Flexible Antenna: A Review of Design, Materials, Fabrication, and Applications

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Abstract. The Flexible antenna is experiencing major growth recently because of the demand for wearable devices, military applications, health monitoring systems, communication devices, and global positioning systems (GPS). The choice of the flexible antenna relies on many factors such as materials used, substrate, antenna performance, processing technique, and the surrounding environment. Numerous antenna designs had been investigated by the researchers using conductive materials such as silver. Substrates such as cotton and elastomeric polymers with different fabrication techniques such as screen printing and inkjet printing had been implemented for various applications. This paper focuses on the previous work of flexible antenna design and miniaturization techniques such as electromagnetic bandgap (EBG) for button antenna. A summary of previous works on the flexible antenna is also highlighted.

1. Introduction
Flexible electronics integrated with a textile substrate whose mechanical properties are able to bend, and twist would considerably offer many advantages in modern electronic devices. A wearable antenna for example can sense, communicate data, harvest energy, and function while being worn[1]. Recently, a lot of interest in wearable devices and antenna sensors in particular due to the simple configurations, sensing, multimodality, and low-cost fabrication[2]. The design of the antenna varies depending on the environment, frequency range, and transmission strength[3]. However, the performance of the antenna depends on the materials used. to design the antenna such as the substrate properties in terms of its ability to adapt to a harsh environment like bending and twisting, conductive materials in terms of resistance, and high tolerance to degradation due to mechanical deformation. In [4], the authors had design A circular antenna, aimed to measure the humidity content of sludge samples as a new method for determining the moisture content of dielectric materials. the wearable textile antenna becomes more involved in on-body applications, due to its ability to detect microstructure deformation and human motion and to monitor and supervise human health[5]. In a comparison with conventional antennas, textile antennas have the advantages of being integrated with the outfits and offer many key features such as lightweight, comfort, and washability. There are many different types of flexible antennas such as a microstrip patch antenna, monopole antenna, and planar inverted-F antenna. Conductive materials used such as gold, silver, and copper are widely used as a radiating element due to their high conductivity. High conductive materials ensure high gain, efficiency, and bandwidth. Silver, for example, had a conductivity of $6.173 \times 10^{7}$ (S/m). Another important consideration to design the flexible antenna is the substrate itself. Felt fabric[6], Jeans[7], and polyethylene terephthalate (PET)[8] are among many other substrates used due to low dielectric constant.
2. Flexible antenna design

The design of a flexible antenna near the human body will affect many parameters such as detuning and impedance mismatching[9]. Researchers had to design the flexible antenna without compromising the antenna performance parameters like bandwidth, gain, efficiency, impedance matching, and radiation pattern. Researches had proposed some of the wearable antenna design such as microstrip patch antenna[10], monopole antenna[11], the planar inverted-F antenna[12], substrate-integrated waveguide antenna (SIW)[13], magneto dipole antenna[14], and electromagnetic bandgap (EBG)-type antenna[15]. Slot monopole antenna[16], and fractal patch antenna[17] are two examples of flexible antenna which can reduce the physical structure of the antenna without compromising on the radiation efficiency. Figure 1. Shows the common types of antenna design.

![Figure 1. Flexible antenna design. (a) Microstrip patch antenna[10]. (b) Monopole antenna[11]. (c) Planar Inverted-F antenna[12]. (d) Magneto dipole antenna[14].](image)

2.1. Antenna miniaturization

The minimization technique of the antenna is commonly related to the electrical and physical properties. It can be divided into two groups, the topology, and materials method. Therefore, each of the groups contains various shapes and types. For example, meander lines, fractal shapes, space-filling curves, high dielectric materials, and metamaterial surface (MT)[18], button-shaped and single and multiband antennas are using metamaterial surfaces are widely used in the WBAN systems. Theses mentioned techniques have successfully minimized the backward radiation and reduced the coupling effect between the body and the antenna[18]. researchers had developed an electromagnetic bandgap (EBG) structures which have the ability to reduce the physical surface of the antenna without compromising on the radiation efficiency of the antenna. this structure (EBG) has shown a great result in improving the bandwidth, reduce the impedance mismatch caused by the body user permittivity, and reduce the antenna size. In addition, studies have shown that Photonic bandgap (PBG) structures, which is another form of EBG, Photonic bandgap PBG is a 3-D structure with stacked EBG layers or a combination of multilayer metallic and tripod array, it has the advantage of preventing the propagation of a certain wavelength due to its periodic nature. It has also shown some help to minimize the effect of the radiation on the cylindrical curvature and it helps to improve the gain and directivity.

3. Flexible materials for flexible antenna

Two most important materials which will affect the performance of the Flexible antennas are the conductive materials and the substrates. The conductive material is chosen according to the electrical conductivity, while the substrate material is based on the dielectric properties, tolerance to its mechanical deformation like bending, wrapping, and twisting, endurance in the external environment, and susceptibility to miniaturization[19]. Material selection is preferred to be chosen based on the abovementioned properties to ensure high gain, efficiency, and bandwidth

3.1. Conductive material

The investigation of conductive materials with high electrical conductivity is preferred to ensure high efficiency of the antenna such as silver with a conductivity of $6.173 \times 10^7$ (S/m)[20]. Resistance and high tolerance to degradation due to mechanical deformations are some of the desired features when it comes to conductive materials. Nanoparticle (NP) inks such as silver and copper are preferred by the researchers for fabricating the antenna because they possess a high electrical conductivity[21]. For example, copper tapes[22], adhesive copper[23], polyaniline (PANI)[24]. In[25], a dual-band antenna
for wearable applications has been developed to improve the low conductivity of conductive polymers by adding carbon nanoparticles. To employ mechanical strain and deformation without a reduction in terms of antenna performance and efficiency various stretchable conductive materials exploit doping to improve their conductivity such as silver loaded fluorine[26], CNT based films[27], and silver flakes embedded silicone[28], [29]. In [30], authors developed a Graphene-based dipole antenna for ultrahigh-frequency (UHF) remote frequency identification (RFID) tag the authors claimed a novel antenna can be an alternative to much more expensive circuits printed with silver-based inks in applications where the interrogation range is not crucial. Nevertheless, authors tend to utilize graphene because of its excellent mechanical properties and decent electrical conductivity[31]–[34]. Table 1. shows two types of conductive materials used by the researchers.

| Ref. | Material type | Conductive materials | Conductivity σ (S/m) |
|------|---------------|----------------------|---------------------|
| [35] | Conductive polymers | PEDOT: PSS | 100-1500 |
| | | Polyaniline (Pani) | 5 |
| | | Polypyrrole (PPy) | 40-200 |
| | | Polyacetylene (PA) | 200-1000 |
| [20] | Metal nanoparticles | Silver nanoparticle | 6.173 × 10⁷ |
| | | Copper nanoparticle | 5.813 × 10⁷ |
| | | Gold nanoparticle | 4.098 × 10⁷ |

3.2. Substrate

Substrate material with low dielectric loss, low coefficient of thermal expansion, low relative primitivity, and high thermal conductivity[36] is the ideal condition for the flexible antenna. To minimize the size of the antenna, the dielectric constant of the substrate needs to be large. However, to increase the antenna efficiency it will cost at large antenna size, which offers a trade-off between the efficiency and the size of the antenna design. In many flexible antenna applications, substrates that possess the features of robustness, washability, flexibility, and stretchability tend to be the most popular and attractive to be used by researchers Table 2 lists the different substrates used by researchers in the designing of a flexible antenna.

| Ref. | Substrate | Dielectric constant (εr) | Return loss (tanδ) | Thickness (mm) |
|------|-----------|-------------------------|--------------------|----------------|
| [37] | Wash cotton | 1.51 | 0.023 | 3 |
| [11] | Kapton polyimide | 3.5 | 0.003 | 1 |
| [38] | FR-4 | 4.3 | 0.02 | 0.8 |
| [39] | Jeans | 1.54 | 0.03 | 2.84 |
| [40] | PDMS | 2.65 | 0.02 | 2 |

3.2.1. Relative constant (Dielectric constant)

The dielectric constant is one of the most crucial parameters, it affects the ability to transmit changing signals through the fabric transmission line[41]. The relative primitivity is expressed as Equation (1):

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon'_r - j\varepsilon''_r)$$  \hspace{1cm} (1)

Where $\varepsilon_0$ is equal to 8.854 × 10⁻¹² F/m which is the permittivity of vacuum[42]. The dielectric property depends on many factors, such as the temperature, the frequency, surface texture roughness, purity, moisture content, and the homogeneity of the materials. Some textiles materials are anisotropic materials and their characterization also depends upon the orientation of the electrical field. As a consequence, textiles show a low dielectric constant as they are very porous materials due to the presence of air, which makes the relative primitivity close to one. In general, the low dielectric constant reduces the surface wave losses. Therefore, lowering the dielectric constant increases the impedance bandwidth of the antenna and increases the spatial waves which make the antenna acceptable with high efficiency and gain. Table 2. shows the dielectric constant for some of the substrates.
3.2.2. Absorption of the moisture
Textile materials are establishing dynamic stability with the humidity and temperature and its constantly exchanging water molecules with the surrounding air. However, the material regains which is the ratio of the mass of absorbed water in the specimen to the mass of dry specimen determines to what extent material is sensitive to moisture. The moisture absorption alters the properties of the textile materials in general. Therefore, the small moisture absorption value for example regain less than 3% is more stable[43]. In general, materials of low regain are desirable to use as a substrate such as polyester fiber which presents a regain of 0.2%[44].

3.2.3. Thickness of the dielectric fabric
The thickness and substrate dielectric constant determines the efficiency performance and bandwidth of the antenna. The thickness may give larger variations because of the very narrow range of primitivity values of the textile materials. Therefore, it is crucial in the design of the antenna because it determines the input impedance as well as the bandwidth and also its resonance frequency[45], the thickness of the substrate material used to design the antenna influences the geometric sizing of the antenna. the thin substrate with low relative primitivity close to 1 and 2 results in a small size of the antenna path, and conversely the thick substrate with low relative permittivity results in a large antenna patch[46], [47].

3.2.4. The electrical surface resistivity of the conductive fabrics
Good performance of the flexible antenna is highly influenced by choosing suitable conductive fabric for the patch and the ground of the antenna. The surface resistivity is the ratio of the dropped DC voltage to the current of the surface per unit length. Fabrics must possess a very low electrical surface resistance to minimize the electrical loss and hence increase the antenna performance. [48]. The bending, twisting, elongation, and curvature of dielectric fabrics have excellent flexibility and elasticity, and they adapt very well to the human body. However, whenever the textile material adapts to a surface topology or human body movement like standing or sitting, it deforms and bends causing changes to its electromagnetic properties and influence the antenna performance, such as the bandwidth and the resonates frequency.

4. Fabrication Methods
In order to provide excellent stability as well as electrical performance for the Flexible antenna, it is necessary to implement a suitable fabrication technique. Researchers had used a variety of fabrication techniques based on their requirements. Screen printing, inkjet printing, sewing, and embroidering are among the common fabrication techniques used.

4.1. Screen Printing
Screen printing is a low cost and highly effective printing technology[49]. Furthermore, it is fast and one of the easiest techniques used to fabricate the antenna. screen printing is considered a versatile technique because it can be used to printing images on most of the materials Figure 2. below shows some of the fabricated antennas using screen-printing techniques.

![Screen Printing](image)

Figure 2. screen-printing antenna. (a) screen printing of strain test patterns[50]. (b) screen printed textile antenna[51]. (c) Meandered-line antenna structure[33].

4.2. Inkjet Printing
Inkjet printing is another fabrication technique for the flexible antenna and it considers one of the low-cost printing technologies[52]. Inkjet printing technique can produce a very high precision pattern due to its use of ink droplets of the size of up to little picolitres[53]. The inkjet printing technique is among
the economical manufacturing methods because it projects the single ink droplet from the nozzle to the desired position without any waste. Because of that inkjet printing outweighs the traditional etching technology[54]. This technology is incompatible with some types of conductive inks because of the clogging of the nozzles and the larger particle size. Figure 3. shows some of the inkjet printing antennas.

![Figure 3. Inkjet printer antenna. (a) Z-shaped antenna using inkjet printer technique[55]. (b) inkjet printer antenna[56]. (c) Flexible inkjet-printed antenna on PET film[57].](image)

4.3. Sewing and embordering

The method of sewing and embroidering is currently employed in many applications of the flexible antenna. This method does not use adhesion material over the fabric which may affect the electrical properties of the material. Furthermore, due to the sewing process wrinkles are formed on the fabric, which results in distorted antenna characteristics. However, this method is not suitable for a spacer textile substrate[58]. For the embroidery technique, the method has been involved to allow a digital image or layout to be embroidered using a computer-assisted embroidery machine. Nowadays embroidery antennas are offering a better solution compared with the traditional antennas in flexible electronics due to the embroidered geometry which is much stretchable than metallic antennas[59]. Figure 4. shows some of the fabricated antennas using embroidering and sewing techniques.

![Figure 4. Embroider Technique (a) E-shape antenna fabricated based on embroidering technique[60]. (b) Embroidered patch antenna[61]. (c) Embroidered NMPA on a flexible felt substrate[62].](image)

5. Applications of Flexible antenna

There are many applications of the flexible antenna due to the increase of wearable devices and the rapid growth of the user’s requirement. For example, the health monitoring system in particular may lead to a good impact on people’s health such as monitoring physiological issues and physical fitness. Flexible antenna is also used in other applications such as sports, smart clothes, and gaming. Flexible antennas are also widely used in the military like a battlefield, helmet, and identifications. There are many other applications of Flexible antennas such as telecommunications, Global positioning systems (GPS), and telemedicine. Table 3. Shows some of the previous studies with different applications of the flexible antenna.
Table 3. Review of the previous Studies about Flexible antenna with different applications

| Ref. | Type of the antenna | Substrate | Fabrication method | Application | Advantages |
|------|---------------------|-----------|--------------------|-------------|------------|
| [8]  | Monopole antenna    | polyethylene terephthalate (PET) | Inkjet printer DMP-3000 | Wearable devices at 1.8 GHz | Obtained efficiency of 93.33%. The proposed design can overcome the cost and size. |
| [50] | RFID                | Thermoplastic polyurethane (TPU) | Screen printing | Radio frequency | The antenna shows a good performance with high elongation. Simulation and experiment results were excellently matched. |
| [63] | Microstrip patch    | Polydimethylsiloxane (PDMS) | Embroidery | Realization of Robust Passive and Active Flexible Wearable Antennas at ISM 2.45GHz | Consistence performance. The antenna could be reconfigurable Experienced no performance change after exposing to harsh environment. |
| [64] | Planar monopole     | Kapton polyimide | Inkjet | Flexible Wireless Devices at 1.2-3.4 GHz | Lightweight and conformal design. Multiband performance in bent configurations. |
| [65] | Square patch antenna| NinjaFlex | Prenta Duo 3D printer. | Wearable antennas and wireless on-body applications. At 2.45GHz | Excellent wireless performance when bent. Good impedance matching and efficiency. |
| [33] | Meandered-line antenna | paper | Screen-printing | Low-Cost RFID and Sensing Applications | Good radiation efficiency. Acceptable return loss, bandwidth, gain, and radiation pattern for mid and short-range RFID. Flexible and stable thermally and electronically. |
| [66] | Microstrip patch    | Elastomeric polydimethylsiloxane | Soft lithographic process | Conformal antenna applications. At 3-4 GHz | Good performance of the flexible antenna with no hysteretic behavior. New and novel fabrication technique. |
| [67] | Inverted-F antenna  | Fabric | Dimatix DMP-2831 Inkjet printer | Wearable electronics applications at 2.45GHz | Shows an acceptable return loss and radiation pattern. No significant difference between the simulated and fabricated results. |
| [68] | Microstrip patch    | Fabric | Screen-Printed with stretchable silver ink DuPont PE873 | Millimetre-wave Applications at 77 GHz band | The antenna array maintains a good performance in flat and bent conditions. The antenna array succeeds in detect moving objects in three different directions. |
6. Conclusion
The area of the Flexible antenna is evolving and relates to more interdisciplinary subjects such as mechanical, electrical engineering, and material science. Flexible antennas that are integrated with textiles can be implemented in medical and telecommunications applications. The advantages of the flexible antenna, which are lightweight, low-cost fabrications, reduced form of factors, and the ability to fit the non-planar surface will open more possibilities for future applications. However, the materials for the antenna design such as conductive materials and substrate, need to be chosen carefully based on the requirement needed, to gain a satisfactory performance. Therefore, conductive materials and substrates with high conductivity such as silver with a conductivity of $6.30 \times 10^7$ (S/m) and low dielectric constant, respectively, are preferred.

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