3-10 A and B), which is better than that of the meshed microstrip antenna (i.e. 3.6 dB) approaching their solid counterpart (5.0 dB). This result indicates that the patch also plays an important role in determining the radiation pattern of flexible antennas. Increasing the filling ratio to 74.2 % improves the forward radiation to 4.7 dB. The experimental measurement of radiation patterns reveals similar results. As shown in the three-dimensional radiation pattern (Figure 3-10 A) and normalized radiation patterns in both the E-plane and H-plane (Figure 3-12), both the experiment and simulation results showed the enhancement of radiation in the +z direction and attenuation in the reverse direction upon stretching, which may result from the increased filling ratio in the ground plane results upon stretching. This enables the tuning of the directionality of the proposed microstrip antenna in the z-direction.
Figure 3-10. Radiation pattern of the arched microstrip antenna. (A) 3D radiation patterns of the stretchable meshed microstrip antenna with a meshed ground plane that has a filling ratio of (left) 64.7 % and (right) 74.2 %, simulated (top) before and (bottom) after the tensile strain of 15 %. (B) The comparison of the normalized radiation pattern in the (top) E-plane and (bottom) H-plane between the (left) simulated and (right) measured results. The filling ratios of the meshed ground plane are (black) 64.7 % and (red) 74.2 %, respectively.
Figure 3-11. Design and performance of the arched microstrip antenna that has a meshed ground plane with a filling ratio of 64.7%. (A) Strain distribution in the resulting arched microstrip antenna before and after a tensile strain of 15%. (B) Simulated and (C) measured $S_{11}$ curves of the arched microstrip antenna. The thickness of the dielectric substrate was measured to be 1.7 mm, which was used in the simulation that also considered the out-of-plane buckling of the serpentine network in the meshed ground plane. (D) The comparison of resonance frequency between the simulation (solid lines) and measurement (dashed line) for a tensile strain from 0% to 15%. The simulation results that do not consider buckling (with a dielectric substrate of 1.7 mm and 1.5 mm) were also plotted for comparison. The thickness of the dielectric substrate was shown to have a large effect on the resonance frequency, where the role of the buckling in the meshed ground plane was relatively small.
Figure 3-12. The comparison of the normalized radiation patterns in the (right) E-plane and (left) H-plane between the (top) simulated and (bottom) measured results for the stretchable arched microstrip antenna with a filling ratio of 64.7 % for the meshed ground plane. The externally applied tensile strain of 0 % and 15 % were denoted in black and red, stretching.

As the out-of-plane buckling displacement in the arc has been shown to increase with the level of the pre-strain[153], the arc with a certain height popped up in the normal direction may pose a challenge for the practical application of the arched microstrip antenna. First of all, the use of the encapsulation strategies[174, 175] could protect the resulting antenna from the environment, partially mediating the problem. Additionally, a multi-arc structure can be introduced in the design of the arched patch, which helps to reduce the overall size of the arc. As an example, two arcs with a significantly reduced arc height (from 3.7 mm to 1.6 mm) can occur by selective bonding at three evenly spaced bonding sites in the arched antenna of 4 cm by 4 cm. As shown in Figure 3-13, the
resonance frequency of the antenna with a double-arc patch and a meshed ground plane (filling ratio of 74.2 %, black dashed line) is predicted to increase from 3.01 GHz to 3.24 GHz for a tensile strain from 0 % to 15 % in the simulation, which is less than the increase with a single arc (black solid line). The monotonic dependence of the resonance frequency on the tensile strain applied on the antenna with a double-arc structure still enables its use in strain sensing. In addition, downsizing the antenna would also allow it to operate in the higher frequency range. For instance, shrinking the overall size of the antenna from 4 cm by 4 cm (black solid line) to 3 cm by 3 cm (blue solid line) upshifts the working frequency from ~ 3 GHz to ~ 4.5 GHz for the arched microstrip antenna with a single arc. Taken together with the substrates with a high dielectric constant[176, 177], the designs proposed in the current study can yield stretchable antennas with tunable size and operating frequency.

**Figure 3-13.** Change of resonance frequency in the stretchable arched antenna with (left axis, black) a different number of arcs (one vs. two arcs) and (right axis, blue) different lateral dimensions (3 cm by 3 cm as opposed to 4 cm by 4 cm shown on the left axis).
To further demonstrate the bendability of the stretchable microstrip antenna, a bending test was conducted by attaching the arched microstrip antenna onto cylinders with different radii of curvature (Figure 3-14 A). In the representative demonstration, we used the “arched microstrip antenna” with a filling ratio of 74.2 % for the ground plane in the experiment. The measured resonance frequency of the arched microstrip antenna increases with the increasing curvature (or a decreasing bending radius) in Figure 3-14 B. When the bending radius is 26 mm, the arc almost flattens and the resonance frequency increases to
2.99 GHz. It can also be inferred that the maximal bending radius for this antenna is close to 26 mm.

Figure 3-14. Bending demonstration of the arched microstrip antenna. (a) Optical images of the arched microstrip antenna bent over cylinders with various radii of curvature. (b) Measured S11 curves as a function of the radius of curvature.
The flexible and stretchable “meshed microstrip antenna” shows a decent sensitivity with a resonance frequency shift of 0.11 GHz and 0.15 GHz for two different filling ratios in the meshed ground plane upon a tensile strain of 15%. The “arched microstrip antenna” has a much better sensitivity with a resonant frequency shift of ~0.27 GHz and 0.36 GHz for two different filling ratios, respectively. Similar to the characterization of the resistive-type and capacitive-type strain sensor[178-180], we define the sensitivity of the microstrip antenna-based strain sensors as $F = \frac{\Delta f}{f_0} / \varepsilon$, where $\Delta f$, $f_0$, and $\varepsilon$ are the resonance frequency shift by stretching, initial resonance frequency, and the external applied tensile strain, respectively. The best sensitivity $F$ (for an “arched microstrip antenna” with a filling ratio of 74.2 for the ground plane) has shown a 3.35 and 1.49 fold increase in comparison to the Ag nanowire-based microstrip antenna[78] (sensitivity $F$ of 0.245 for a tensile strain of 15%) and liquid metal-based microstrip antenna[172] (sensitivity $F$ of 0.552 for a tensile strain of 15%), respectively. Considering the high sensitivity and compliant characteristic of the proposed microstrip antenna, “arched microstrip antenna” can be applied on a curvilinear surface (e.g., the human skin) as a mechanical strain sensor. As shown in Figure 3-15 A, a stretchable “arched microstrip antenna” formed from a pre-stretch of 15% on an Ecoflex substrate was placed on the wrist for movement detection. The arched patch unfolds to its initial flat configuration as the wrist bends downward by around 30° or 45° and the motion was captured by the increase in the resonance frequency (Figure 3-15 B). When the wrist returned to the initial position, the $S_{11}$ curve fully recovered to the initial shape with little hysteresis.
Figure 3-15. Demonstration of the arched microstrip antenna for motion detection. (A) The top, bottom, perspective views of the arched microstrip antenna and its integration on the wrist for motion detection. (B) Measured resonance frequency as a function of the bending angle in the wrist.

The change of the resonance frequency was observed to be robust and stable during multiple downward and upward bending cycles, as demonstrated by the five consecutive measurements after 200 cycles (Figure 3-16). When it comes to sensing applications such as strain
sensing, linearity is one of the most important parameters that characterize the performance of the sensor. The strain sensor with a linear response is associated with ease of use and uniform sensitivity across the range of measurement. But it should be noted that sensors without linear responses can still be used after calibration. This type of sensors could also present opportunities to the applications that may benefit from non-uniform sensitivities. Nevertheless, the nonlinear dependence of the resonance frequency on the level of tensile strain in the current study originates from the deformation-induced change in the electromagnetic field.

Figure 3-16. Cycling performance of the motion detection sensor was demonstrated by measuring the change in the resonance frequency for 5 consecutive cycles of bending and recovering after 200 cycles.

3.3 Conclusion

Although the characterization of the antenna radiation property was performed by the vector network analyzer, a remote receiving antenna could also be used to measure the change of the $S_{11}$ curve via wireless interrogation[162]. In a typical setup for wireless interrogation of antennas, the incident electromagnetic field from a wideband horn antenna is reflected by the
sensing antenna to the horn antenna for measurement [181] [162, 182, 183]. By remotely switching between the short and open states of the sensing antenna with a photocell, two sets of reflections are measured, with one resulted from the environment only and the other one resulted from the combination of the environment and the sensing antenna. Reflection from the sensing antenna only is obtained by subtracting the two reflection measurements and the resulting peak corresponds to the resonance frequency of the sensing antenna. As an alternative, the antenna can be integrated with commercial chips and external power modules to transmit electromagnetic energy. By measuring the receiving power with a circularly polarized reader antenna, the shift of the resonance frequency of stretchable antennas can also be determined[172, 184]. When the antenna is designed to operate at certain frequencies that match that of the commercial chips, the calibration between the receiving power and the measured signal such as strain could be used for wireless measurement of the signal of interest such as strain.
Chapter 4

Strain-insensitive Hierarchically Structured Stretchable Microstrip Antennas for Robust Wireless Communication

4.1 Introduction

The former part introduced a general way of structural engineering on stretchable patch antennas. Based on the relationship between the resonance frequency and mechanical deformations, the proposed stretchable antenna can be used in wireless strain sensing on human or structural health management. However, the mechanically tunable resonance frequency restricts its applications in wireless communication due to the frequency detuning effect. Considering the volume of data generated in the sensing modules of flexible/stretchable electronics, a stable wireless communication module is necessary to upload the data to external devices for real-time analysis and determination. Therefore, stretchable patch antennas with a stable resonance frequency upon deformations are desired for these applications.

It was found that the resonance frequency decreases with stretching in the meshed microstrip antenna, while increases in the arched microstrip antenna. These results inspired to combine these two designs in a single antenna in a hierarchy structure achieve a minimal resonance shift upon stretching. The fabrication process is similar to that mentioned in the previous part except that the meshed patch and ground was attached to a pre-strained Ecoflex substrate with designed bonding sites. Two benefits come from this design. First, the overall stretchability is improved by the additional pre-strain level. Second, two
distinct geometry changes upon stretching: the arched mesh becomes the strain-free flat mesh and then the strain-free mesh is further stretched. The opposite resonance frequency shift during the two processes compensates each other and leads to a relatively stable resonance frequency.

4.2 Stretchable Microstrip Antennas with Hierarchy Structures for Wireless Communication

The fabrication process is similar to that described in section 2. The meshed serpentine layout was designed in the Auto CAD software and then import into the control system of a green laser system. Commercial copper foils with a thickness of 20 μm fixed on a silicon wafer by water were cut into the programmable patterns by the laser system. The cutting power and speed were optimized to achieve the best resolution. An adhesive and soft silicone gel was used to laminate the patch and ground onto the Ecoflex substrate for all the cases. Simply attaching the meshed serpentine patch and ground to the Ecoflex substrate (with a thickness of 1.5 mm) with the glue and then cutting the substrate into a 50 mm × 50 mm rectangular shape after 20 minutes’ cure time completed the fabrication process of the meshed microstrip antenna. In the fabrication of the arched microstrip antenna, the ground was attached to a pre-strained Ecoflex substrate (pre-strain level of 5%, 10%, or 15%) with the adhesive glue. Depending on the number of arches (single or double-arched), the patch was selectively loaded with the adhesive glue and then attached to the substrate. After the release of pre-strain, the arched microstrip antenna featured by the wavy ground and arched patch were completed. The microstrip antenna with both the arched ground and patch was fabricated in a similar way except that the ground and patch
were also selectively bonded to the pre-strained substrate. Afterward, an SMA (SubMiniature version A) was manually soldered with the as-fabricated antennas with a soldering iron.

It is straightforward to design the 3D microstrip antenna with the arched patch and ground to improve the overall stretchability (shown in Figure 4-1 A). The overall stretchability of the microstrip antenna was improved by the pre-stain level. It reaches to \(\sim 20\%, 25\%\) and \(30\%\) for a pre-strain level of \(5\%, 10\%\) and \(15\%\). The height of the arc increases with the pre-strain level. For example, a \(5\%\) pre-strain corresponds to an arch height of \(5\) mm. The arched mesh recovers to a flat geometry when the stretching equals the pre-strain level. In this process, the local strain was gradually released and reached around zero. Upon further stretching, the unfolding of the serpentine mesh helps to release the local strain until the maximal strain reaches the fracture limit. As a result, two different \(S_{11}\) curve shifts were observed during the whole stretching process (see Figure 4-1 B-D). The \(S_{11}\) curve shifts to the right gradually in the stretching range from 0 to the pre-strain level. Upon further stretching, the \(S_{11}\) curve shifts to the left. As a result, the resonance frequency increases first and then decreases upon stretching (Figure 4-1 E). Overall, Due
to the introduction of a large air gap between the patch and microstrip, the reflection is very high (> -10 dB), implying poor radiation performance.

Figure 4-1. Frequency response of the arch/arch microstrip antenna induced by different pre-strain level (from 0% to 15%) to stretching. (A) Optical images of the arched microstrip antennas induced by 5% pre-strain. The meshed lattice in the ground plane is aligned along the 0° direction. (B)-(D) $S_{11}$ curves of the arched microstrip antennas induced by different pre-strain under
stretching from 0% to 15%. (E) Resonance frequency of the arched microstrip antenna induced by different pre-strain under stretching from 0% to 15%.

A 3D microstrip antenna with an arched patch and wavy ground was shown in Figure 4-2 A. Similarly, the $S_{11}$ curve shifts to the right until the stretching level reaches the pre-strain level (the first phase) and then shifts to the left upon further stretching due to the elongation of the meshed structure (the second phase). It was also observed that the resonance frequency increases nonlinearly in the stretching range of (0%, pre-strain) (Figure 4-2 E) possible due to the complex effect from the change of substrate thickness, effective dielectric constant, and geometry. The reduced air gap leads to the increase of the dielectric constant upon stretching, which tends to shift the resonance frequency to a lower value. However, the decreased effective length due to the reduced air gap leads to the resonance frequency shift to a higher value at the same time. The decreased effective length likely plays a dominative role in the mechanic-electromagnetic property of the arched stretchable microstrip antenna. Then, the resonance frequency of the arched microstrip antenna began to shift to lower values in the second phase. The two opposite shifts help to ensure the resonance frequency of the arched microstrip antenna within a narrow range upon stretching, which is essential for stable communication. For example, the resonance frequency of the arched microstrip antenna induced by 5% pre-strain almost recovered to its initial value upon 15% stretching. However, it is not the case for the arched microstrip antenna induced by 15% pre-strain because the right shift of the resonance frequency is more significant than the following left shift. In order to address this issue, we can reduce the right shift during the first phase of the hierarchy 3D structure evolution.
Figure 4-2. Frequency response of the single-arch/wave microstrip antenna induced by different pre-strain (from 0% to 15%) upon stretching. (A) Optical images of the arched microstrip antennas induced by 5% pre-strain. (B)-(D) $S_{11}$ curves of the arched microstrip antennas induced by different pre-strain upon stretching. (E) Resonance frequency of the arched microstrip antenna induced by different pre-strain upon stretching.
Inspired by our previous results, the right shift of resonance frequency can be reduced by ~50% by the introduction of the double-arched solid patch. Two arches are induced by an additional bonding site at the center of the patch (Figure 4-3 A). With the same pre-strain of 15%, the arch height in the double-arched microstrip antenna was much lower than that in the single-arched ones. The reduced arch height helps to improve the stability of arched microstrip antennas upon external turbulence. Further reduction of the arch height can be achieved by increasing the number of arches. As shown in Figure 4-3 B-D, the right shift of S11 curves was effectively suppressed in the dual-arched microstrip antennas. For example, induced by the same pre-strain of 15%, S11 curves for the double-arched microstrip antenna shifts by ~0.02 GHz, much less than that for the single-arch one (0.12 GHz). As a result, the S11 shows perfect recovery upon further stretching (Figure 4-3 D). As shown in Figure 4-3 E, the resonance frequency of the double-arched microstrip antenna induced by 10% or 15% pre-strain has much better recovery than that of the single-arched one. Impressively, for the double-arched microstrip antenna induced by 15% pre-strain, the change of resonance frequency is below 0.03 GHz (1.5%) in the whole stretching range (0, 25%). Stretchable microstrip antennas reported in previous research by using stretchable conductive materials or stretchable structures show the strain-tunable resonance frequency, promising applications in wireless strain sensing. Considering the intrinsic narrow bandwidth of microstrip antennas, the detuning effect upon mechanical deformation may restrict their applications in communication. Structural engineering offers the design flexibility, such as the non-dimensional geometric parameters (normalized thickness, normalized width, and arc angle) and detailed morphology of 3D structures (Wave or arch), to optimize the reflection and resonance frequency response. To the best of our knowledge, this is the first demonstrated microstrip antenna that has almost unchanged resonance frequency in a large stretching range (0 - 25%).
Because 2.40-2.485 GHz is a widely used frequency range in wireless communication (e.g., Bluetooth and Wi-fi), the stretchable antennas with a stable resonance frequency around 2.45 GHz can be directly leveraged for wireless data transmission or powering. The double-arched microstrip antenna with a pre-strain of 15% can be easily attached to the curvilinear surface of human arms without causing discomfort (Figure 4-4mA). Improved adhesion between the antenna and arm can be achieved by coating a thin adhesive Silbione layer on the wavy ground. Because of the reduced antenna dimension from 43.9 mm × 35.3 mm to 35.5 mm × 28.5 mm, the double-arched microstrip antenna resonates at 2.45 GHz, as confirmed by the experimental measurements (Figure 4-4B). The negligibly small influence of human bodies on the resonance frequency of the antenna also demonstrates the effectiveness of the meshed ground in this new design (Figure 4-4B). Further improvement in the on-body performance (e.g., screening effect and radiation directionality) can be achieved with a dense ground mesh.

The wireless communication performance of the double-arched microstrip antenna is measured with a commercial RF evaluation kit consisting of a transmitter and a receiver (SmartRF06). The transmitter integrated with a PCB-based omnidirectional antenna and a CC2538 RF chip is programmed to transmit RF power at 7-15 dBm (5.01 mW). The receiver with a sensitivity of -100 dBm is integrated with the double-arched microstrip antenna. The stretchable microstrip antenna was either placed in the air or on the human skin with stretching. The communication performance is evaluated in the open space at a university campus (Figure 5A). Although the receiving power decreases rapidly with the communication distance for both the in-air and on-skin case, the receiver is still able to receive -100 dBm at a distance of ~ 160 m. It is believed that the working distance can be improved further by increasing the transmitting power from the source. Compared to the previous demonstration with a stretchable monopole antenna [92], the stretchable microstrip antenna in this work exhibits better communication performance in the free space with a much larger receiving power. Moreover, the significantly enhanced on-body
performance of the stretchable microstrip patch antenna further results in a small difference in the receiving power between the on-body and free-space demonstrations, which is also much smaller than that of its monopole counterpart [92]. These improved on-body performance parameters in wireless communication are attributed to the almost unchanged resonance frequency and radiation properties of the stretchable microstrip antenna. It should also be noted that the working distance of the wireless communication can further be improved by increasing the transmitting power in the transmitter. The proposed stretchable microstrip antenna has better communication performance in on-body applications, manifested by a much smaller receiving power difference between the in-space and on-skin case. For example, at a communication distance of 40 m, the receiving power difference was reduced by 90% from the in-space to on-skin case for the stretchable monopolar antennas, which is much higher than that for the stretchable microstrip antenna (21%). This can be explained by the negligible resonance frequency change of the stretchable microstrip antenna induced by the human body or applied strain.
Figure 4-3. Frequency response of the double-arched microstrip antennas induced by different pre-strain (from 0% to 15%) upon stretching. (A) Optical images of the double-arched microstrip antenna induced by 5% pre-strain. (B)-(D) $S_{11}$ curves of the double-arched microstrip
antenna induced by different pre-strain upon stretching. (E) Resonance frequency of the double-arched microstrip antenna induced by different pre-strain upon stretching.

![Image](image.png)

Figure 4-4. Wireless communication performance of the double-arched stretchable microstrip antenna. (A) Conformal attachment of the stretchable microstrip antenna on human arms and the experimental setup to evaluate the wireless communication performance. (B) Measured S11 curves of the stretchable microstrip antenna in the free space or on human bodies with/without strain. (C) Receiving power by the stretchable microstrip antenna in the free space or on human skin as a function of the transmitter/receiver distance.

4.3 Conclusion

We introduced a hierarchy structure (i.e., the arched meshed structure) to the patch in the design of stretchable microstrip antennas. Two merits come with this design: improved overall stretchability
and a stable resonance frequency, which is due to the opposite shift of resonance frequency in the meshed and arched structure upon stretching. It was found that the design flexibility in structural engineering offers the freedom of tuning the resonance frequency response of stretchable antennas upon mechanical deformations.
Chapter 5

Conclusion

In this work, we have explored the structural engineering of the stretchable antenna to enable its wearable or on-body application. Employing the serpentine meshed layout or 3D hierarchy structure on the radiation part made of conventional metals leads to combined merits of good mechanical stretchability and radiation performance. The radiation efficiency of structural engineering based stretchable antenna was more than 20% higher than that of stretchable antennas made of conductive composite or liquid metals due to its good conductivity. The design flexibility, including the geometric parameters and 3D morphology, provides the freedom to improve the mechanical stretchability. For example, the introduction of the arched structure to the mesh patch leads to an improvement of stretchability. The resonance frequency response to mechanical deformations can also be tuned according to specific applications. For example, the resonance frequency of a meshed patch antenna shifts to the right upon stretching, while the arched patch shifts to left. Also, the multi-arched patch shows a less frequency shift than the single-arched patch. The easy soldering process for conventional metals avails the integration, promising more potential in practical applications.

Considering the detuning effect of antennas upon deformations or being attached to human bodies, it is crucial to design antennas with the robust radiation properties upon deformations. The first method adopted in this work is to address this issue is to design stretchable wideband dipole antennas. Despite the resonance frequency shift upon deformations, the wideband property was able to cover the targeted frequency range for wireless communication or powering. The extraordinary radiation performance in wearable fashion was also verified. The second method is to design stretchable antennas with nearly unchanged resonance frequency upon deformations. It
was shown that the combination of meshed and arched structures in the patch leads to the stable resonance frequency upon a large stretching range (0 – 25 %). Due to the ground effect, the negative effect of losing human bodies on the stretchable microstrip antenna can be eliminated, which is more suitable for on-body applications.

The design flexibility provides lots of freedom for optimization, but it also means that the process is more labor-consuming. More efforts are needed to improve the optimization efficiency, such as using machine learning. We are also looking forward to integrating novel microwave structures or devices, such as stretchable metasurfaces or reflectors, to improve on-body performance. The integration of the proposed stretchable antennas with commercial chips or rectifier circuits for practical applications, such as powering and wireless sensing in stretchable devices will be the next step.
Appendix A

Fabrication of the stretchable wideband dipole antenna

A soft, elastomeric substrate such as Ecoflex was first prepared by mixing the two components with a ratio of 1:1 on a ceramic plate coated with a layer of Ease Release (Mann Release Technologies, Inc.) to facilitate easy release of the substrate. By using a doctor blade, the substrate thickness was controlled to be ca. 1 mm. After rinsing with ethanol and distilled (DI) water, the polyimide (PI) film was coated with the 2% APTES (diluted in ethanol) by dipping in the solution for 1 min, followed by rinsing with DI water. Upon completion of drying, both the PI film and Ecoflex substrate were treated with UV/Ozone for 2 mins to remove organic contaminants for improved surface bonding. Next, a CO2 laser (Universal M-360) was used to transform the PI film into LIG patterns designed with AutoCAD. After aligning the PI film onto the Ecoflex substrate, the raster mode (power of 16% and speed of 10%) and the vector mode (with a 10% power and 3% speed) were selected to create and carve the desired LIG patterns, respectively. Pulses per inch (PPI) of 1,000 and a high image density were adopted during the engraving and cutting processes. Before peeling off the excessive PI film from carving (i.e., the region outside the outlines of the LIG patterns, self-mask), silver nanoparticle (AgNP) ink (JS-A911, Novacentix Inc.) was sprayed and kept at the room temperature for 20 s to vaporize the solvent in ink. Peeling off the PI self-mask left the AgNP ink only on the LIG patterns. Upon exposure of a xenon light (Xenon Corporation, X-1100) with three pulses (i.e., single pulse mode with a duration of 529 μs at an energy of 1000 J and a voltage of 3000 V), a conductive Ag pathway formed on the LIG pattern because of the xenon-induced sintering of the AgNPs from transient high temperature. Lastly, annealing the sample at 80 °C for three hours led to strong covalent bonding between the
Ag/LIG pattern and the Ecoflex substrate. The remaining PI layer underneath the Ag/LIG pattern naturally served as a stiffener to help reduce the local strain in the conductive pattern upon mechanical deformations (e.g., stretching, bending, or twisting) because of strain isolation. After connecting the stretchable antennas to the feed line by coaxial cables for easy hand soldering, another thin layer (50 µm) of a soft, elastomeric polymer was used to encapsulate the antennas. The encapsulation layer was designed with spatial-dependent modulus, which used a soft Ecoflex layer in the region of dipole arms and a stiff PDMS (Sylgard 184) layer with a 1:4 mixing ratio in the region of soldering locations for enhanced stretchability.
Appendix B

Fabrication of the stretchable microstrip antenna

The meshed serpentine layout designed in the Auto CAD software was imported into the control system of an ultraviolet picosecond laser system (BX15, Edgewave). Commercial copper foils with a thickness of 20 μm (BangKai) fixed on a silicon wafer by water-soluble tape were patterned into the programmed mesh design by the laser system. The cutting power and speed of 0.4 μJ and 2000mm s⁻¹ were optimized to achieve the best spatial resolution. A soft, adhesive silicone gel (v1510, Valigoo) was used to assemble the patterned patch and ground onto the Ecoflex substrate in a rectangular shape of 50 mm × 50 mm with a thickness of 1.5 mm. Depending on the number of arches (i.e., single- or double-arched), the meshed patch and ground were selectively bonded to the prestrained Ecoflex substrate with a pre-strain of 5%, 10%, or 15%. The release of the pre-strain resulted in the arched microstrip antennas with arched patch and ground. When the selectively bonded ground was replaced by fully bonded ground, the stretchable antenna with an arched patch and a meshed ground was obtained. The meshed microstrip antenna was obtained by the fully bonding of the meshed serpentine patch and ground to the Ecoflex substrate without the pre-strain. Soldering the as-fabricated antennas with a SubMiniature version A (SMA) connector with a soldering iron (Sn42Bi58, KZ-1513) completed the fabrication process.
References


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