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Recent Advances in Wearable Antenna Technologies: A Review

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Abstract—Wearable antennas have received a great deal of popularity in recent years owing to their enticing characteristics and opportunities to realize lightweight, compact, low-cost, and versatile wireless communications and environments. These antennas must be conformal, and they must be built using lightweight materials and constructed in a low-profile configuration when mounted on various areas of the human body. These antennas ought to be able to function close to the human body with limited deterioration. These criteria render the layout of wearable antennas demanding, particularly when considering factors such as investigating the usability of textile substrates, high conductive materials during fabrication processes, and the effect of body binding scenarios on the performance of the design. Although there are minor differences in magnitude based on the implementations, several of these problems occur in the body-worn deployment sense. This study addresses the numerous problems and obstacles in the production of wearable antennas, their variety of materials, and the techniques of manufacturing alongside with bending scheme. This is accompanied by a summary of creative features and their respective approaches to address these problems recently raised by work in this area by the science community.

1. INTRODUCTION

Wearable devices are set to increase to 578 million in 2019, which reflects a fivefold improvement compared to 2014 apps [1]. Wearable devices are the ones where a human can wear and have the potential to communicate explicitly to each other or via integrated cellular communication. They connect with other devices through their integrated wireless modules, which interface with other elements such as batteries, sensors, and antenna. Antennas are one of the essential aspects of wearable gadgets as they lead to a portable link for the overall effectiveness of the devices. Wearable devices have various applications in our everyday lives. These are not restricted to wristwatches, exercise shoes, virtual reality glasses, and include other medical devices as well [2, 3]. Across the healthcare industry, wearable tools are used to track vital health problems of the patients. These wearable devices have a glucose control device for measuring the insulin level of a patient, capsule endoscopy for testing the inner digestive tract, handheld sensor machine, and heart rate tracking thermometer, blood pressure, and body temperature. Wearable tools may also be used with evacuation and disaster management services, including boots, socks, raincoats, and helmets [4]. While developing portable antennas for use as part of the outfit of the wearer, many things need to be addressed. Wearable devices ought to be unobtrusive, versatile, and work close to the human body with minimal deterioration [5, 6]. Wearable antennas are often tricky in terms of production, the availability of inventory on different body sites, the impact of the host body, and the

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loss of efficiency due to structural deformation are problems that need to be addressed throughout the design phase [7]. Wearable antennas have to be upgraded with multiple main characteristics. Preferably, wearable antennas should be designed and tested to facilitate operation at lower frequencies in order to be circularly polarized and support satellite location sensing when being used outdoors [8, 9]. The main advantage of such wearable devices is that wireless connectivity from or to the body through conformal and wearable antennas must be enabled.

Wearable antennas play a crucial role in centric on-body wireless communications and attract substantial interest in the researches. Since wearable antennas work close to the human body, the loading impact attributable to the loss aspect of body tissues combined with their strong dielectric constants and conductivity renders it challenging to construct a high radiation output antenna [10–12]. It is further exacerbated by the need and demands that these antennas be lightweight low cost, maintenance-free, and do not need setup. It is worth mentioning that one of the main research interests of wearable antennas for Wireless Body Area Network (WBAN) applications [13] is the patch antenna as a consequence of the wide ground plane used in its construction, owing to its fairly high directionality. In addition to the directivity, microstrip patch antennas give enormous benefits for on-body wearable devices. The three primary ones being: simplicity of design, cost-effectiveness, and the relative separation provided by the ground plane between the radiating component and the surface, which results in a substantial reduction in the energy consumed by the skin [14]. Patch antennas, though, appear to be small in bandwidth and might need to be fairly wide if they are to be adequate to body interference [15–18].

Wearable antennas are those antennas that work within the human body, such that the human body consumes some of the radiated energy. Thus, the antenna output reduces [19–22]. Wearable antennas are also challenging in terms of textile-based antenna performance concerning (dielectric constant (εr), loss tangent (δ), and thickness (h)) of the substrate materials, the high conductivity of the materials (σ), and the antenna in bending scenarios. It is worth mentioning that the properties of the employed materials control the behavior of the antenna such that the bandwidth and efficiency of a planar microstrip antenna are primarily determined by the dielectric constant and thickness of the substratum [23, 24]. Metamaterials are groups of several individual components made from traditional microscopic materials like metals or plastics, but the products are typically organized in repeated patterns [25]. Furthermore, Conductive Metamaterials increase total synchronization and decrease radiation from tiny antennas [26], minimize the specific absorption ratio (SAR) in the head [27], and monitor electromagnetic near-fields across the antenna, which can be used to minimize the absorbed strength in human body tissues. Note that this article is outlined as follows: Section 1 provides a general introduction to wearable antenna designs, performances, and applications. Section 2 investigated the performance of textile wearable antennas with respect to their size, substrates, and frequency bands [29, 37, 42–44, 46, 57, 59, 60]. Furthermore, the bending scenarios of antennas in several radiuses and the impact of bending on the efficiency were addressed in Section 3 [59, 67, 70, 71, 73, 79, 85, 91–93]. On the other hand, Section 4 exposed the high conductive substrate materials and discussed their effect on the design and fabrication of different wearable antennas [111, 115–119, 124, 125, 132]. Moreover, the entire review was summarized in Section 4. Finally, the conclusion of the whole article is presented in Section 5.

2. TEXTILE WEARABLE ANTENNAS

An intelligent fabric is any textile that offers the physical state of the wearer by means of the attached electronic system. They are also classified as smart garments, e-textiles, smart materials, garment tracking, etc.. The e-textile invention went back to the 20th century and started largely as a consequence of the production of a conductive polymer by [28] in 1977, for which he won the Nobel Prize thirty-three years ago. Inside smart clothing, textile antenna plays a significant role in delivering wireless features such as detecting, identifying, processing, controlling, etc. without giving the user any pain [29]. With the advancement of fashion technologies, there has recently been a growing need for a smart wearable antenna. In addition to preserving the original role of heat protection and beautification, these textiles are often crucial to the advancement of knowledge science, materials science and other associated fusion technologies. Work into wearable device technologies has gained increasing attention [30–36].

Telecommunications are an integral aspect of daily life and enable citizens to exchange knowledge through computers and other electronic devices. To this end, the demand for a wireless communication system is increasing. In [37], Mohan et al. used two separate substrates to conduct a report on the output characteristics of the UWB antenna based on the Rectangular patch antenna design. Compact UWB antennas were built for two substrates in the proposed research, and attention was given to a low-cost flame-resistant FR4 and the jeans substrates. Since both antenna designs had fulfilled the UWB antenna requirements, it was observed that the antenna built using FR4 reached reflection coefficient at frequency ranges between (3.8–10.9) GHz, while the jeans based antenna design displayed a reflection coefficient at frequency ranges (2.6–9.8) GHz with omnidirectional radiation pattern. Due to the lightweight existence of textile content, it could be more beneficial to build antenna using jeans fabrics, because it can be easily inserted into clothes. However, the performance of the antenna, including omnidirectional radiation patterns, gain, size reduction, and textile antenna miniaturization needs to be optimized. The results derived from the bandwidth characteristics revealed that the proposed UWB antenna design can operate well in excessive wideband range and was considered to be appropriate for use in UWB applications. Analytically, the quality and suitability of cloth fabrics must be further studied, as well as the firmness and durability of cloth being a significant consideration in the final selection of products alongside SAR value reduction which can be considered as the main objective in most of the antenna designs.

Owing to their wide possible applications such as health control, sport, navigation, and military, WBAN systems were gaining more publicity in past years [38, 39]. Wearable antennas are important research works in both academia and business, being one of the key components of the WBAN network for wireless contact with other gadgets on or off the human body [40, 41]. Accordingly, Turkmen et al. [42] introduced a lightweight and adaptable textile antenna design and analysis for WBAN systems. The antenna was constructed from a textile jeans substrate with desirable characteristics such as lightweight low dielectric properties alongside copper tape used for the radiator patch and ground plane of the antenna, as shown in Figure 1. According to the results, the proposed antenna realized optimum reflection coefficients (S_{11}) and radiation patterns under different antenna bending conditions with better reflection results in Y-axis bending. Under this act, the antenna can be a suitable choice for WBAN applications. The antenna efficiency parameters (return loss and radiation pattern parameters)

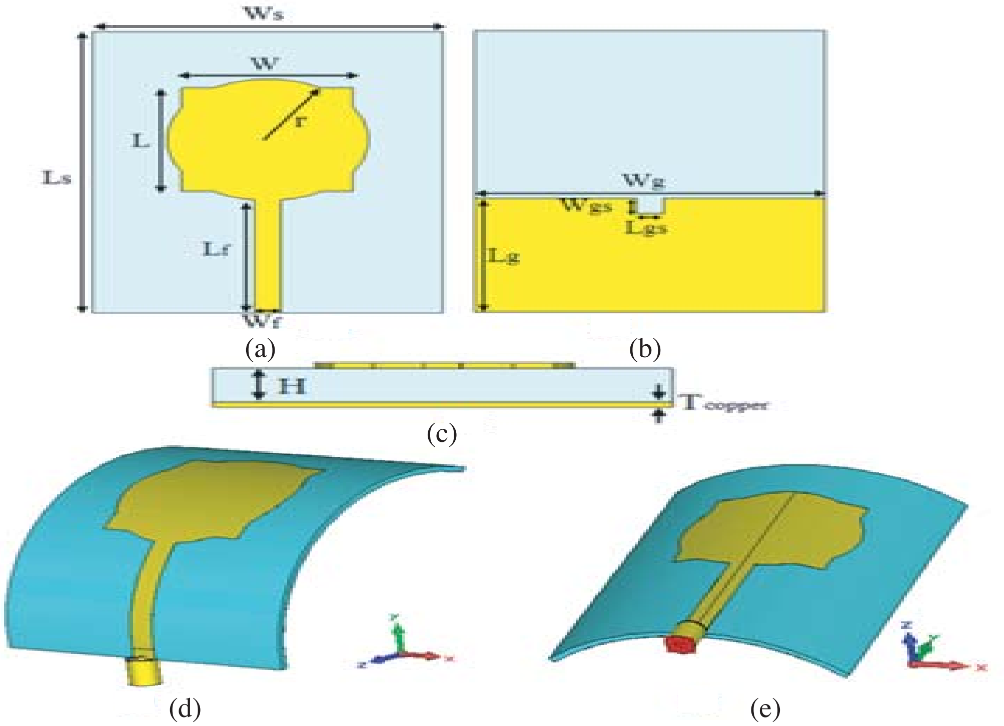
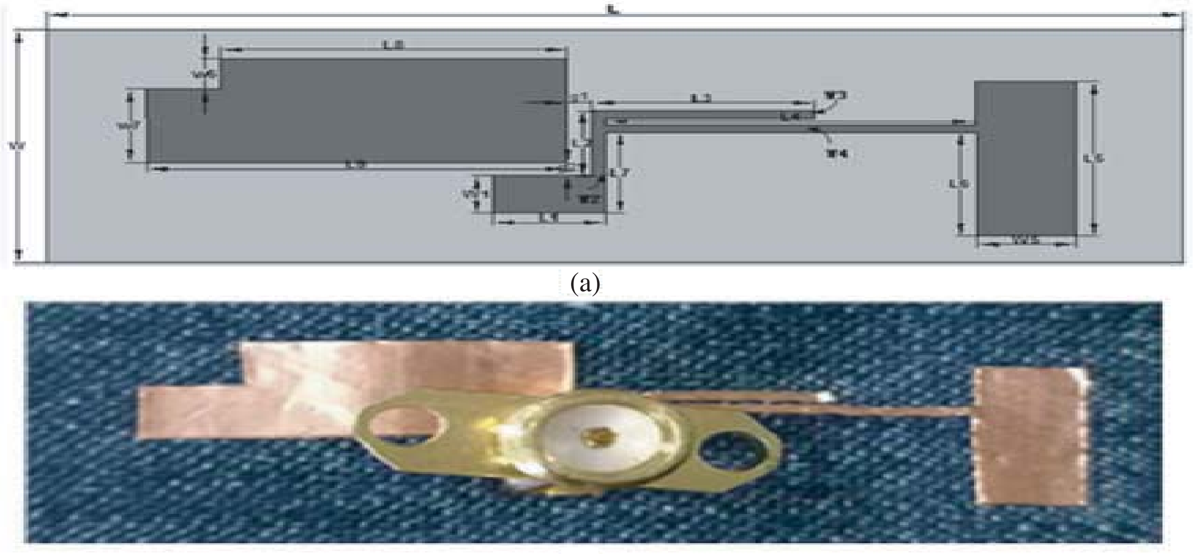


Figure 1. Proposed antenna: (a) Front, (b) back, (c) bottom, (d) bending X-axis, (e) Y-axis [42].

were tested for planar and bending conditions in free space. For planar configuration, the antenna displayed larger operating band between 2.2 GHz and 17 GHz, spanning the frequency spectrum UWB (3.1–10.6 GHz). For bending configuration, the active frequency bandwidth of the antenna is reduced by about (1–1.5) GHz from the upper frequency area due to the increasing in antenna bend range. For planar and bending configuration, depending on the planar condition there is a variation in the antenna twist states in all twisted directions.This adjustment doesn't have a significant impact on the antenna's radiation efficiency. Nevertheless, the radiation pattern with the bending scenario around Y-axis is more stable than the bending around X-axis.

In the same trend, Wang and Li [43] introduced a design of a flexible double band woven antenna with miniaturized construction. The proposed antenna was constructed at (2.45) GHz and (5.8) GHz ISM band utilizing denim as antenna substrate and copper tape as a radiation part (see Figure 2). Using denim, a dielectric constant of (1.54) was realized based on a simple method with return loss. The study revealed that all facets of antenna efficiency were not significantly impaired when the antenna was positioned close to the human body. Additionally, the robust functionality of the antenna indicates its suitability for portable wearable devices. Furthermore, the proposed antenna realized maximum gain value specified by (6.34 and 4.7) dB at (2.45 and 5.8) GHz respectively. However, there is a slight shift in the resonant frequency and variance bandwidth with the antenna being put in free space relative to the on-body state, and yet the frequency spectrum still appropriate at 2.45 GHz and 5.8 GHz for (ISM).



(a)

(b)

Figure 2. (a) Structure parameters of proposed textile antenna. (b) Prototype of denim antenna [43].

Moreover, Li and Li [44] exhibited a unique textile woven antenna operated with ISM band. The designed wearable antenna had a limited impact on the human body and conveniently manufactured on textiles (see Figure 3). The conceptual portable textile antenna was built for futuristic wireless networks to work on (2.45) GHz (5.8) GHz commercial, science, and medical (ISM) frequencies. Furthermore, the proposed antenna is classified as a compact size with an omnidirectional radiation pattern. It was supposed to be a perfect choice for human body based wearable antennas due to its extraordinary operating frequency, scale, and incorporation into the clothing property.Noteworthy, the two center-resonant frequencies for on-body states were significantly changed towards low frequency and affected the result slightly compared with the antenna in free space situation.

A smart garment is any apparel that supplies the physical state of the wearer via the connected mobile device; it is often referred to as smart clothing, e-textiles, smart fabric, display clothing, etc. Owing to the usage of readily accessible materials for its development, Jayabharathy and Shanmuganantham [29] introduced an essential structural and cost-effective antenna design (see

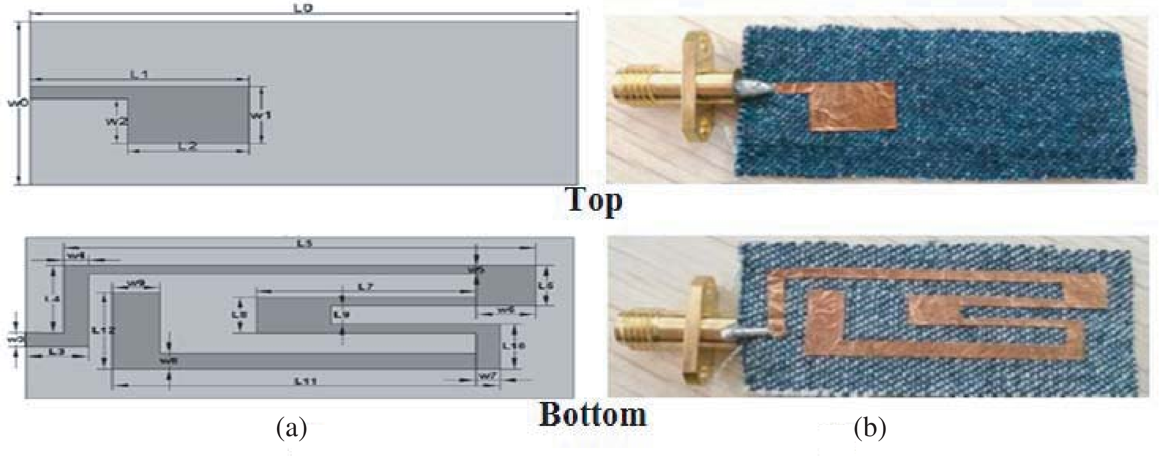


Figure 3. (a) Wearable antenna configuration. (b) Photo of the fabricated antenna [44].

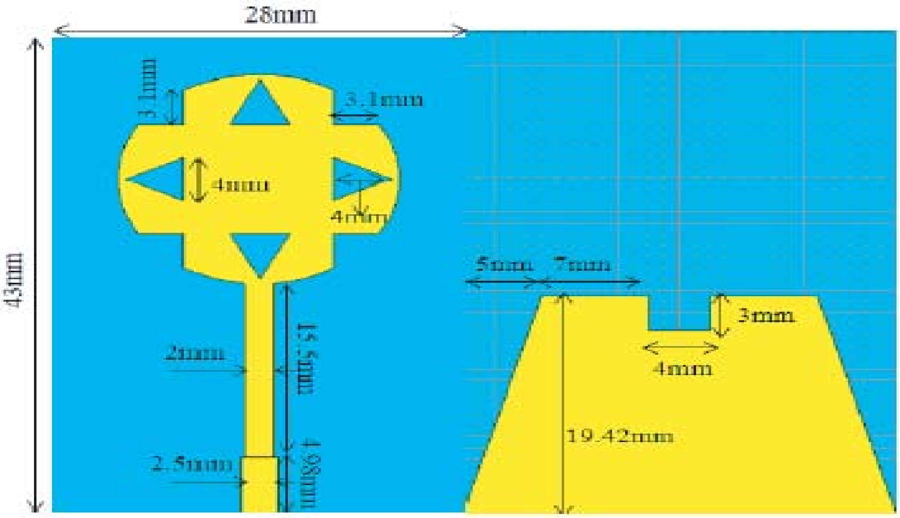


Figure 4. Front and back view of the antenna [29].

Figure 4). The proposed module was extended to cover the larger frequency range, which could widely support short-range tracking, missile guidance, and other radar applications. The proposed antenna obtained reasonable reflection coefficient values and decent gain; accordingly, it can be used in different health monitoring fields. Moreover, it can be mentioned that the antenna based cotton and leather substrates provided limited results comparing with jeans, and the proposed antenna realized narrow gain ranges of (2.2–3.2) dB.

Furthermore, smart clothes have the potential to track the bio-signal of an individual and transmit this knowledge in order to provide details about the wellbeing of a person in real-time. In recent years, portable antennas have gained interest because they could be built into the clothes [45]. A new wearable UWB semi-circular slot antenna was constructed by Amit et al. [46] utilizing (flannel, cotton, and jean) based textile materials. As a comparison, it was observed that the reflection coefficient with phantom based any fabric is higher than (10) dB, which satisfied the requirements of the design. However, when considering FR-4, the corresponding antenna impedance and bandwidth are low. Flannel offers higher efficiency than other materials, as the pattern was homogeneously relative to cotton and jeans. Furthermore, the proposed textile antenna covered acceptable frequency range rendering the antenna to be well suited for wearable devices relevant to smart clothing. Furthermore, the results reveal a mismatching between the simulated and fabricated tests by (29 and 22) dB impedance matching and return loss respectively. When considering FR-4, the antenna impedance matching and the bandwidth are low. Whereas flannel does even higher than other materials, as the structure is homogeneous in comparison to jeans and cotton.

For diagnostic uses, microwave imaging was commonly used to image the interior of human bodies and to identify pathogens as they already grow for their early stages [47, 48]. These diseases might involve strokes of the brain, breast cancers, bone fractures, and damage to the sub-skin [49–56]. In light of this, Lin et al. [57] proposed novel low-profile ultra-wideband full-textile antenna architecture for portable medical imaging systems in the microwave. The antenna offered an easy-to-fabricate monopole frame made of lightweight polyester fabrics and conductive copper taffeta, resulting in a small and versatile framework for functional applications that conforms to the curved nature of human bodies. The calculated tests revealed that the antenna achieved an UWB operational bandwidth of 109 percent, better omnidirectional radiation, and appropriate gain of (2.9) dBi. The antenna also maintained its output in the presence of tissue-mimicking phantoms during bending or operating (see Figure 5). In contrast, on-phantom calculations indicate that there was little impact on the working bandwidth and the perceived gain of the antenna as it operates in the vicinity of human bodies. The time-domain return loss of the antenna differed dramatically with the scale of the implemented fragment, which adapted the functionality of the antenna with microwave medical imaging for such usage scenarios. Noteworthy, this paper did not introduce or analyze many sophisticated post-processing algorithms to recreate images and increase their accuracy based on the captured microwave signals. Besides, the strategy to improve the forward radiation of the antenna in a low-profile way was utilizing the electromagnetic bandgap or faulty ground structure may be a viable solution and deserved to be unveiled.

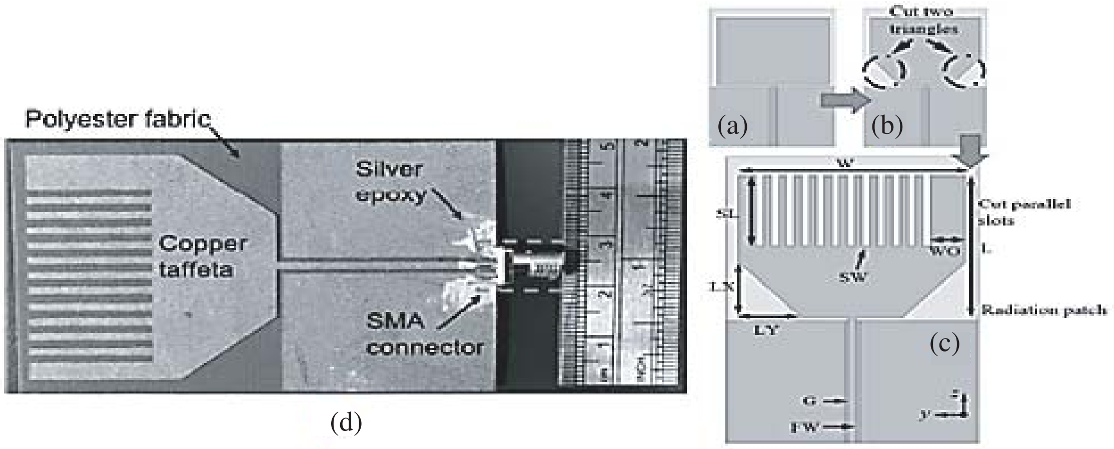
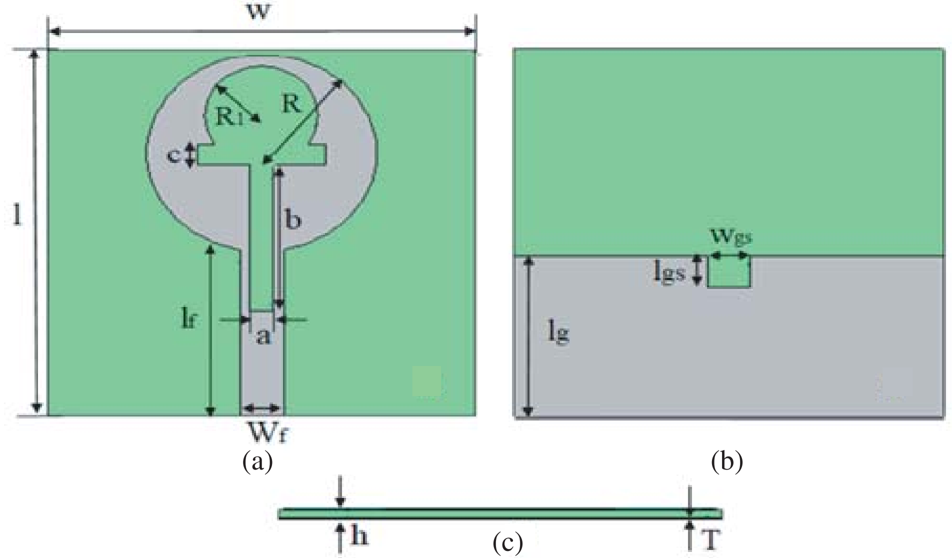


Figure 5. (a) Monopole antenna. (b) Cut two triangles — bottom. (c) Cut parallel — top. (d) SMA prototype [57].

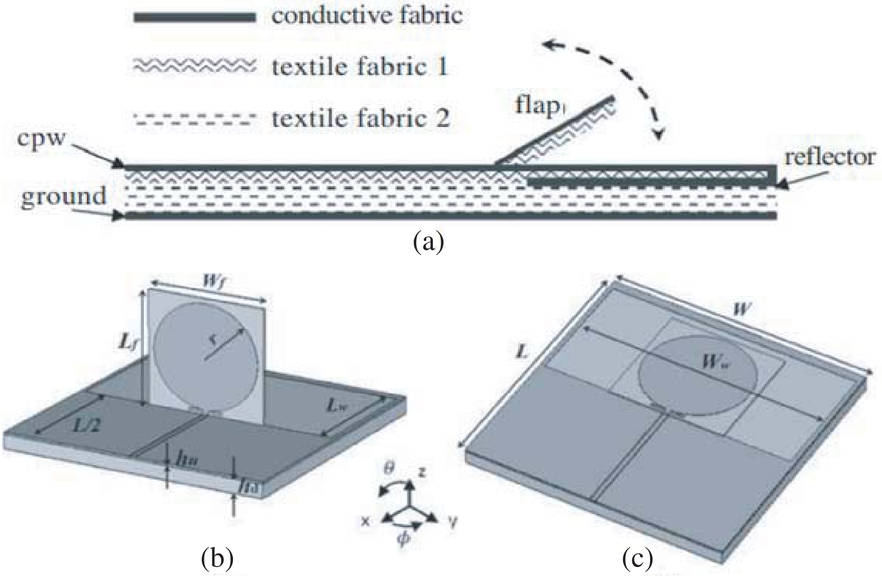
The use of electro-textiles and smart clothes in connectivity, culture, health, and safety involves the installation of several electronic tools directly onto textile substrates to increase the security and efficiency of the consumers [58]. In view of this, an innovative Ultra-wideband textile (UWB) antenna was proposed by El El Gharbi et al. for portable applications in [59]. The proposed antenna was constructed and introduced with desirable characteristics such as a robust full embroidered topology and low dielectric loss on a felt textile substrate with full antenna dimensions (30 × 30 × 0.7) mm (see Figure 6). This small size of UWB antenna output ranges from (3.1–11.3) GHz, indicating a fractional bandwidth of 114 percent, where the performance approaches 60 percent and the gain obtained hits (4) dB. However, some influences such as the SMA connections, soldering defects, and the production cycle of embroidery adaptation that were not accounted for in models caused few minor differences in the measured performance.

Furthermore, Di Natale and Di Giampaolo [60] presented and addressed a UWB flexible all-textile antenna that can be reconfigured between a monopole and a microstrip-like antenna (see Figure 7).



(a) (b) (c)

Figure 6. Geometry of proposed antenna: (a) Front view, (b) back view and (c) bottom view [59].



(a)

(b) (c)

Figure 7. (a) Side view of the antenna. (b) Monopole configuration. (c) Microstrip-like configuration [60].

The antenna is centered on a circular radiating disk that functions as a monopole when orthogonally positioned on a ground plane, and as a microstrip patch when situated parallel to an adjusted ground line. The numerical analysis demonstrates that both topologies have a sufficient UWB functionality with FCC-compliant bandwidth and a reasonable network fidelity factor that enables the antenna to be used as an air interface for wearable sensors and short-range communication tools. The variance of the average gain oscillates between (2 and 6) dB in the case of the monopole, and between (2 and 8) dB in the case of microstrip topologies. Noteworthy, the results indicate that the antenna is unresponsive to the body owing to the ground surface and that the characteristics do not alter dramatically with or without the body in terms of the reflection coefficient and the radiation pattern.

The overall evaluations among the works given in the aforementioned analysis in Section 2 were summarized as exposed in Table 1.

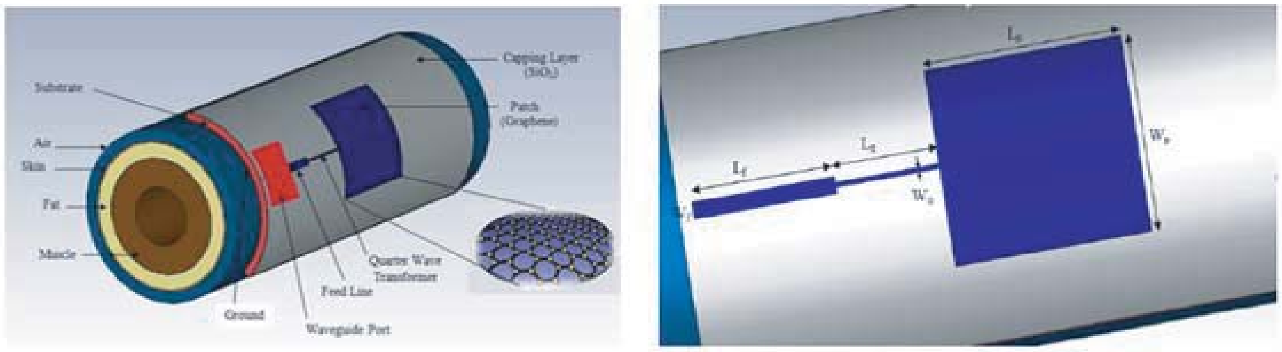
Table 1. Overview on textile wearable antennas.

Ref.	**Size (mm)**	**Frequency Band (GHz)**	**h (mm)**	**Substrate**	εr	**Eff (%)**	**Application**
[37]	—	3.1–10.6	1.6	FR4	4.4	—	UWB devices
			1	Jeans	1.67		
[42]	45 × 60	2.2–17	1	Jeans	1.68		WBAN
[43]	46 × 16	2.45 and 5.8	0.05	Denim	1.54	—	Wearable and ISM
[44]	42 × 13	2.45 and 5.8	25	Denim	1.54	—	Wearable devices
[29]	28 × 43	3–8 9–13	1.2	Jean	1.7	—	Health monitoring
[46]	33 × 35	3–10 4–9	1	Jeans	1.7	72	Health monitoring
				Flannel			
				Cotton			
[57]	45 × 40	1.198–4.055	0.08	Polyester Fabric	2.193	56.48	Microwave medical imaging
						70.96	
[59]	30 × 30	3.1–11.3	0.7	Felt	1.2	< 60	Wearable devices
[60]	90 × 90	2.61–10.1 2.73–10.1	0.6	Denim	1.43	—	WBAN

3. BENDING SCENARIOS IN WEARABLE ANTENNAS

For mounting on non-conform surfaces and using rigid substrates, many wideband, extensive band (EWB), and UWB notched antennas have been published [61–66]. When using the antennas around angled surfaces, they experience bending or flexing, which can alter the antennas' reflective properties. Since the antennas are built on flexible substrates, in various bending situations, the constructed antennas are tested concerning the bending in order to verify the performance of the antennas. Throughout the activity, textile antennas are expected to be bent or otherwise conformed to a particular surface, and so experiments under various bending circumstances are important to explore differences in bending-dependent features. The antennas are either mounted or twisted over a ring, which could be a typical arm or chest form pattern [59, 67].

A WBAN consists of body-located wireless nodes that can communicate with each other and/or with an external base station using an effective antenna. Multiple antennas used by body region networks are the monopole Microstrip Patch Antenna (MPA) [68] and the dipole microstrip patch antenna [69]. Accordingly, Bala et al. [70] investigated the advantages of graphene in constructing a curved patch-based antenna for flexible WBAN applications. The overall dimension of graphene curved patch antenna was (35 × 35) mm (see Figure 8), which efficiently obtained (−25.05 and −25.17) dB reflection coefficients, (10.5 and 2.8) dB maximum gain, (1.118 and 1.12) voltage standing wave ratio (VSWR) and (79.09 and 74.86)% radiation efficiency at resonating frequency of (2.4 and 3.94) GHz respectively. Furthermore, the results proved that the proposed antenna could act perfectly in operating frequency range (1–4.88) GHz alongside with acceptable SAR value. Due to the functionalization of the graphene, the basic curved based square patch antenna achieved wideband activity and is also ideal for UWB WBAN biotelemetry applications.The curved graphene patch antenna was located crosswise along the length of the body resulting in small resonant frequency differences, while it is found that any change in patch width results in the resonant frequency shifting to a higher band. Due to extreme absorption defects in the GHz range, the radiation performance of the planar graphene patch antenna

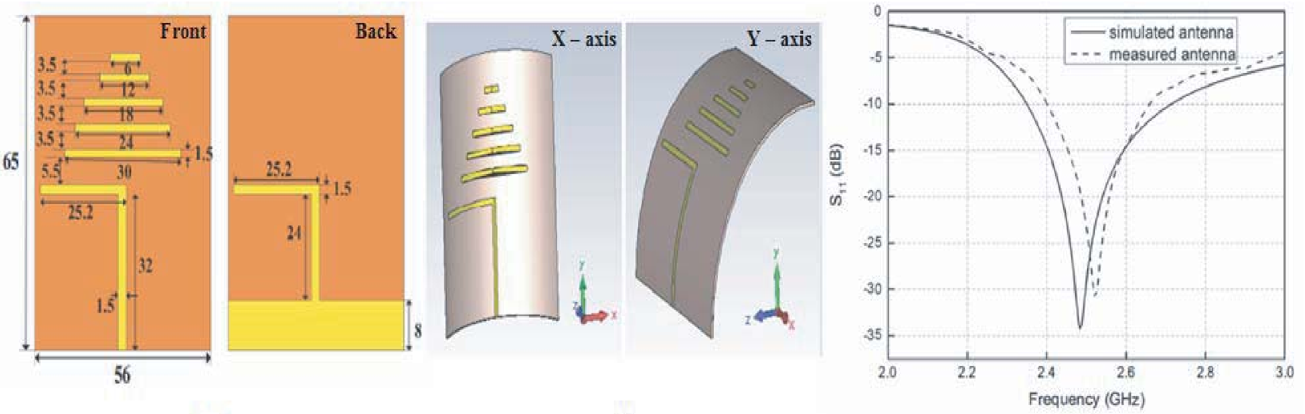


(a) (b)

Figure 8. (a) Graphene-based curved patch antenna model. (b) Dimensional view [70].

is degraded and may therefore be balanced by the usage of silicon substrate content with a higher dielectric constant.

Furthermore, Liu et al. [71] studied the impact of the bending on the performance of the antenna by demonstrating a design of a flexible Yagi-Uda antenna based on polymer substrates for WBAN applications. The overall antenna size is exposed in Figure 9(a), where the whole module was formalized to satisfy the ISM frequency range specified by (2.45) GHz. The effect of the bending conditions on the x and y axes of the proposed antenna exhibited that the input matching got awful with an increase in the bending degree of the design. The reflection coefficient of the proposed antenna was measured in the range of (10 MHz–43.5 GHz) and reached an impedance bandwidth in the range of (2.4–2.5) GHz considering that the return loss was less than (-10) dB (see Figure 9(c)). It should be reported that the average radiation path at the H-plane of the antenna is deviated by bending across y plane (see Figure 9(b)). Nevertheless, the corresponding antenna output remained fairly stable under bending circumstances. Moreover, it can be revealed that due to the feeding cable impact induced by the tiny ground plane a slight difference between simulation and calculation was conspicuous.



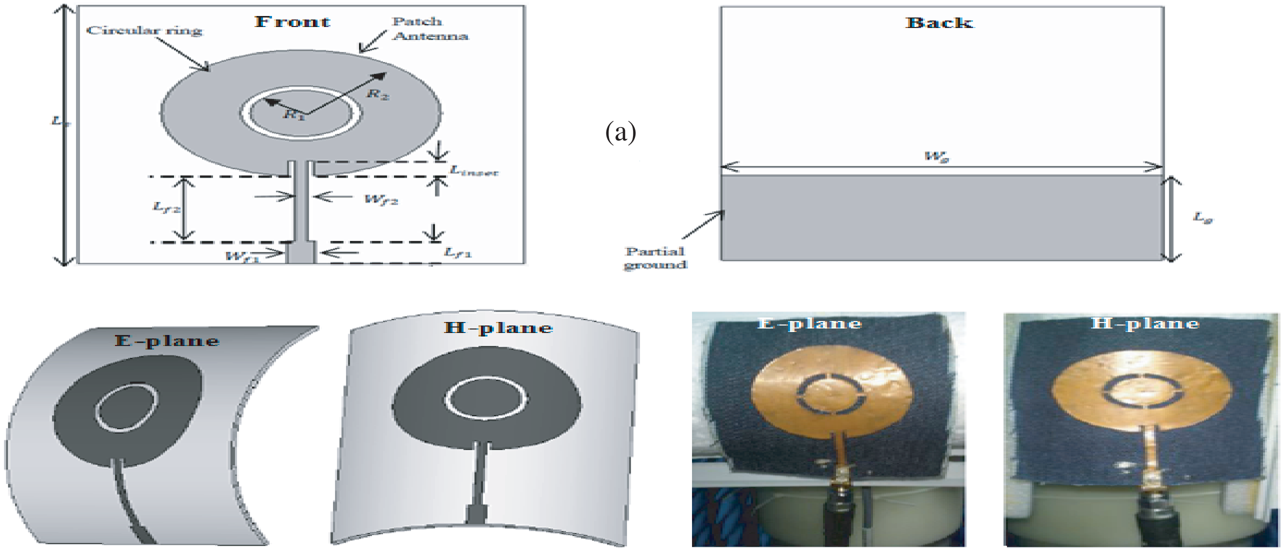
(a) (b) (c)

Figure 9. (a) Proposed antenna geometry. (b) Antenna bending. (c) S_{11} response [71].

The increasing growth of portable low-power systems has intensified the need for WBAN Deployment solutions. The antennas can be used by emergency personnel such as paramedics or police officers in devices tracking body tension during physical operation, measuring heart rate and blood pressure [10, 72]. In accordance with that, Ferreira et al. [73] discussed the impact of bending on the efficiency of the 2.4 GHz rectangular microstrip textile patch antenna for WBAN. The conductive component of the antenna was a combination of copper and nickel, mixed as a substrate of polyester fiber and denim. The results showed that bending curvatures have an important effect on the cost and cumulative distribution of radiation. Noteworthy that the overall antenna structure was tested in three generic locations: the chest, arm, and wrist. Relative to a flat antenna case, the wrist-equivalent curvature reduces the average gain by around (2–4) dB. The front-to-back radiation density of the antenna declines with a rise in the bending curvature, which can be a favorable property for WBAN instances. The bandwidth remained nearly the same in all calculated situations. The resonant frequency, on the other side, had specific actions based on how the antenna is bent along its width or duration. Once the antenna was subjected to a bending curvature on its diameter, a downhill frequency offset was detected, and an uphill frequency offset was investigated for bending along the length axis of the antenna.Therefore, when developing textile-patch antennas for WBAN applications, the antenna output may be greatly restricted by the resonant frequency offset with respect to antenna curvature angles.

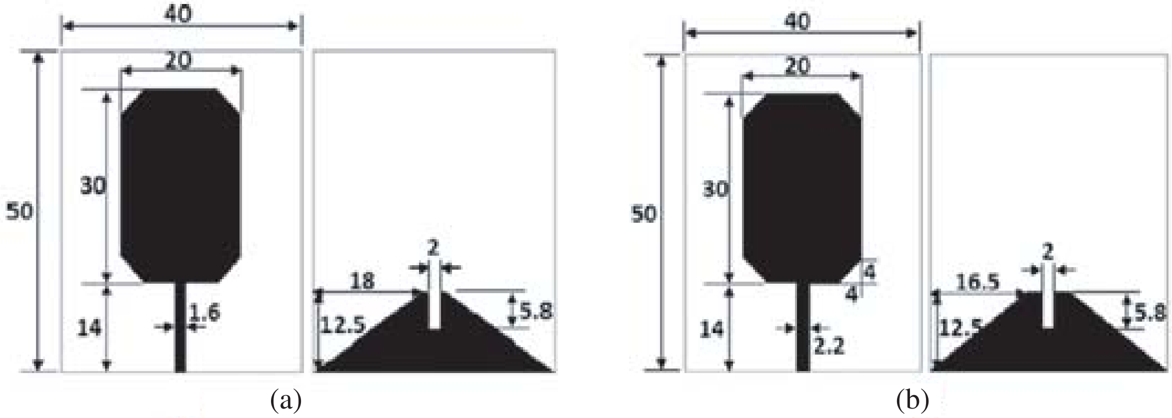
The key emphasis on antenna architecture is the lightweight wearable high-performance antenna creation for on the body use [74–78]. Meanwhile, Isa et al. [79] studied the performance of a dual-band textile-based circular patch antenna in different bending scenarios. For this analysis, three bending cases were studied depending on several bending radiuses. The circular microstrip patch with a size of (70×70) mm was developed to be suitable for tiny human limbs (arms, legs) and relatively some larger sides in the human body (see Figure 10). The results indicated that bending along the E-plane had a dominant impact on the performance of the antenna. Based on the proposed case studies, the bent antenna caused variation in the period of resonance owing to the modest influence of the bending on the resonance frequency. The reflection coefficient of the antenna was influenced by bending in the narrower radius due to the reduction in the resonance range of the antenna. Furthermore, the impact on bandwidth was roughly marginal, assuming that no resonance had been impaired. Briefly, it can be inferred that the implications are negligible. Hence it had been demonstrated that the expected textile antenna can operate reasonably under bending constraints. Bearing in mind that the proposed dual-band antenna operates in both (2.4) GHz and (5.2) GHz respectively, alongside with wider bandwidth is achieved across (1.95–5.79) GHz. Worthwhile that the return loss declines marginally for all situations, particularly at high band frequency in comparison with the flat antenna output resulting from the maximal bending which is considered awful for the outer ring of the patch.

The flexible antennas are a number of antennas used for a range of uses such as tracking, telephone control, sports control, (WBANs), Wireless Sensor Networks (WSNs), and Wireless Personal Area Networks (WPANs) [80, 81]. Several antennas were implemented in the last couple of years relating to



(b) (c)

Figure 10. (a) Circular monopole patch antenna. (b) Bending positions. (c) Experimental setup [79].



(a) (b)

Figure 11. Proposed antenna geometry. (a) Polyamide. (b) Teslin paper [67].

flexible/wearable communications systems [38, 82–84]. In light of this, Mohandoss et al. [67] introduced a compact, low-profile and durable planar monopole antennas aimed for UWB and Body Centric communication technology (BCWC) was constructed and tested for their efficiency across conformal surfaces. In this work, two microstrip based lightweight antennas were designed using polyamide and Teslin substrates. The antennas realized several features summarized as follows: overall dimensions of the proposed antennas specified by $(50 \times 40 \times 0.8)$ mm and $(50 \times 40 \times 0.712)$ as depicted in Figure 11, operating frequency of (1.8–13.3) GHz and (1.4–13.4) GHz, maximum gain of (5.53) and (4.4) dBi, better radiation patterns and return loss (S_{11}) of (11.5) GHz and (12) GHz for polyamide and Teslin, respectively.

The performance of the antennas was evaluated based on flexible scenarios such that bending across the length, widths, radius, and angles of the antenna (see Figure 12). Therefore, time-domain research was conducted in free space and with pulse excitation in different bent situations to verify the antennas for UWB applications. The properties of the propagation coefficient (S_{21}) and the community latency for various bending situations were calculated and the fidelity parameter for both scenarios was greater than 0.82 which classify these antennas to be a good candidate for UWB-BCWC, high-speed data

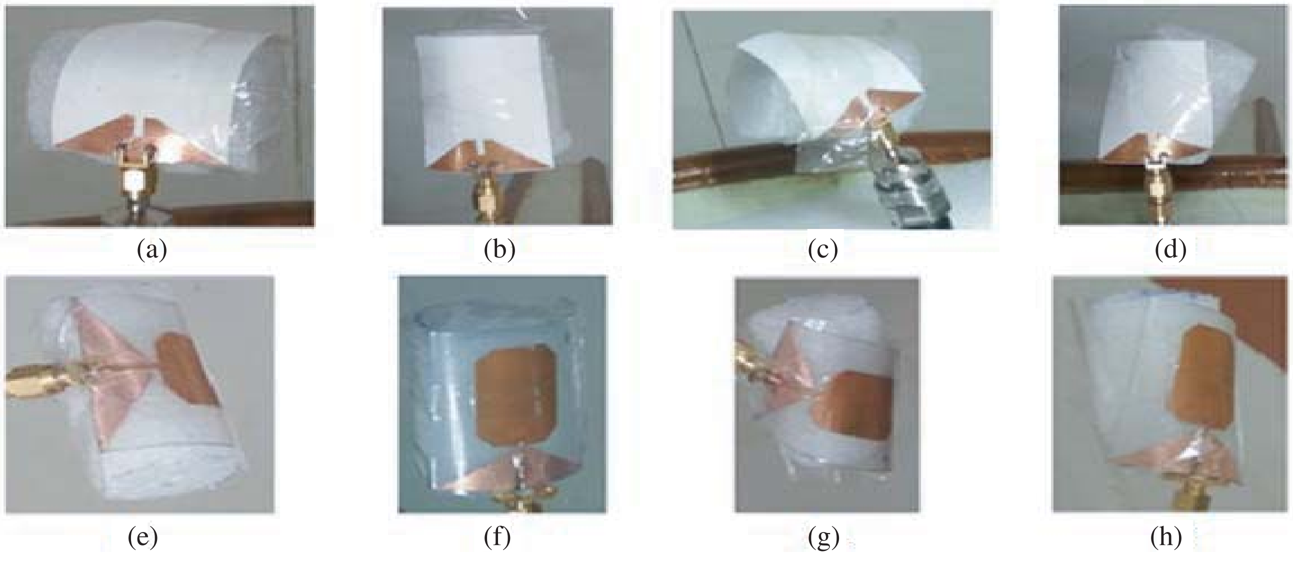

(a) (b) (c) (d)
(e) (f) (g) (h)

Figure 12. Inward bending. (a) X-bend, (b) Y-bend, (c) X-bend with +45 deg and (d) Y-bend with +45 deg, (e) X-bend, (f) Y-bend, (g) X-bend with +45 deg and (h) Y-bend with +45 deg [67].

connectivity of wireless personal area networks and flexible wideband pulse frameworks. However, it is found that there exists frequency change between simulated and measured (S_{11}) for Teslin antenna could be attributed to adhesive employed by the Teslin papers to render it a single substratum in comparison to the polyamide antenna.

In [85], Mersani et al. introduced a compact monopole antenna to diagnose skin cancer in a person afflicted by xeroderma pigmentosum diseases for use in radiography. The proposed antenna reacted successfully with the specified criteria and showed UWB behavior. The overall dimensions of the proposed antenna specified by ($36 \times 48 \times 6.12$) mm realized impedance bandwidth (8.2–13) GHz and maximum gain of (7.04) dBi. The antennas are built to be mounted under the body; thus, they would be subjected to curvature restrictions. Hereby, the return loss values descended awfully than the values in the source antenna in the bending conditions (see Figure 13). Such results proved the effectiveness of antenna sensitivity in and out of the curved environment. On the other hand, for the antenna with AMC the rear radiation rates are lower than the independent antenna, and also the same actions were noticed when putting the AMC antenna on the body. Besides, owing to interference and also energy absorption in the body, the gain and output of the AMC antenna mounted on the body are reduced as in comparison to the AMC antenna mounted in free space.

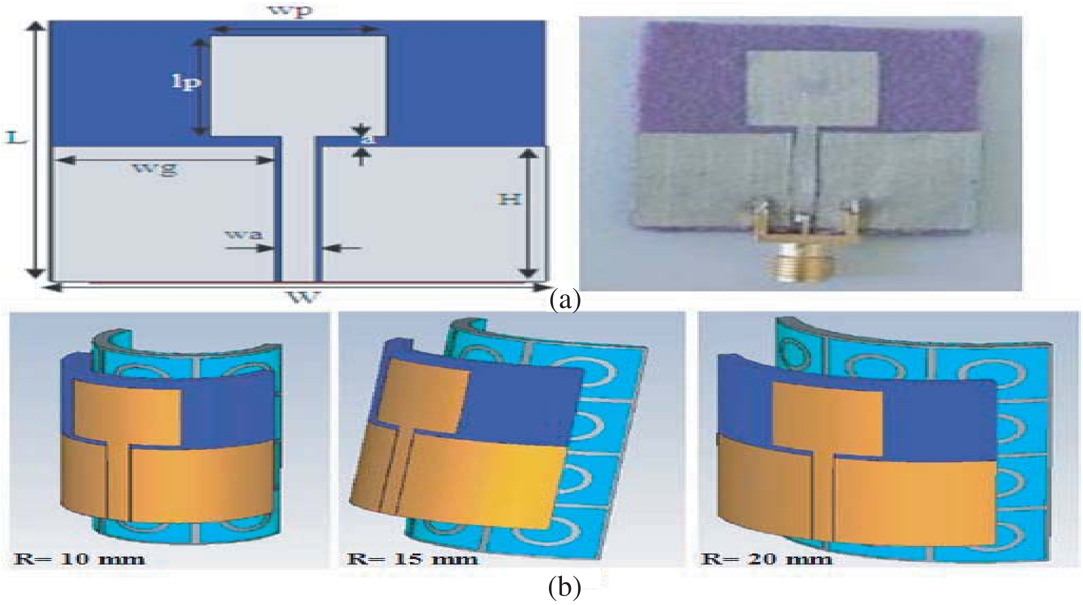
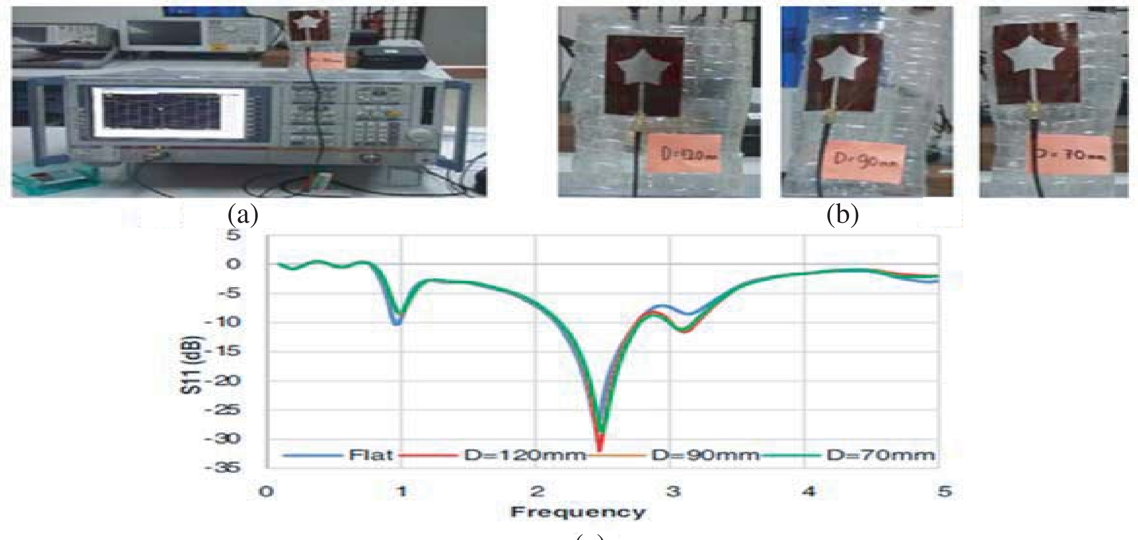


Figure 13. (a) Geometry of the patch antenna. (b) Bending antenna [85].

Several flexible antennas were made on numerous flexible substrates such as textile [86, 87], paper [88], and thin-film [89, 90]. Accordingly, a star patch Kapton Polyimide Film based antenna was designed by Seman et al. [91], which was able to function at (2.45) GHz. The size of the antenna was specified by $(75 \times 50)\,\text{mm}^2$ and tested in different bending scenarios (see Figure 14) knowing that the results had proven that the performance of the antenna is not compromised. Furthermore, the results showed that the antenna grasped an optimized bandwidth of 24.9% covered by the stated (2.45) GHz frequency and lowest return loss in the flat state. Additionally, the bending scenarios were diameter-based examination depending on specific diameters as shown in Figure 14. Though, the antenna had to be installed into a transceiver device and validated to evaluate the real output in the specific indoor and outdoor environment.

It is worth mentioning that the consistency of the efficiency has been observed in which the resonant frequency change is less than 2% when the system is bent on a curved surface with a 90 mm radius. Hereby, the proposed antenna can be a suitable candidate for wearable devices. Similarly, Gupta et al. [92] studied and evaluated the efficiency of conformal UWB portable antenna in the domination of different bending radii. The proposed antenna was constructed on RT Duroid flexible substrate with



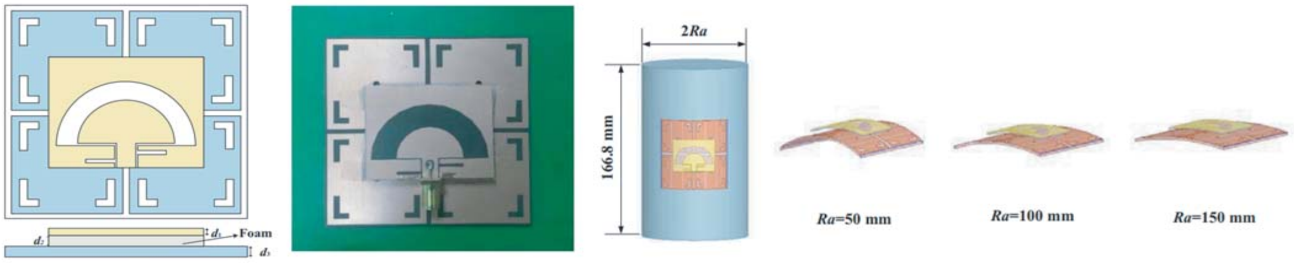
(a) (b)

(c)

Figure 14. (a) Star patch antenna. (b) Bending $D = 120\,\mathrm{mm}$. (c) S_{11} under bending scenarios [91].

overall dimensions of $(35 \times 31)\,\mathrm{mm}^2$ and studied depending on (25 and 50) mm bending radius applied on the arm of a 5 years old healthy child and a 35 years old healthy adult respectively. With respect to the reflection coefficient of the conformal UWB antenna, an identical response was achieved for the various curvature radii, knowing that the realized reflection coefficients were less than (10) dB in both bending radius of UWB wearable antenna and operating frequency range of (3–10) GHz. As a result, due to the durability, flexibility, and the thickness of the proposed antenna, the design can be classified as an optimum choice for UWB wearable applications. However, the calculated findings could be attributed to a slight variance in the cardboard in which the antenna has been covered for compatibility evaluation. Moreover, the cardboard itself can have some dielectric properties and would undoubtedly influence the operating frequency.

Furthermore, Yin et al. [93] proposed and illustrated a wearable antenna with L-slot AMC configuration for ISM fields (see Figure 15). The radiation of the antenna back lobe was effectively minimized by introducing an AMC layer, which increases antenna efficiency. The front to the back value of the antenna is greater than 20 dB in ISM medical range, reaching a gain of 7.47 dBi. The SAR value is smaller than 0.15 W/kg, which is much smaller than the universal implementation level, showing that it does not affect human safety and still has good efficiency even under different bending scenarios. Due to these characteristics, the proposed antenna can be a suitable option for wearable devices such as medical tracking and medical sensing in WBAN. Nevertheless, there are certain variations in the tests obtained that can arise from adjusting the gap between the upper antenna and the AMC reflector



(a) (b) (c)

Figure 15. (a) Proposed wearable antenna structure. (b) Top view of the fabricated antenna. (c) The integrated antenna with different bending degrees [93].

during the study, creating an inexplicable delay, and welding the antenna feeding port and field test area can even influence the actual antenna verification.

Owing to the versatility of the textile material antennas, they are readily bendable to conform to the structure of the human body and provide consumer convenience; even under bending circumstances, the antenna can retain its optimum efficiency. Hence, under specific bending conditions, lightweight wearable antenna efficiency parameters should be evaluated [59, 94]. As presented before, El Gharbi et al. [59] presented an Ultra-wideband textile (UWB) antenna designed for wearable applications. Besides, El Gharbi discussed the effect of bending on the performance of the antenna. For this experimental analysis, as seen in Figure 16, the proposed textile UWB antenna was used in two separate concave and convex bending conditions. Furthermore, each location was determined by taking into account the normal bending radius between (30 and 45) mm in the human body. The comparison results showed that the availability of the smallest radius and firmest bending result in wide detuning. Based on bending scenarios, tiny bandwidth change in percentage between the measured and simulation results was recorded and justified by several potential reasons: the flexibility of the embroidery production system, the influence of humidity and temperature on the successful dielectric permittivity of the felt, the non-uniformity sample thickness (rugosity).


(a) (b)

Figure 16. Measurement environment of textile bending UWB antenna. (a) Concave. (b) Convex [59].

Furthermore, the overall evaluations among the works given in the aforementioned study regarding Section 3 were summarized as exposed in Table 2.

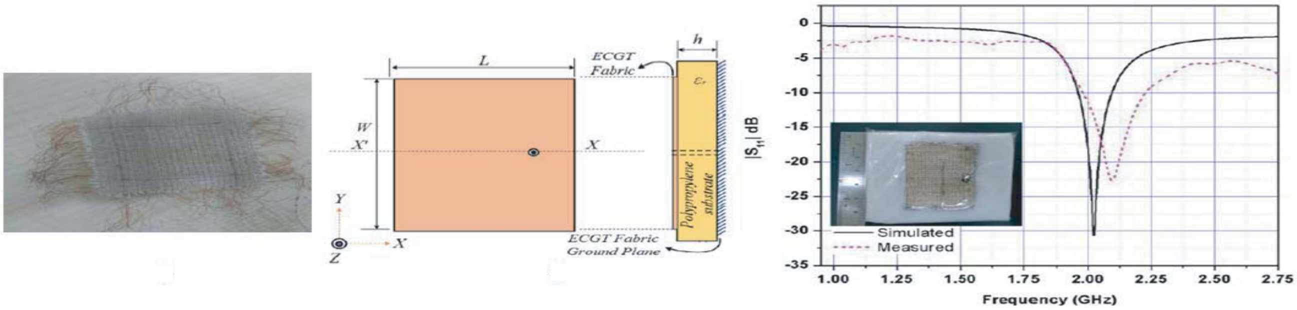
4. WEARABLE ANTENNA BASED CONDUCTIVE MATERIALS

The interest in wireless wearable communication technologies had been increasing drastically for recent years. The aim is to meet the wearable specifications of the device, such as durability, compactness, robustness against harsh climate, low-cost, and ease of manufacturing. Recently, many attempts have been documented utilizing different exotic materials from cloth, textiles, embroidered fabrics, liquid metal, polymers, to Nano-materials [95–104]. The usage of polymers, especially the polydimethylsiloxane (PDMS) type, has been labeled as one of the most important methods, owing to its peculiar features such as exceptional strength, water resistance, heat, and mechanical resilience, which are necessary for convenient wearing and extended utilization [105, 106]. In the field of developing wearable antennas, there has been growing demand and production, which are convenient and can be easily incorporated into the incorporated microwave device. The modern microstrip antennas have the intrinsic drawback of being static, which also prevents their implementation into a fully portable device. On-body Antennas can be created from textiles [30, 107–110] and connected to the body or clothes or can be worn as an antenna button [80]. In [111], the layout, production, and characterization of electro-conductive textile fabric (ECGT) based rectangular textile wearable antenna (RTA) was stated by Gangopadhyay et al. The design comprises conductive cotton and copper filament yarns that were twisted together to create an integrated fabric. It is worth mentioning that the established ECGT had

Table 2. Overview on bending scenarios in wearable antennas.

Ref.	Substrate	Radius (mm)	Rad. Eff. (%)	BW	SAR (W/kg)	Application
[70]	Silicon	30	79.09, 74.86	3.88 GHz	0.000148	Medical
[71]	Polyimide	20, 30, 40, 50, 60, 70, 180, 360	—	360 MHz	—	WBAN
[73]	Denim	28.5, 42.5	—	140 MHz	—	ISM
[79]	Jeans	33.5, 47.5, 58.5	—	3.84 GHz	—	WLAN
[67]	Polyamide	8, 15, 30, 80	87, 92, 96	11.5 GHz	—	UWB and (BCWC)
	Teslin-paper		82, 86, 89	12 GHz		
[85]	Felt	10, 15, 20	64	4 GHz	0.102	Medical imaging
[91]	Polyimide film	Diameter = 70, 90, 120	—	24.9% $\approx$ 400 MHz	—	Wearable devices
[92]	RT Duroid	25, 50	60	7.1 GHz	—	Off-body wearable
[93]	Polyimide	50, 100, 150	—	2.45	0.15	ISM
[59]	Felt	30, 45	> 60	8.2 GHz	—	Wearable devices

realized a surface resistivity of (2.97) Ω/square (see Figure 17). In summary, the proposed antenna obtained percentage bandwidth around (6.7 and 10)%. The overall gain was obtained as (5.5 and 7.6) dBi at (2.021 and 2.054) GHz, respectively, with antenna efficiency around (61.42)%. It has to be mentioned that the behavior of the antenna needed further optimization, especially to improve the poor efficiency of the module.



(a) (b) (c)

Figure 17. (a) Copper filament. (b) Geometry of ECGT-RTA. (c) Comparison of S_{11} result [111].

A versatile antenna is a crucial component of the new wireless wearable gadgets. The durability criterion exists because the majority of wearable devices are subjected to regular physical deformation in their operating setting. The flexible antenna must deal with the conditions of the body while retaining the comfort of the individual. In recent years, this necessity has sparked a rapid advent of utilizing innovative materials for producing lightweight wearable antennas [99, 102, 112–114]. In view of this, Simorangkir et al. [115] successfully reported how PDMS integrated conductive fabric materials can be employed to design adaptable, robust, frequency re-composition and wearable antenna. The conductive side of the PDMS substrate-based antenna design was realized using NCS95R-CR, a nylon ripstop fabric covered by nickel, copper, silver and a water-resistant layer is presented in Figure 18.

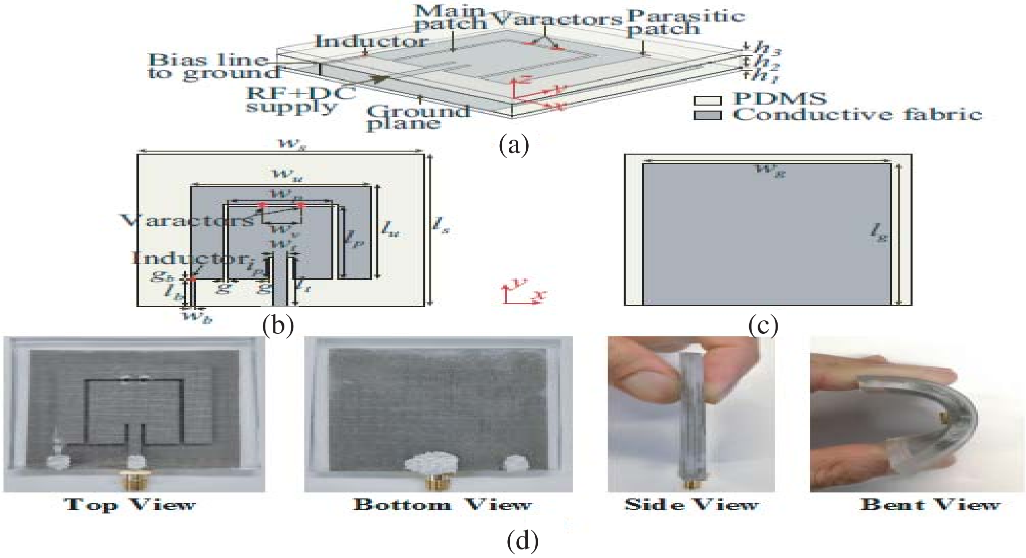


Figure 18. (a) Cross-sectional view, (b) patch layer, and (c) ground layer, (d) fabricated antenna [115].

As an approximation to the phantom, the frequency-modulated spanned from (2.3–2.68) GHz with (33)% moderate percentage bandwidth at (2.6) dBi maximum gain. It was confirmed through several compressive experiments that an antenna manufactured using this method could withstand physical curvature and machine washing while retaining its re-configurability. Such findings validate the usefulness of the proposed strategy to realize versatile adjustable electronically tunable antennas with different re-configurability forms. Hence, the design can be an appropriate candidate for new wireless wearable systems. Meanwhile and in the same field, a modern lightweight UWB antenna was introduced by Simorangkir et al. [116] for portable applications, which was extremely sensitive to human body mounting and physical deformation. The proposed antenna depicted in Figure 19 used two conductive fabric embedded polymer (PDMS) to realize the robustness and flexibility. These PDMS based substrates were the combination of nickel-copper-silver-coated nylon ripstop with ($\sigma = 1.02 \times 105$) S/m and nickel-copper coated ripstop with ($\sigma = 5.4 \times 104$) S/m. The antenna preferences had been shown firstly by retaining a complete ground plane that provided the requisite separation between the antenna and the human body while wearing. The expectations of the antenna were evidenced by the intense physical robustness applied to the PDMS embedded conductive fabric manufacturing technologies. In the phantom-based on-body measurement, the antenna reached (6) GHz with the operation and in (3.68–10.1) GHz, (4.53) dBi total gain and (27)% total efficiency relative to free space measurements. As a result of this, the proposed antenna can be a good candidate for UWB wearable applications, knowing that the employed lossy materials alongside with antenna efficiency need to get further optimization.

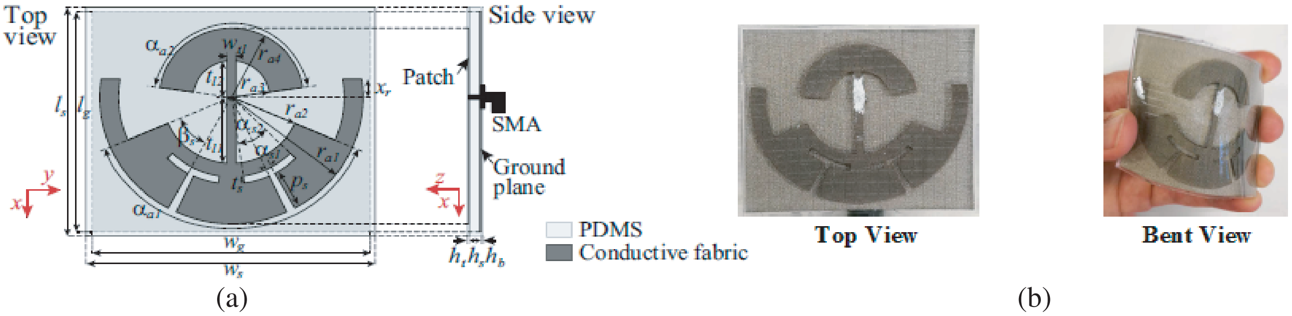


Figure 19. (a) Proposed UWB antenna. (b) Fabricated UWB antenna [116].

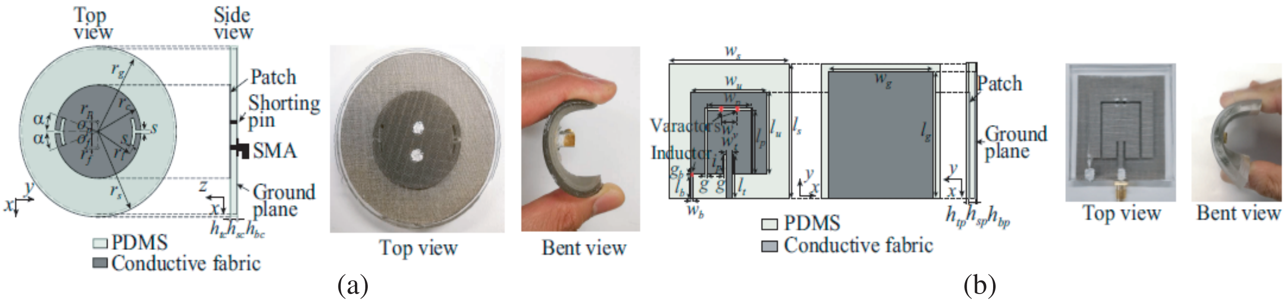


Figure 20. PDMS-embedded antenna. (a) Dual-band. (b) Frequency-reconfigurable [117].

Furthermore, a recent solution to the realization of robust, lightweight wireless antennas was adequately demonstrated by Simorangkir et al. [117]. This work addressed the design, manufacture, and calculation of two antennas identified as dual-band dual-mode (see Figure 20(a)) and a frequency-reconfigurable patch antenna (see Figure 20(b)) as a test platform. The PDMS-based conductive fabric antenna was fabricated using NCS95R-CR in the patch and nickel copper-coated ripstop fabric in the ground plane.

Certain laboratory studies confirmed that antennas produced with the suggested method can resist physical curvature and machine washing, validating the suitability of this method to the effective application of both passive and active versatile wearable antennas. In [118], a dual-band, coplanar, versatile antenna was mounted based on silver ink on a paper substrate introduced by Baytöre et al. The designed antenna was inexpensive and straightforward to produce because it was based on photographic paper that is simple to procure commercially. An inkjet printer with conductive silver (Ag) Nano ink was used for manufacturing electrically conductive flexible circuits of the antenna. The resonance frequency of the antenna was shifted marginally owing to the instabilities occurred during bending conditions. For further BPMS based conductive fabric antenna, Simorangkir et al. [119] studied the operative keys of the challenging humble PDMS metal used in the fabrication of flexible antenna employed in wearable applications. The system incorporates the use of conductive cloth as a radiator with PDMS, which concurrently serves as a substrate and as a secure encapsulation. Four PDMS-ceramic composition woven conducting fabrics defined by (nickel-copper silver-coated nylon ripstop, copper-coated polyester taffeta, nickel copper-coated ripstop and silver-coated ripstop) were selected among the available conductive fabrics. The use of a PDMS-ceramic composite as part of the substrate of the antenna results in a scale decrease of over 50 percent relative to a mere PDMS (see Figure 21).

The manufactured antennas were evaluated in different wearable circumstances, and hence consistent efficiency was achieved even after dealing with severe circumference such as extraordinary bending and machine washing. Owing to the validity of researches in the scope of potential applications ranging from healthcare surveillance, protection, defense, and entertainment, significant research efforts have been made over the last few years on wearable electronics. A considerable number of work

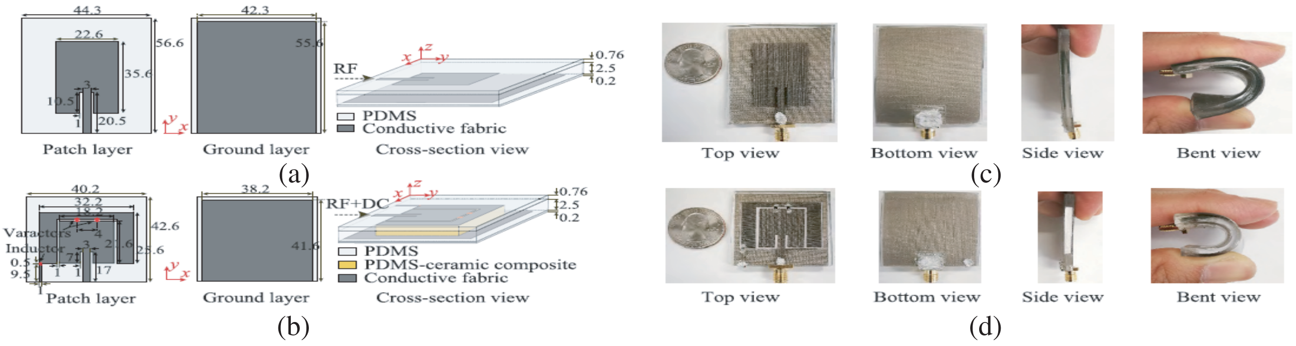
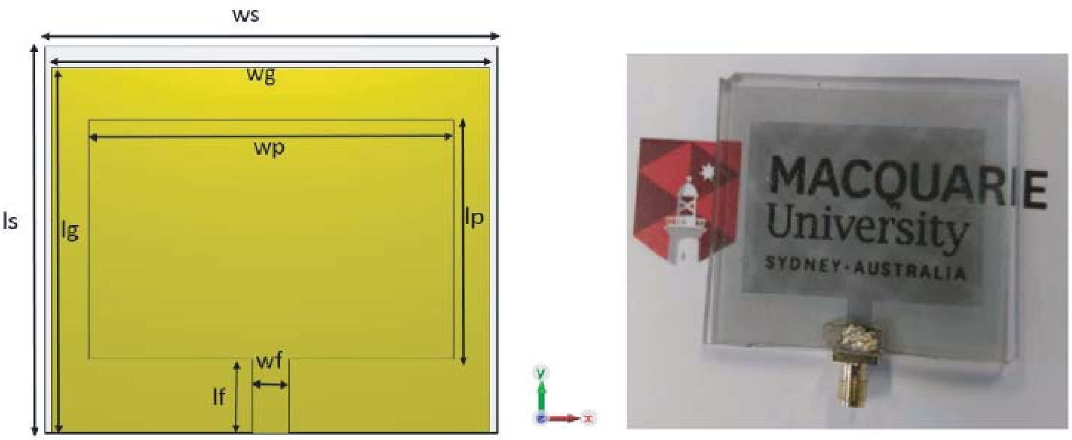


Figure 21. Designed antennas. (a) PA. (b) RFPA, Fabricated. (c) PA. (d) RFPA (dimensions in mm) [119].

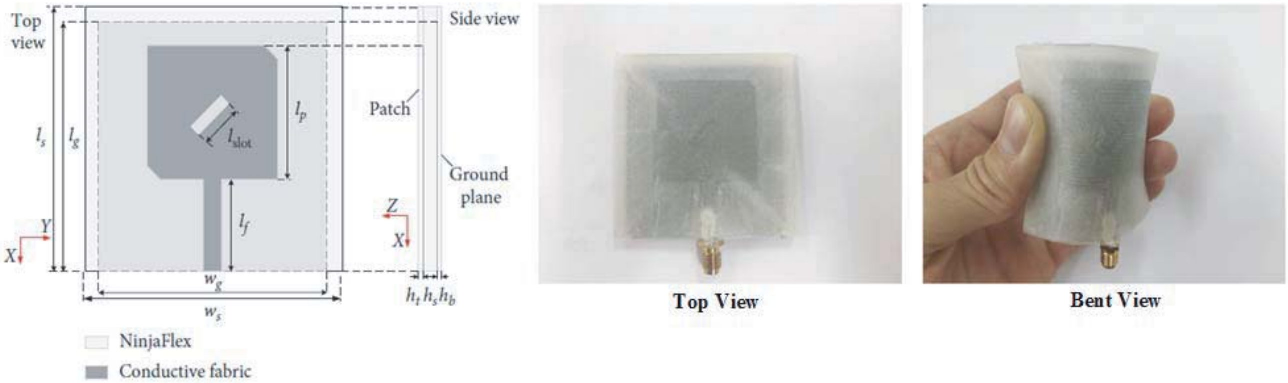


(a) (b)

Figure 22. (a) Antenna geometry. (b) Fabricated prototype of the antenna [124].

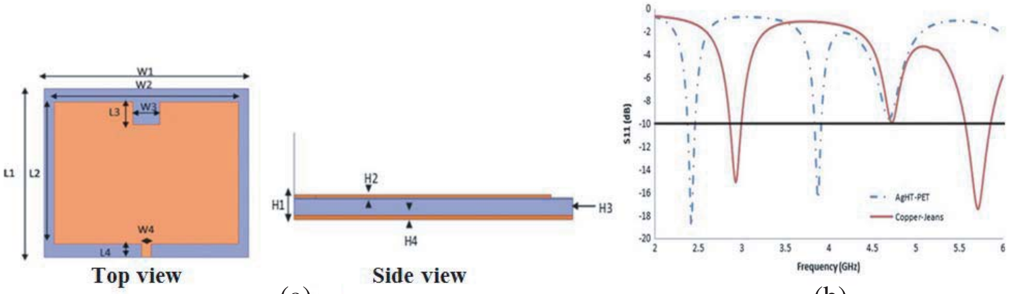
activities were organized in which non-conventional substrates such as conductive fabrics [115, 116], copper tapes [120], silver paste [121], conductive ink [122] and conductive threads [123] are employed in antenna fabrication. Hence, upon testing a transparent flexible antenna built from translucent conductive fabric embedded in PDMS, it is assumed that the approach suggested by Sayem et al. [124] was appropriate for the manufacture of the translucent wearable antenna. Since the fabric is quite soft, it binds tightly to PDMS, increasing the structural robustness. The prototype of the antenna shown in Figure 22 was produced using VeilShield transparent conductive fabric and realized 2.45 GHz operational range suitable for ISM applications. This work reported one drawback, which was the increased sheet resistance after embedding, leading to a reduction in antenna gain. In contrast, the proposed approach resulted that the antenna is almost transparent, lightweight, and robust.

Due to the difficulty of the working setting, the antennas added to WBAN are needed to equip comprehensive functionality. A circularly polarized (CP) portable antenna was designed by Li et al. [125] based on the FDM platform (fused deposition modeling) as exposed in Figure 23. The conductive cloth was used on the NinjaFlex substrate to realize conductive sections of the patch antenna. The antenna was encapsulated with additional NinjaFlex layers, realizing 2.45 GHz operating frequency based on the modified patch. Bending and washing experiments were conducted to verify the output consistency, and a strong agreement was found between simulated and calculated effects. The tests indicated that the antenna realized (11)% bandwidth (1.8) dBi peak gain, (30.7)% antenna efficiency, and around (70) MHz for ARBW. Owing to its compact design, low profile, CP radiation, durability, washing capability, and



(a) (b)

Figure 23. (a) Proposed antenna. (b) Photographs of the fabricated CP antenna [125].



(a) (b)

Figure 24. (a) The patch antenna design. (b) Comparison of S_{11} for transparent [132].

security, the designed scheme will be an attractive candidate for WLAN, WiMAX, and WiFi applications on the human body.

In any contact device, antennas are useful for radiating or receiving electromagnetic waves [126]. Wireless networking has shown different antenna architecture developments, such as meta-material antennas [127, 128], fractal antennas [129], UWB and modular antennas [130, 131]. Based on these conductive materials, two specific forms of transparent and non-transparent versatile antennas (see Figure 24) were tested by Kantharia et al. [132] based on various criteria such as gain, return loss and radiation pattern. In contrast to the non-transparent antenna, a transparent antenna is inconspicuous and can be used in several technologies. In terms of return loss and impedance bandwidth, the employed conductive materials which are versatile provide excellent efficiency. Accordingly, the gain and radiation pattern was compatible at the target wavelength, rendering the proposed antenna ideal for wireless applications.

Table 3. Overview of the conductive materials.

Ref.	**Substrate**	**Conductive Material**	(σ) **— S/m**	ε**r**	**Size**	**Frequency (GHz)**
[111]	Polypropylene	ECGT Fabric	2.09×10^7	2.2	48 × 46	2.021 and 2.052
[115]	PDMS	Nylon ripstop	—	2.82	59.8 × 59.8	2.3–2.68
[116]	PDMS	Nickel nylon ripstop	1.02×10^5	2.7	80 × 67	3.68–10.1
[117]		Nickel ripstop	5.4×10^4			
[118]	Paper	Silver Nano Ink	—	3.6	48.2 × 48.2	2, 2.45, and 3
[119]	PDMS	Nylon ripstop	7.7×10^5	2.7	—	2.45
		Polyester taffeta	2.5×10^5			
		Ripstop	4.2×10^5			
		Silver coated ripstop	8×10^4			
[124]	PDMS	VeilShield transparent	—	—	60 × 55	2.45
[125]	NinjaFlex	Embedded NinjaFlex	—	3	60 × 60	2.45
[132]	PET	AgHT-4	—	2.5	45.13 × 53.21	2.42 and 3.88
	Jeans	Copper		1.7		2.93 and 5.71

Finally, the overall arguments on the researches given in the aforementioned investigations regarding Section 4 were summarized as exposed in Table 3.

5. SUMMARY

A variety of possible materials is available that could be used to build portable antennas. To have an antenna configuration that fits the functional antenna requirements, SAR analysis, comparisons of various antenna bending, and body comparisons must be performed. Wearable antennas are exciting, and along with the rapidly increasing wireless networking technologies, they promise a fantastic future. Reports of patch antennas have primarily concentrated on lightweight materials for the creation of portable antennas. The characteristics of the employed materials affect the actions of an antenna. The bandwidth and performance of a planar microstrip antenna, for instance, are primarily defined by the dielectric constant and thickness of the substrate. The usage of textiles in portable antennas demands their structures to be characterized. It is predicted that the conductive fibers should have weak and reliable electrical resistance to reduce losses. Component durability is also necessary to enable the antenna to be deformed over the fabric. Substrate selection is a crucial phase in the construction of a garment or woven antenna, to be durable for a specific use. The developed wearable antennas are primarily planar microstrip patch antennas, as they radiate mostly perpendicular to the planar structure and their ground plane often supports the human body effectively.

Textiles typically have a relatively small dielectric constant, which decreases surface wave losses and improves the antenna impedance bandwidth. For portable antennas, textile fabrics are chosen with respect to performance and versatility. It raises the spatial waves and thus improves the antenna impedance spectrum resulting in improved antenna resonance frequency, enabling antennas to grow with reasonable performance and high gain. For the modeling antennas, the thickness of the dielectric content can often be used to optimize the bandwidth of the planar antenna, knowing that this interest, therefore, cannot maximize the performance of the antenna. Hence the option of the thickness for the dielectric material is a balance between the output and bandwidth of the antenna. The substratum thickness often impacts the structural size of the antenna. The design of an integrated wearable antenna is critical, negotiating the trade-off between the efficiency of the antenna, its scale, and the difficulty for the continuous development of WBAN applications. The most prominent concern is the absorption of radiation in the human body owing to its relation to the antenna; therefore, the SAR value must be lowered as far as possible. Other problems with these antennas need to address the reliability under wet environments, impact on the atmosphere, dielectric properties, features of radiation around human skin, etc.

Throughout the activity, textile antennas are expected to be bent or otherwise conformed to a certain surface, and so experiments under different bending scenarios are required to examine differences in bending-dependent morphology. A bendable antenna was invented to be mounted on the body of the person. Mechanical deformation such as folding is possible when applied using textiles or lightweight fabrics since human or living beings often use wearable antennas. Wearable antennas should be built to be as symmetrical as possible in such a manner as to impact them while being bent in numerous directions minimally. Noteworthy, AMC systems have been found to be less prone to mechanical deformation in wearable devices. It has also been shown that utilizing the meta-surface, the consequences of stretching, and the presence of the human body in its vicinity can be mitigated. Furthermore, bending influences their radiation efficiency as predicted in the case of wearable CP antennas. Instead, owing to variations in its efficient range, bending influences the resonant frequency of linearly polarized antennas.

Moreover, external curvature is one of the critical issues to ensure that portable antennas work efficiently. While changing the frequency response of the wearable antennas, due to variations in the initial concentration on the radiating components, it also influences the polarization. To end with this, it must be remembered that the level of bending influences the resonant frequency of the antenna, the SAR intensity, and the pattern of radiation. It is crucial to formulate certain strategies to remove such consequences in order to build a wearable antenna. Additionally, a person must aim to position an antenna such that it will not be bent along the y-axis since it will cause a more severe loss of efficiency. Last, the antenna should be rendered as low as necessary through bending to prevent the major difference in the overall duration of the antenna.For further material analysis, upon testing a clear, flexible antenna built from translucent conductive fabric embedded in PDMS it is assumed that the existing approach is appropriate for the manufacture of transparent wearable antennas. As a result, the textile substrate is a strong choice, since it binds tightly to PDMS, increasing structural effectiveness of an antenna. The only downside in such type is the decreased surface resistance after embedding that contributes to a loss in antenna gain.

6. CONCLUSIONS

Wearable antennas are one of the main elements of wearable and portable equipment design. They are suitable for worn-out wireless networking and sensing applications owing to their lightweight, versatility, relatively inexpensive, and conformal features. This analysis ends with the introduction of applications where wearable technologies are considered to be of maximum value. Furthermore, the paper addressed the forms of versatile materials used and state-of-the-art technology employed to realize such constructs. The choice of material styles may be rendered dependent on factors such as specification, operational frequency bands, smallest-dimensional precision, smooth fitting into wearer garments, robustness to the rough environment, and the impact of bending scenarios. Although antenna requires low-loss dielectric material and highly conductive materials for effective receipt/transmission of EM radiation, extremely conductive products include aluminum, metallic inks, conductive polymers, and PDMS integrated conductive fibers are modern varieties used as wearable antenna conductive components. On the other side, due to its lightweight properties, several versatile substrate materials were presented as perfect solutions. It is inferred from the analysis that the most critical part of the specification is to eliminate coupling with the body while incorporating additional functionality to the layout of the antenna. This aspect intended to maintain stable antenna function on the body, accompanied by more improvements such as bandwidth extension as well as allow the antenna to operate with optimized performance with respect to the type of antenna topology. Finally, the paper studied the bendable antennas in several radiuses and analyzed their impact on the performance of the antenna. Consequently, it can be noted that the bending degree affects the resonant frequency, SAR strength, and radiation pattern of an antenna.

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