

Current Trends on Wearable Antennas, Fabrication Techniques and Materials

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Introduction

We are witnessing a rapid increase of Information and Communication Technologies (ICT). The tremendous growth of new services and demand has led to the design and development of new devices which can satisfy various demands in terms of shape, size and functionality. Undoubtedly, the Internet of Things (IoT), generic term to describe the ability of physical objects equipped with sensors and processing units to connect and exchange data with other devices, has been decisive for the deployment of those equipment. On the other hand, with the deployment of 5G, a new wireless mobile network standard, everything can be connected with higher data rate and speed, lower latency and more reliability. The spread of 5G networks is essential for the full usage of IoT and virtually connects everything (or everyone) to everything. According to (Galov, 2022), the number of connected devices will be around 29.4 billion by 2030.

Besides, academic studies on antennas, which are indispensable elements of wireless communication and internet of things applications, continue intensively. Along with the developing technology, it is important that antennas are portable on the user in terms of not interrupting the communication, as well as being able to work with high gain in the newly allocated frequency bands. Here, portable means that the devices are part of the user body, clothes, or accessories, rather than being carried in their hands or in pockets like mobile phones or tablets. In fact, the word *wearable* is more often preferred to the word *portable* and it is used for any electronic device that is worn as an accessory or embroidered into clothing or implanted under the skin or tattooed on the skin. Wearable antennas can be integrated into many portable devices worn on the user, as shown in Figure 1. These devices can be, for example, smart glasses, smart belt, as well as smart shirts and trousers (Rodrigues et al., 2018).



Figure 1. Wearable technologies that can be worn on the user (Rodrigues et al., 2018)

Wearable technologies are used in many areas today. They are frequently used in applications such as monitoring the physical activities of people (Tokucoglu, 2018) and patients (al Bassam et al., 2021), and monitoring the life signals of elderly people (Baig et al., 2013) etc. For instance, measuring body health signals such as cardiac rhythms, blood pressure, temperature and transferring them to a central hospital instantly is vital in the follow-up of patients (al Bassam et al., 2021; Dias & Cunha, 2018; Roudjane et al., 2018). On the other hand, in sportive activities, wearable technologies are used to obtain location and direction information of athletes, monitor their performance and track targets, as well as monitor their health status (Tokucoglu, 2018). Likewise, in the defense industry, wearable technologies are designed and developed for purposes such as monitoring the health status of soldiers, navigation and communication (Sharma et al., 2020). In the next five years, the military wearable technologies market is expected to reach 3.4 billion USD (Marketsandmarkets, n.d.). In mining, wearable technologies are of vital importance to instantaneously locate workers with wireless communication and, if necessary, to evacuate them from dangerous areas.

One of the most important components of a wearable device is the antenna part used to send and receive signals to be processed later. Depending on the application and the type of wearable device, the antenna needs to be tailored to extract the most useful information from the sent/received signal with the lowest degradation. If the wearable device is embedded in the clothes of the user, the antenna should be made from flexible materials for achieving a highly embedded device that is not obtrusive. However, the flexibility of the antenna that has to be considered when designing an antenna is also a factor for degradation of the signal. In parallel, the antenna should be low profile for compactness purposes. Additionally, the antenna designer should pay attention to the proximity of the antenna to the body that is likely to degrade the performance of the device.

This book chapter is dedicated to reviewing current trends on wearable antennas. The second part of this review will be on a brief history and applications of wearable devices. Then, the antenna, an essential element of wearable devices will be reviewed. In particular, some of the different fabrication processes existing in the literature and materials used for the antenna fabrication will be explored.

Brief History and Applications of Wearable Antennas

Although some consider the introduction of wearable devices back to the Middle Ages, to the invention of the first glasses, modern wearable technologies reached their current usage with the development of computers in the middle of the 20th century (Ometov et al., 2021). The rapid development of portable computers has brought different applications in many other fields. The emergence of the first hearing aids in the 80s with the increase in the functionality of wrist watches in parallel to technological developments can be shown as the first examples of wearable technologies. The 70's and 80's were also the years when wristwatches with calculators were introduced to the market. Examples are Hamilton Pulsar (1975), HP Algebraic Calculator (1979) and Seiko Data-2000 (1983). The advances of wearable devices have been boosted by the introduction of the Bluetooth Technology (BT), a protocol for connecting different devices wirelessly (Ullah, 2009). This enables remote control and wireless transfer of information between any two or more wearable devices equipped with the BT. This highly popular technology stands out because it is cheap, easy to use and does not have to be on the line of sight of communication (Verma et al., 2015). In 1999, the first Bluetooth headset was released as one of the first wearable devices using the Bluetooth technology to communicate with a cell phone (Seneviratne et al., 2017).

In parallel, we witnessed the development of a new type of wearable device which can be mounted on the head next to the eye of the user and displays images as if it were seen by the eye. One of the early initiatives, the so called EyeTap project (Mann et al., 2005), is considered as the father of the first prototype of Google glasses which were available to the public in 2014 (Wikipedia contributors, 2022). The ambition of Google was to build a head-worn computer that will help to “explore and share the world”. These new technologies contributed to the widespread use of Augmented Reality (AR) technologies (Carmigniani et al., 2011).

The existing commercial wearable devices may be classified as: accessories, e-textiles, and e-patches. The above-mentioned devices are considered as accessories because they are not part of the clothes nor the body of the user. These are accessory devices in the form of wristbands, wristwatches and glasses. They can be worn and removed at will. On the contrary, e-textiles are the product of the integration of electronics with the traditional textiles (Komolafe et al., 2021). Thus, sensing physical activities, communicating with other electronic devices can be easily performed. For delivering drugs to the patient and

for monitoring biometric parameters such as body temperature, heart rate etc., e-patches are employed (Vijayalakshmi et al., 2018). These devices are placed directly on the skin of the user.

Although one the first e-textile devices (electrically heated gloves) was released in 1910, most of them have been developed after 2000, triggered by the rapid rise of modern technology (Hughes-Riley et al., 2018). Technologically more advanced e-textile devices consisting of electronic devices incorporated into pockets of the clothing have been proposed (Heilman & Porges, 2007). Heart rate monitoring sport bra (Navalta et al., 2020), ECG sensors in garments (Uz Zaman et al., 2020; HealthWatch contributors, n.d.), smart socks equipped with textile sensors to count footsteps, distances etc. (Sensoria contributors, n.d.) are some of the many examples that can be found in the literature. For more applications of wearable e-textiles, readers can refer to (Uz Zaman et al., 2022; Stoppa & Chiolerio, 2014; Komolafe et al., 2021; Dacuna & Pous, 2009).

Wearable Antenna Fabrication Techniques and Materials

An antenna is a key component of a wearable device. It allows the device to communicate with other surrounding equipment and to get rid of the cable bundle if the communication must be made with other on-body devices. Although, theoretically an antenna can be in various forms, it should obey certain criteria that will qualify it as wearable. For instance, to be unobtrusive, its overall size should be as small as possible. Thus, as opposed to bulky antennas, like horn antennas, its thickness should be the lowest possible. These antennas are said to be planar or low profile antennas. Low profile antennas are widely used in applications such as RFID localization (Dacuna & Pous, 2009), communication (An et al., 2018), biomedical (Islam et al., 2022) etc. These low-profile antennas are generally made of a substrate under which a metallic ground plane exists and a metallic patch to radiate the electromagnetic wave to the surrounding medium. Depending on the material of the substrate and the fabrication process, these antennas can be characterized as flexible, conformable etc. Below, various wearable antennas will be presented. They will be examined within two categories: the process of fabrication and materials used for their manufacture.

Fabrication Techniques

Various techniques have been considered for the fabrication of wearable antennas. Among other techniques, screen printing (Blayo & Pineaux, 2005), inkjet printing (H. R. Khaleel et al., 2013; Le et al., 2013) and embroidery (Tsolis et al., 2014) methods are probably the most popular ones.

The antenna can be easily and economically printed employing the screen printing technique (Figure 2a). It consists of transferring the ink to the substrate through a stencil. As shown in the figure, a squeegee blade is used to force the ink downward. Despite the advantages underlined above, this process has some disadvantages. Because of the

nature of the process, it leads to printed patterns with low resolution and the thickness of the layer deposited can not be controlled. This can be a problem for antenna applications where precise thickness is needed (el Gharbi et al., 2020).

The inkjet printing method is an alternative printing technology (Figure 2b). Small amount of droplets, in the order of 1 pL, are deposited on the surface of a substrate either using the continuous inkjet or the drop-on-demand technique. The amount of liquid deposited to the substrate is controlled by a computer and directly deposited to the position where the antenna pattern is. Thus, highly precise patterns can be printed without the need for a mask. This makes the technique very efficient and economic when compared to other techniques. In the drop on demand process, a single drop of the ink can be ejected by increasing the pressure within the reservoir either by a piezoelectric actuator or a resistive heater. Most electronic boards manufacturers use the drop on demand technique. Although many other types of metal inks such as copper or gold exist, silver nano-particle ink is preferred for printing conductive circuits because of its relatively low curing temperature and high electrical conductivity (Kim, 2020).

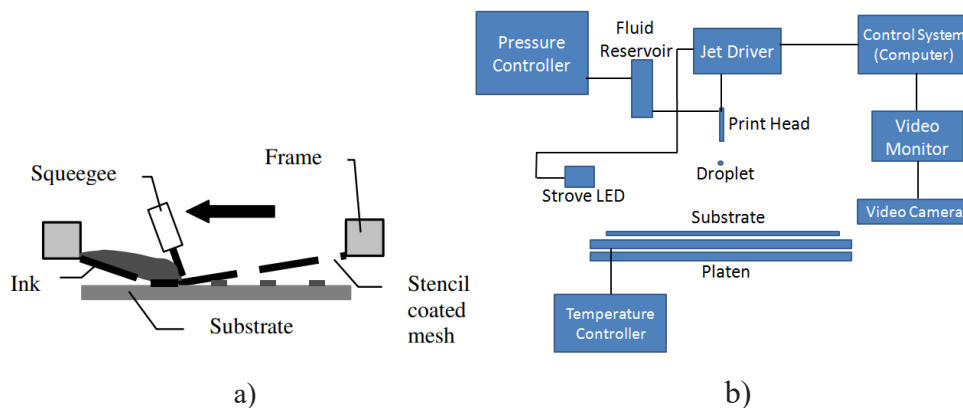


Figure 2. Printing processes, a) screen printing (Blayo & Pineaux, 2005), inkjet printing (H. R. Khaleel et al., 2013; Le et al., 2013)

In recent years, embroidering has become popular among scientists and engineers for fabricating wearable antennas (Tsolis et al., 2014). It uses conductive threads and specialized computer assisted machines to sew the metallic part of the antenna on a fabric substrate. The process of embroidering is shown in Figure 3. First, the antenna geometry is drawn on a computer, then after the digitization step, it is sent to the computerized embroidering machine that is purposely used to embroider the antenna on a textile. This technique is the preferred one when it comes to the fabrication of textile antennas since there is no need to use adhesive material to glue the patch to the substrate. In fact, as will be discussed below, using a third material between the patch and the substrate may change the antenna physical properties and deteriorate the antenna performance. There are several criteria that have to be considered when using embroidering technique to fabricate textile antennas. First, the conductivity of the thread has to be as high as

possible. For this reason, silver threads are mostly used for embroidering the antenna conductive parts on the substrate. Second, the threads should be strong enough but flexible at the same time so as not to split under hard working conditions (Ali et al., 2020).

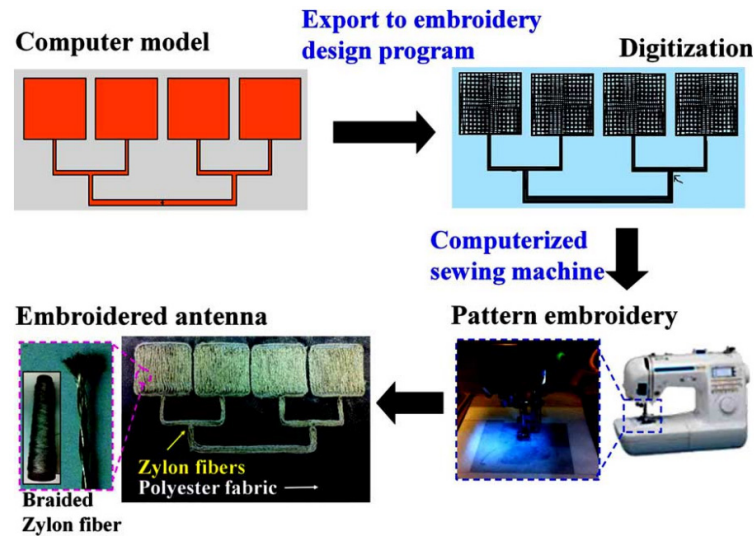


Figure 3 Process of fabrication of the embroidered antenna (Wang et al., 2012)

Recently, Laser Direct Structuring (LDS) method is gaining attention for the fabrication of conformable and wearable antennas. LDS is an innovative technology for fabricating antenna structure on thermoplastic materials specifically manufactured for that purpose. As shown in Figure 4, the fabrication process is implemented following 4 distinct operations. First, the part on which the metallic part will be patterned is fabricated by the injection molding technique. Commercially available thermoplastic materials provided with LDS additives (thermoplastic doped with a metal-organic compound) or any other plastics, metals, glass, FR4 can be used for the molded part. In the latter case, the material should be coated with some special painting material to prepare the surface for the LDS process. The LDS ready material is a special plastic doped with a mixed metal oxide that can be activated with a laser beam. The second step is the activation of the surface where the antenna pattern will be metallized. The laser patterning of the conductive traces is essential for the copper to adhere firmly to the surface of the part. Once the surface of the part (antenna) is activated by treating it with the laser beam, the part can be metalized (deposition of the copper ions to the activated surface) by the electroless plating process. Subsequently, other surface finishing techniques such as reduction of the oxidation can be employed (Yang et al., 2017; Stafford, 2014; Kumar et al., 2020).

Although the LDS technique is well-known for structuring electronic circuits for molded interconnect devices, to the best of the author's knowledge, it has not been fully exploited for flexible and wearable antenna fabrications. For many years, it has been considered mainly to manufacture antennas for consumer devices such as smartphones, laptops

and tablets (Friedrich et al., 2016). Only recently, other devices such as smart watches and wristbands have been shown as potential applications for the LDS method (Kumar et al., 2020; Berkelmann et al., 2018). Future direction of research should definitely include other wearable antenna applications such as flexible and textile ones. The appropriateness of textile materials for LDS technique should be studied and examined.

In (Kumar et al., 2020), LDS technique has been proposed for the fabrication of an antenna for a wristwatch wireless sensor (Figure 5a). In the aforementioned work, the antenna structure is printed on an ASA thermoplastic enclosure. In order to allow metallization of the selected parts, the part is then coated with an LDS epoxy layer. After having implemented a π -type matching network, it has been shown that the measured results exhibit acceptable impedance and radiation characteristics.

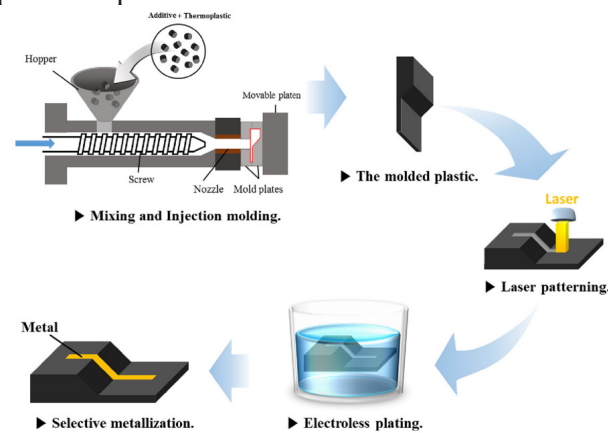


Figure 4. Laser Direct Structuring Process (Yang et al., 2017)

In (Berkelmann et al., 2018) authors proposed the LDS technology for the fabrication of off and on-body communication antennas to fit the 3D surface of a human body. A slotted patch antenna and an inverted-F antenna are designed to operate at the same frequency band of 2.4 GHz for Wireless Body Area Networks (Figure 5b). The Vectra 840i LDS, a Liquid Crystal Polymer (LCP) is used as a substrate for structuring the antennas. It has been shown that by utilizing the LDS technology, the desired excitation of the electromagnetic wave components for both off and on-body communication is possible. Moreover, this technology allows a compact and conformal integration of the antenna system to the human wrist.

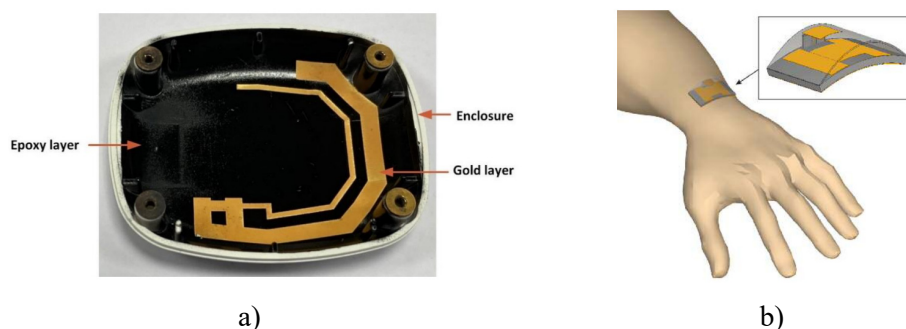


Figure 5. a) Wristwatch device showing the antenna unit (Kumar et al., 2020), b) Wristband on a 3D human wrist model (Berkelmann et al., 2018)

Antenna Materials

The choice of the material is utmost important for the fabrication of the wearable antenna. Both of the dielectric (substrate) and the conductive (ground and radiating patch) parts of the antenna should be chosen properly. In fact, the nature of the material of the antenna will directly affect its performance as well as its integration to the garment. An appropriate selection of the material will contribute to the flexibility and conformability of the antenna. In this work, although other materials exist, only textile and polymer based antennas and related works will be presented and discussed.

Textile Based Antennas

Early textile antennas were based on rigid conductive copper foils directly glued to the textile materials. It is known that one of the first studies on antennas on fabric materials was conducted in 2001 by (Salonen et al., 2001). In the aforementioned study, a flexible PIFA antenna working as single band and dual band in Bluetooth and UMTS bands was designed and manufactured. It has been observed that the working performance of the antenna structure, which is claimed to have been the first commercial thin and flexible antenna, is satisfactory. The same author, in another study, examines the effects of different fabric substrates on a GPS antenna (Salonen et al., 2004). In this study, it is mentioned that fiber-reinforced synthetic fabric, whose trade name is Cordura, can be preferred because of its resistance to mechanical changes and the presence of water. In (Salvado et al., 2012), the authors compare many fabric materials used in antenna manufacture. As expected, Cordura® + copper foil gives good results.

According to the authors, the first all-fabric PIFA antenna was manufactured using conductive copper polyester taffeta, in 2012 (Soh et al., 2012). As seen in Figure 6a, the antenna is completely made of fabric, and the conductive copper taffeta fabric is sewn directly onto the felt fabric with thread. More recently, a low-profile ultra-wideband antenna capable of operating between 1.198–4.055 GHz for microwave medical imaging has been developed by applying conductive copper taffeta fabric on a polyester fabric (Lin et al., 2020). By using conductive copper taffeta fabric instead of traditional copper foil, a 100% textile wearable antenna was developed and the flexibility, which is a very important parameter in wearable antennas, was increased (Fig. 6b). In this study, copper taffeta was attached to the polyester fabric with a very thin thermal film and iron steam. In addition to providing a solid adhesion, it has been reported in (Loss et al., 2016) that the addition of the adhesive thermal film may experience shifts in conductivity and dielectric properties of the material, which will affect the performance of the antenna. Since the copper taffeta fabric is a highly conductive and corrosion resistant material, the decrease in antenna performance due to the weakening of the conductivity caused by corrosion can be prevented.

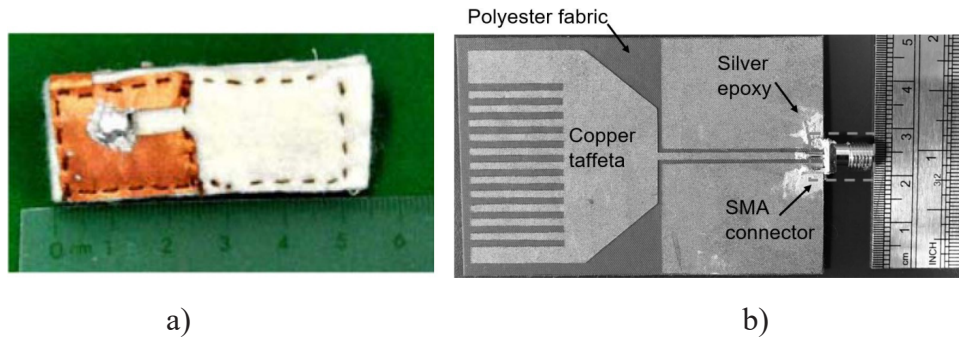


Figure 6. a) PIFA antenna (Soh et al., 2012) and b) UWB antenna (Lin et al., 2020), made of copper taffeta on polyester fabric.

In (Loss et al., 2016), it is aimed to harvest energy at 900 MHz and 1800 MHz frequencies by integrating the antenna directly on the fabric made of Cordura ® fabric.



Figure 7. Smart coat with integrated dual band antenna for energy harvesting (Loss et al., 2016)

In this study, instead of copper foil as a conductive material, the structure forming the antenna is embroidered on the fabric with a conductive thread (Figure 7). It is thought that in this way, the antenna will be more invisible and can be easily hidden in the clothing. In addition, the use of a conductive thread instead of a copper foil, which is a harder and solid material, is important for the ease of use of the clothes. Processing antennas directly on fabrics with embroidery machines provides advantages for mass production. Especially with the digitalization of embroidery machines, the transfer of the antenna pattern directly to the computer-controlled machine facilitates the processing of antennas in different colors and complex forms (Kiourti & Volakis, 2015). Embroidered antennas are easy to apply and mechanically robust, which makes them advantageous over other fabric antennas. However, it is necessary to pay attention to aspects such as the conductivity, durability and flexibility of the thread used, and the direction and density of embroideries (Chauraya et al., 2012). The direction and the density of the embroidery (Zhang et al., 2012) not interfering with the flow of the electric current will

positively affect the antenna performance.

One of the antennas embroidered directly on the fabric is given in (Moradi et al., 2013). In this study, RFID tag performances operating at UHF frequencies were examined according to embroidery direction and patterns, and the reading distance of the antenna was tested on the body. In 2005, the authors developed another approach by integrating the antenna directly into the embroidered logos on the garment (Soh et al., 2012). A similar study can be found in (Atanasova et al., 2022). Thanks to the high sensitivity of the embroidery machine, more resistant, flexible, lightweight and colorful logo antennas have been developed. More recently, an RFID tag antenna that can operate in the 870-990 MHz range has been produced with X-static (©Kwontex, Korea) conductive yarn formed by twisting many silver-plated thin elastic nylon fibers (Figure 8). In this study, the effects on antenna performance of parameters such as yarn density and the antenna deformation were investigated. It is concluded that increasing the yarn density would also increase the resonance frequency (Truong et al., 2021). In another study, a compact textile antenna, knitted with Zari silver conductive material, was embroidered on a cotton substrate in order to monitor the heart rate. Besides the humidity, deformation, and wrinkles, the effect of the human body on the antenna performance is investigated (Anbalagan et al., 2020).

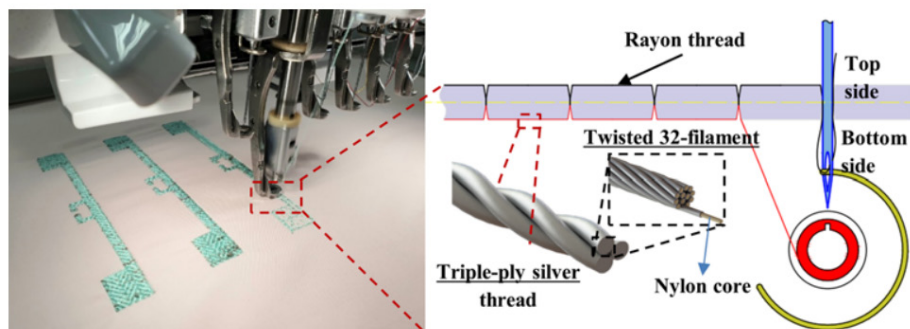


Figure 8. Embroidering RFID tag antenna using X-static conductor thread (Truong et al., 2021)

In (el Gharbi et al., 2022), the authors embroidered a curved dipole antenna on a cotton t-shirt to monitor real-time breathing (Figure 9). The conductive parts of the antenna are made of a Shieldex® brand conductive thread. It has been shown that the antenna operating at the 2.4 GHz frequency consistently detects the person's breathing in different positions (standing and sitting) and in different breathing patterns. It is predicted that the developed antenna can be used to detect problems such as respiratory failure in newborn babies, sleep apnea and asthma in children and adults.

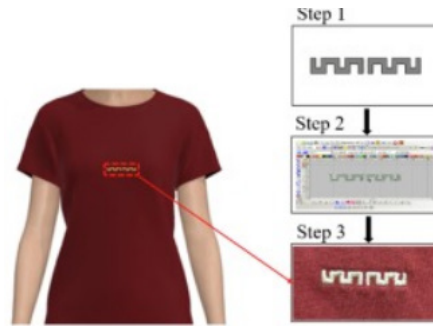


Figure 9. Embroidered antenna integration into a cotton T-Shirt for breath monitoring (el Gharbi et al., 2022)

Polymer Based Antennas

Polymers have the great advantage to be highly flexible and stretchable that make them suitable for wearable applications. As such, polymers are mostly used as substrates. Due to the proximity of the antenna to the human body, it must be robust against any deformation. For instance, if the antenna is mounted on a clothes, it must withstand any bendings and twistings of the fabric. Moreover, polymers are highly resistant to water and they can be used without altering their electrical properties. Among various polymer materials, the polyimide, the Polyethylene terephthalate, (PET), the polydimethylsiloxane (PDMS) materials are the most widely used ones (H. Khaleel, 2015).

The Kapton material, a polyimide film, is one the most commonly used substrates for wearable antenna applications. This material can withstand extreme temperatures while maintaining its physical properties (H. R. Khaleel et al., 2013). In (H. R. Khaleel et al., 2012), authors presented a compact elliptical UWB monopole wearable/flexible antenna (Figure 10a). The antenna is printed on a 50.8- μ m Kapton polyimide substrate. It has been shown that the impedance matching and the radiation pattern characteristics of the antenna has a very small change when the antenna is subjected to deformation. In a more recent study, an UWB antenna, where the Kapton material is used for the substrate and a conductive nanocomposite material based on a polymer (polyaniline: PANI) and charged by multiwalled carbon nanotubes (MWCNTs) are used for the ground plane and the radiating patch respectively, is developed (Hamouda et al., 2018). Flexible polymer antennas intended to be used in IoT applications and based on Polyethylene Terephthalate (PET), Polytetrafluoroethylene (PTFE) Teflon, and Polyvinylchloride (PVC) substrates operating at 2.45, 4.45, and 7.25 GHz frequencies were fabricated and their bending capabilities are evaluated in (Khan et al., 2021). Next, a highly flexible antenna based on the use of PDMS material was proposed in (Simorangkir et al., 2016; Simorangkir et al., 2018). A conductive silver fabric was embedded into the PDMS substrate which has the advantage of having flexibility as well as water and thermal resistance (Figure 10b).



Figure 10. a) Elliptical UWB antenna based on Kapton polyimide material (H. R. Khaleel et al., 2012),
b) PDMS-embedded conductive fabric antenna (Simorangkir et al., 2018)

Conclusion

In this chapter, some of the most recent works on wearable antenna technologies have been reviewed. After a brief history and their evolution timeline, commonly used fabrication techniques and materials have been presented. Due to their wide use, textile and polymer-based antennas are considered in this work. Among textile materials, embroidered patches on fabrics have shown to provide much more strength and flexibility compared to patches made of copper foils. High flexibility, resistance to high temperatures and water make polymer-based antennas the preferred solution for applications where extreme conditions prevail. Regarding the fabrication process, the embroidering technique has become popular for integrating textile antennas directly on the clothes. Depending on the electrical and mechanical properties of the thread used for embroidering the metallic patch and the density of the stitches, high performances can be reached. A more recent approach based on laser direct structuring was also presented for manufacturing wearable antennas. Although this technique is promising for the development of more complex design, only few works exist. This technique should be proven on substrates such as textile and flexible polymers.

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