CHAPTER 1

Fabrication and Measurement Techniques of Wearable and Flexible Antennas

Yue Li¹, Zhijun Zhang¹, Zhenghe Feng¹ & Haider R. Khaleel²
¹Department of Electronic Engineering, Tsinghua University, Beijing, China.
²Department of Engineering Science, Sonoma State University, Rohnert Park, CA, USA.

Abstract

When compared with other antenna types, flexible and wearable antennas are generally characterized by compactness, reconfigurability, flexibility, and durability. Therefore, the fabrication processes and materials used in flexible and wearable antennas are quite unconventional and need to be addressed and evaluated. Moreover, additional measurement setups and tuning methods are often required in wearable and flexible applications to reflect a realistic setup and to yield a practical design and optimal performance. In this chapter, the fabrication and measurement techniques and related issues of flexible and wearable antennas are introduced and discussed in detail.

1 Introduction

Wearable and flexible wireless systems are gaining exceptional popularity due to their profound potential in a variety of vital fields. Hence, development of flexible and wearable antennas is an important area that needs to be addressed since the processes involved are quite different from conventional antennas based on rigid substrates. Additional requirements are enforced when it comes to wearable and flexible applications. For example, in body-centric applications, flexible materials must be biocompatible and compliant with health and safety requirements. On the other hand, textiles are adopted as conductive materials or substrate materials for applications that require clothing integration.

A general design procedure of flexible and wearable antennas is illustrated in Fig. 1. First, materials are selected according to the design requirements, including
the conductive and substrate materials. Secondly, the electrical properties of the uncharacterized materials must be obtained, such as electrical conductivity of conductive materials, and loss tangent and permittivity of dielectric materials. Based on the information mentioned above, radiating element and feeding structures of flexible and wearable antennas are designed, simulated, and optimized in the third step before fabrication. In the fourth step, a fabrication method is selected according to the antenna topology and materials used in the design process. In addition to a series of conventional measurements, such as Scattering (S-parameters), efficiency, and radiation patterns, more qualitative tests must be conducted to comply with the requirement of wearable applications. These tests include: specific absorption rate (SAR), bending effects, durability, robustness, humidity and thermal tests, which are often not of importance in other antenna applications.

In this chapter, we mainly focus on the material selection and characterization, fabrication, and measurement of flexible and wearable antennas (steps 1, 2, 4, and 5 in Fig. 1). In Section 2, the properties of conductive and substrate materials used in flexible and wearable antennas are summarized. In Section 3, state of the art and conventional techniques used in wearable antenna fabrication are introduced. The impedance matching strategies for bandwidth enhancement of flexible and wearable antennas are also introduced in this section. In Section 4, customized measurement settings and qualitative tests of flexible and wearable antennas are discussed in details.

2 Material Selection

The fabrication process of flexible and wearable antennas depends mainly on the materials involved in the designed structure. Properties of conductive and dielectric
materials used in flexible and wearable antennas, in addition to processes involved in the characterization of such materials, are surveyed in this section.

2.1 Conductive materials

Similar to conventional antennas, a typical flexible/wearable antenna consists of two parts: conductive (ground plane and radiating element) and dielectric (substrate, which acts as a platform for the radiating element). In this section, a detailed classification of these two groups is provided, and illustrated in Fig. 2.

For conductive materials, the following requirements need to be fulfilled:

- Low resistivity/high conductivity.
- Deformability, flexibility: such as the capability for bending, crumpling, and stretching.
- Weather proof: resistant to material degradation due to environmental factors such as oxidization and corrosion.
- Tensile strength: the material must be able to withstand repeated pressure, deformation, etc.
- Integration with textiles: the ability of the material to be sewed or embroidered.

a. Pure metallic materials are widely adopted in wearable textile-based antennas, such as silver paste [1], copper gauze [2], and copper foils [3]. The advantages of using such materials include: high conductivity, cost effectiveness, and fabrication simplicity (for example: using soft PCB fabrication process [4]). It is worth noting that when the above-mentioned materials are integrated with clothing textiles, adhesive laminates or supporting foams are usually utilized instead of sewing and embroidering.

b. Metal-plated textile is another widely used conductive material in the fabrication of wearable and flexible antennas, it is often termed “electro-textile” and “E-textile”. Metal-plated textiles possess the property of high ductility and can be sewed directly into clothing using textile yarns. Soft materials such as Kevlar, nylon, and vectran are coated with metals. The effective electrical conductivity of such textiles can reach up to 1E+6S/m [5]. The conductive thread is the...
basic component of E-textiles. As described in [5], two types of conductive threads are available: multifilament and monofilament. E-textiles are created from conductive threads through weaving or knitting [5]. Different kinds/brands of E-textiles are exploited in recent published literature, such as Nora [6], FlecTron [7], lessEMF [8], and Zelt [9].

c. Conductive ink, made of carbon or metal particles, is a promising material for flexible antenna design. Conductive inks have the merits of fabrication simplicity, compatibility with standard screen-printing and inkjet-printing process, and low cost. The effective conductivity is dependent on the material’s intrinsic property, added solvent impurities, and the thermal annealing process [10].

2.2 Substrate materials

Substrate materials are mainly utilized to support the conductive elements of the antenna. Various types of flexible substrates are adopted depending on the properties of the conductive materials utilized in the design. In this part, both cutting edge and conventional flexible substrates and films are surveyed.

a. For soft PCB processes, flexible films are the major core materials for supporting overlays, such as polyimide (PI) films [11,12], polyester (commonly refers to Polyethylene TerePhthalate (PET) films [13,14], and liquid crystal polymer films (LCP) [15,16]. These materials have the merits of high flexibility, low loss tangent, and availability of low thicknesses. Table 1 summarizes the advantages and disadvantages of each material [4]. The Kapton, as a high-performance PI film, shows good soldering tolerance for flexible antenna fabrication and withstands high temperature, which is required in thermal annealing of inkjet-printed antennas [4]. These soft films can hold deposited pure metal materials [11,13,15,16] and conductive inks [12,14].

b. Textile in clothing (nonconductive fabric) can be utilized as a platform for antennas, especially when combined with metal-plated textile conductors. Various types of textiles are employed, such as: cotton, silk, wool, viscose, and felt [17,18]. The relative permittivity and loss tangent of such materials are highly dependent on construction (knit or woven), constituent materials, and thickness [5]. Some textiles have anisotropic qualities, such as Cordura and Ballistic fabrics [19]. Therefore, parameters characterization is quite essential for the

<table>
<thead>
<tr>
<th>Property</th>
<th>PI films</th>
<th>PET films</th>
<th>LCP films</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal rating</td>
<td>200°C</td>
<td>70°C</td>
<td>90°C</td>
</tr>
<tr>
<td>Soldering</td>
<td>Applicable</td>
<td>Difficult</td>
<td>Possible</td>
</tr>
<tr>
<td>Wire bonding</td>
<td>Possible</td>
<td>No</td>
<td>Difficult</td>
</tr>
<tr>
<td>Moisture absorption</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Dimensional stability</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
selected clothing textile before the antenna design and simulation step. Non-conductive textiles can sometimes be designed with metallic pieces such as zippers and metallic buttons as the radiating parts [20].

c. Other flexible substrates are also employed for special purposes. For example, paper substrates can be utilized in screen-printing and inject printing processes based on conductive inks. Paper is widely deployed since it is a low cost, environmental-friendly material and can be modified to have hydrophobic and fire-retardant properties [21]. However, it is also lossy and frequency-dependent. A dispersion model is required for accurate RF simulation and analysis [22].

For applications that require high permittivity, ceramics and polymers are widely used. Ceramics are rigid hence they are not often used in flexible and wearable applications unless for highly miniaturized structures. Polymers, on the other hand, such as polydimethylsiloxane (PDMS) are a good candidate having the merits of excellent rheological properties. PDMS substrates are also water-resistant and stable under high temperatures, and can be modified to have higher permittivity values. However, there are some drawbacks associated with PDMS such as high cost and manufacturing complexity, as described in [23–26].

Foam substrates are mainly used for the purpose of mechanical support since it has a dielectric constant very close to that of air. Foam substrates can be embroidered within clothing, with no precise patterning of conductors required. The cost is also low. In [27], a wearable cavity antenna is fabricated using foam substrate.

2.3 Material characterization

The propagation and loss properties at the desired frequency band(s) need to be known for the candidate material prior to antenna design and fabrication. For conductive materials, conductivity and surface resistance have to be characterized, while permittivity and loss tangent have to be characterized for substrate materials. For clothing textile materials with different constructions and thicknesses, most of the parameters are unknown and need to be measured.

a. Conductive materials can be characterized using waveguide cavity method and microstrip resonator method [28]. In waveguide cavity method, shown in Fig. 3a, the quality factors (Q) and transmission coefficient S21 with and without the conductive textile could be measured. Then, the conductive loss is calculated, and thus the conductivity and surface resistance of the conductive textile can be extracted. In the second method, the microstrip resonator is used instead of the waveguide cavity, as shown in Fig. 3b and the measurement steps are similar to that of the waveguide method. However, the dielectric loss of the substrate should be obtained first. Transmission line method is feasible for the same purpose [29]. By measuring S21 with different transmission line lengths, the conductive loss can be extracted.

b. For dielectric textiles, the permittivity and loss tangent properties are mainly of interest. The most popular characterization method is the resonator method. A T-resonator microstrip line method is proposed in [30] and shown in Fig. 4a. The T-branch has a length of a quarter-guided wavelength. Based on the
resonant frequency, effective permittivity and loss tangent can be extracted using the formula in [30]. Another characterization method is proposed in [31] called the matrix-pencil two-line method. The scattering transfer cascade matrix is used to present an additional parameter SL, as shown in Fig. 4b. The propagation factor $e^{j(l_1-l_2)}$ (where $l_1$ and $l_2$ are the lengths of the two lines) is determined by the eigenvalue of scattering matrix of SL. Effective permittivity and loss tangent can then be extracted.

3 Antenna Fabrication

3.1 Fabrication methods

Based on the description of conductive and substrate materials in the previous section, there are several widely adopted fabrication processes of flexible and wearable antennas. This section reviews the commercial methods in addition to techniques used by the research and development sector. An overview of each technique, in addition to their advantages and drawbacks, is discussed:

- **Line patterning:** Line patterning is one of the simplest and most inexpensive solutions for fabricating RFIDs and flexible electronics. This technique was
proposed by Hohnholz and MacDiarmid in 2001 [32]. The design of a negative image of the desired pattern is first developed using a computer-aided design program, followed by depositing a conductive polymer on the substrate. The last step involves taking out the printed mask by sonicating the substrate (by applying an ultra-sonic energy) in a toluene solution for about 10 seconds. Flexible field effect transistors, filters, resistors, and RFIDs are amongst the components produced using this method.

- **Flexography:** In flexography, a print-making process of an image is involved, which is performed by inking a protuberating surface of the printing plate matrix while the recessed (suspended) areas are left free of ink [33]. Flexography gained a significant interest by RFID antenna manufacturers due to its relatively high resolution, cost-effectiveness, and roll-to-roll production capability. Furthermore, this technique requires a lower viscosity ink than the inks used in screen-printing method, which yields dry patterned films of a thickness of <2.5 µm. In contrast to the inks used in screen-printing, inks used in flexography must have higher conductivity to compensate for the difference in sheet resistance since the efficiency of the fabricated antennas relies directly on the electrical conductivity of the radiating element. It should be noted that the consistency of ink and line width has a significant impact on the sheet resistance as well [34].

- **Screen-printing:** Screen-printing is another cost-effective technique used by flexible electronics manufacturers. This technique is characterized by its simplicity and being an additive process, which makes it environmentally friendly. A mask with the desired pattern is developed first and then applied directly on a flexible substrate/film where the conductive ink is administered and thermally treated to evaporate excess solvent. Flexible transparent antennas and RFIDs have been successfully prototyped using this technique [35,36]. It is worth mentioning that there are some drawbacks associated with this technique, which includes the limited control over the thickness of the deposited ink, number of layers, and resolution of the deposited patterns.

- **Photolithography:** Photolithography-based manufacturing has emerged in the 1960s targeting the PCB industry. It involves using a photo-resist and chemical agents to etch away the unwanted area corrosively to produce the desired metallic patterns. This technique had gained notable popularity due to its capability of accurately producing patterns with fine details [37]. Currently, the fabrication of antennas and RF circuits based on photolithography is preferred to be conducted utilizing positive photoresists due to the fact that negative photoresists often give rise to edge-swelling phenomenon, which compromises the consistency and resolution of the resulting pattern. When photolithography is used to produce flexible electronics, single or double-sided substrates are utilized where the desired pattern is obtained by etching regions of either or both sides. It is worth mentioning that stacking multi-flexible patterned layers is also possible using this technique. The major drawbacks of photolithography are: low throughput, involvement of hazardous chemicals, and production of by-products, hence it is not suitable for commercial production.
• **Thermal evaporation:** Thermal evaporation is a physical vapour deposition process, which is recognized amongst the most widely used thin-film deposition techniques. This method involves a vacuum process where a pure material coating is administered over the film surface. This process is conducted by heating a solid material inside a vacuum chamber where vapour pressure is created. Consequently, the evaporated material is deposited on the substrate. In antenna and RFID applications, the coating material is usually a pure atomic metal. It should be noted that this process is usually accompanied by a photolithographic process [38].

• **Sewing and embroidering:** Using sewing or embroidering machine is mainly employed in textile-based antennas, which is preferred over direct adhesion of E-textile over the fabric since no adhesive materials are introduced which may affect the electrical properties of the material [39]. Wrinkling and crumpling should be minimized to maintain the material qualities. For wearable antennas on clothing application, this is the most preferred fabrication process.

• **Inkjet printing:** Inkjet printing of antennas and RF circuits using highly conductive inks based on nano-structural materials are gaining extreme popularity nowadays. Inkjet material printers operate by releasing pico-litre sized ink droplets, which give rise to high-resolution patterns and compact designs. Extensive details about this new technology is presented in Chapter 2 of this book.

### 3.2 Impedance matching strategy in wearable and flexible antennas

In many applications in which components are preferred to be as compact as possible, the substrate materials of flexible and wearable antennas are required to have higher permittivity to achieve greater miniaturization factors. As a result, these antennas suffer from high-quality \((Q)\) factor, which leads to bandwidth degradation. Matching the impedance using lumped components (inductors and capacitors) is extremely useful in the tuning of such types of antennas. A simple integrated circuit is used at the feeding terminal of antennas to enhance the impedance bandwidth and radiation characteristics. In many cases, the impedance matching step is considered as important as the antenna design step.

A comprehensive method of impedance matching for general purpose antennas using lumped components is systematically introduced in [40]. Here, a design example of wearable antenna matching is introduced.

As is well known, there are four different ways to match any given impedance. As shown in Fig. 5a and b, four different circuits can be utilized to match the impedance at location \(X\) in the Smith Chart. As shown in the left circuit of Fig. 5a, a series capacitor moves the impedance from location \(X\) along the large counter clockwise curve, and a shunt inductor moves the impedance along the small counter clockwise curve to the matching point \((50 \, \Omega)\). The goal of impedance matching is to match different portions of the impedance locus, which is equivalent to different frequencies in a wide bandwidth.
Based on this strategy, a wearable patch antenna we have reported in [2] is matched to achieve wide impedance bandwidth. Figure 6a shows a planar inverted-F antenna (PIFA), also treated as a shorted patch antenna. The antenna is fed at the shorting edge, and the width of the central cut ($d_{cut}$) is utilized as a tuning parameter. There are three steps involved in matching the reported PIFA to achieve a wider bandwidth.

- Step 1: The impedance curve is moved to an appropriate position before integration with matching circuits. As a comparison, the impedance curve of a conventional patch operating at the same frequency is shown in Fig. 7a with the dashed line. The impedance bandwidth is depicted in Fig. 6b. By adding the shorting part and tuning the parameter $d_{cut}$, the impedance curve moves to the upper left corner of the Smith Chart. An equivalent circuit of the PIFA is given in Fig. 7a. The shorting part is modelled as a shunt inductor ($L_p$), and the narrow
I
nnovation In Wearable And Flexible Antennas

The feeding strip is modelled as a series inductor \( L_p \). By decreasing \( d_{cut} \), the \( L_p \) increases and reflects more effect on the lower band. Therefore, the curve shrinks into a small circle and shifts to the upper left corner of the Smith Chart.

- **Step 2**: A series capacitor \( C_m \) is connected directly to the feed first. As illustrated in Fig. 7b, the value of \( C_m \) is adjusted to move the impedance curve to the equal admittance circle \( Y = 1 \) at the lower left corner of the Smith Chart.
- **Step 3**: A shunt inductor \( L_m \) is placed after \( C_m \). As illustrated in Fig. 7b, adjusting the value of \( L_m \) moves the impedance curve to the matching circle \( \Gamma < 10 \text{ dB} \) of the Smith Chart.

According to the three matching steps, the impedance bandwidth has been broadened with \( \Gamma < 10 \text{ dB} \), presenting a dual-resonant characteristic as shown in Fig. 6b. Compared with the single resonant of unmatched conventional patch, the achieved bandwidth of the matched PIFA is around 5.2% (417.8–440.1 MHz), which is more than double the bandwidth (2.4% (10 MHz)) in the conventional design. It can be concluded here that the matching strategy using lumped components is an extremely useful tool for bandwidth enhancement of flexible and wearable antennas, especially in scenarios where the bandwidth is compromised due to bending or rolling effects.

4 Antenna Measurement

For conventional antennas, basic parameters must be measured to validate the simulated design and/or analytical results. These parameters include S-parameters (reflection coefficient and transmission coefficient), radiation patterns, efficiency,
polarization purity, and gain. Vector network analyser and anechoic chamber are indispensable equipment for such measurements. For flexible and wearable antennas, other measurements such as SAR, robustness, durability, bending, and crumpling effects tests must also be conducted since they are often required by the Federal Communication Commission (FCC) and quality control departments.

4.1 Specific absorption rate (SAR)

For wearable applications, the effect of antennas on human body must be quantified. SAR refers to the maximum electromagnetic power deposition inside the human body due to wireless radiation. The unit of SAR is W/kg or mW/g, and normally averaged over a small volume of 1 or 10 g of tissue. Figure 8 illustrates the SAR measurement under 1 and 10 g average. In vitro measurement consists of a body phantom and two cubes. The larger cube is for 10 g average. The location of the 10 g cube indicates the maximum average SAR over 10 g, while the smaller cube is for 1 g average, and its location indicates the maximum average SAR over 1 g.

The acquisition system used in SAR measurement is described in [40]. A phantom filled with a synthesized liquid is used to mimic the human body electrical properties. The SAR values can be collected by an electric field probe when the antenna is operating. The FCC has regulated the SAR values at different bands. In the United States, SAR must be <1.6 mW/g with 1 g average for a given wireless system; while in Europe, SAR is regulated at 2.0 mW/g or less with 10 g average.

4.2 Performance on human body

SAR expresses the effect of antenna’s radiation on human body. However, the human body also implies negative effects on the performance of antennas. Antenna

![Figure 8: Cube of 1 and 10 g average on phantom (reprinted with permission of John Wiley & Sons, Singapore).](image-url)
parameters that are negatively impacted by the proximity of human tissues include: impedance bandwidth, return loss, radiation efficiency, and radiation patterns. For practical applications, the antenna should be simulated and measured on the human body to evaluate this effect and to reflect realistic results. As introduced in the above section, the human body phantom is a useful tool in such measurements. It is also worth mentioning that the numerical human model is another widely used tool for SAR evaluation in electromagnetic simulation packages.

There are several classifications for phantoms with different parameters and options, which can be found in [41]. For low-water based tissues (i.e. bones), the permittivity and loss factor of phantom are lower than high-water content tissues (i.e. muscles) in which the permittivity and loss factor are higher. When measuring a low-power dissipation antenna, in vivo measurement is a safe and convenient way, as shown in Fig. 9. Generally, the resonance of the AUT is shifted to lower frequencies and the efficiency is decreased while the radiation patterns are less sensitive when the AUT is within close proximity to the tissues.

4.3 Bending and crumpling effects

When operating on human body, bending, crumpling and sometimes, twisting actions are inevitable in flexible and wearable antennas. For practical applications, the antenna performance changes, often negatively, due to these effects, and can be explained by the electric field distribution. Hence, some tests are required to be conducted for operative reliability.

We have reported a detailed procedure for flexible antenna tests in [42] and can be summarized as follows:

- Durability and robustness tests are performed by repeated trials of the fabricated antennas under bending, crumpling, and twisting to monitor the deposited conductive material for any deformations, discontinuities, and to ensure there are no wrinkles or permanent folds introduced which might compromise the antenna’s functionality and performance.
- Resonant frequency and return loss are characterized under bending conditions since they are prone to shift/deteriorate due to impedance mismatch, capacitive coupling, and a change in the effective length of the radiating structures. Bending tests are conducted by conforming the antenna under test on foam cylinders of
different radii to mimic different extents of bending (obviously smaller radii give rise to larger extents of bending) while it is connected to the network analyser.

- Radiation patterns and directivity of the antenna are examined for distortion and/or degradation. This is done by another set of principal patterns measurement when the antenna are conformed on foam cylinders with different radii.

On the other hand, crumpling formers are usually employed to measure the antenna performance under the bending and crumpling conditions. The effect of crumpling in different directions is inconsistent. Under bending and crumpling conditions, the impedance matching deteriorates with a shift in operating frequency. The radiation efficiency varies accordingly, while radiation patterns are tilted and/or distorted. The amount of distortion is dependent on the extent of bending and crumpling. The reader is referred to [43,44] for additional useful discussions in this area.

4.4 Other related measurement setups

Other measurements are needed when a flexible or wearable antenna is operated in a specific situation. Here, two widely conducted tests are introduced:

- **Washing factors (Washability):** Wearable textile-based antennas are usually exposed to dirt, dust, and sweat, which might compromise their performance. Furthermore, textile antennas that are integrated within clothing are subject to be soaked with water and/or washed/laundered. The performance of the antenna is required to be consistent after it is washed. As an example for antenna washability characterization, the reflection coefficient and radiation efficiency of a wearable antenna are measured after one, three, and six washing cycles to examine its performance as a quality control measure in [45]. Obviously, the performance stability mainly depends on the conductive and substrate material selection.

- **Environment factors (humidity and thermal tests):** The material properties are sensitive to the environmental variables, such as humidity and temperature. Since in some cases wireless systems are required to operate under harsh environments, performance stability techniques are essential. When an antenna is expected to operate in a humid environment, the influence of the relative humidity should be analysed. In [46], the effects of humidity on the reflection coefficient and permittivity are investigated by changing a controllable humidity from 10% to 90% (10% a step). Obviously, with an increased relative humidity, the permittivity and the loss tangent are both increased [46]. The influence of cold environments is investigated in [47] under different levels of snow and ice. Coating the antenna with special materials can reduce these effects.

References


