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ON-OFF Body Ultra-Wideband (UWB) Antenna for Wireless Body Area Networks (WBAN): A Review

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ABSTRACT Ultra-wideband (UWB) technology can offer broad capacity, short-range communications at a relatively low level of energy usage, which is very desirable for wireless body area networks (WBANs). The involvement of the human body in such a device poses immense difficulties for both the architecture of the wearable antenna and the broadcast model. Initially, the bonding between the wearable antenna and the human body should also be acknowledged in the early stages of the design, so that both the potentially degrading output of the antenna as a consequence of the body and the possibility of exposure for the body may be handled. Next, the transmission path in WBAN is affected by the constant activity of the human body, leading to the time-varying dispersion of electromagnetic waves. Few researchers were interested in this field, and some substantial progress has recently been considered. On the other hand, this paper covered both wearable and Non-wearable UWB antenna designs and applications with respect to their substrate characteristics. Finally, this review prospectively exposes the upgraded developments of (ON-OFF) body antennas in the area of wearable and Non-wearable UWB and their implementations in the WBAN device and aims to evaluate the latest design features that inspire the performance of the antennas.

INDEX TERMS ON-body antenna, OFF-body antenna, wearable antenna, ultra-wideband (UWB) antenna, wireless body area network (WBAN).

I. INTRODUCTION

A Wireless Body Area Network (WBAN) links individual nodes (sensors and actuators) that are situated in the clothing of a person, body, or skin. The network usually extends throughout the entire human body, and a wireless medium of communication links the nodes. Those nodes are positioned in a star or multi-hop topology according to the implementation. WBAN has gained significant interest owing to the wide variety of possible uses, such as safety screening, recreation, emergency response services, and caring for deprived children and elderly persons [1], [2]. Ultra-wideband (UWB) technology is a strong choice in a WBAN network to reduce the power spectral range, which translates into better battery life and decreased electromagnetic sensitivity for constant on-body operation [3], [4]. The wearable antenna is a crucial component of contact with certain instruments in WBAN networks, whether on or off the human body [5]. Constructing a wearable antenna for such schemes is extremely difficult, particularly for ultra-wideband service. The first aspect in the architecture is the connection between the antenna and the human body, which influences the efficiency of the antenna and theoretically results in high sensitivity to electromagnetics. The next eventual problem is while carried on the neck, to deal with the antenna deformations. Measures must be taken into consideration to ensure the output will not

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dramatically deteriorate. A further critical concern is the robustness of results in diverse settings. It covers factors such as temperature, humidity, and distance between human bodies and other clothing, capacity between wash, etc. More specific criteria such as low profile, compact size, mechanical stability, user convenience, ease of manufacturing, and low cost are considered significant for a wearable antenna. Besides, WBAN transmission networks are often very unusual in typical outdoor and indoor settings, relative to conventional networks [6], [7]. Scattering from the body is a shifting function owing to the motion of the user, which can improve or exacerbate the concept of multi-paths. The movement of body pieces, e.g., eyes, arms, and legs, can modify the reflected polarization of the wave, which results in polarization disparity. Losses related to absorption in the human body are far more significant than certain forms of losses and would result in a comparatively higher loss along the road. Several researchers are interested in overcoming all these problems at present. Many various styles of engineered UWB antennas have already demonstrated a very fair efficiency in WBAN systems recently [8]–[30] before the survey work in [31]. In addition to the wearable antenna designs and applications that normally employ flexible and textile substrate materials in the fabrication processes, the paper unveiled, discussed, and investigated the Non-wearable antenna configurations that use the conventional substrate materials to meet their design specification. Insight of this, the recent development in the area of wearable ultra-wideband antennas and their use in WBAN structures are valuable to retrospect. This paper is structured tidily to address and contrast many types of UWB antennas for both on-body and off-body communications concerning their applications. Furthermore, the paper discussed and analyzed antenna designs to evaluate different features that impact the performance and efficiency of the antenna such as the compact sizes, omnidirectional radiation patterns, bending conditions, UWB coverage, and substrates types with respect to their dimensions and the other features that govern the patch like relative permittivity (εr), loss tangent (δ) and thickness of the dielectric materials (h). Noteworthy, this paper is summarized as follows: a brief introduction to the wireless body area network-based UWB antenna design is given in section I. Then, detailed analysis is demonstrated in section II on (OFF-Body) communication by covering both monopole [33]–[56] and rear ground plane antenna types [57]–[69] alongside with their UWB applications. Section III concentrates on (ON-Body) communication antenna analysis and applications [70]–[86]. On the other hand, the paper classified and considered the operating frequency bands standard by 802.15 family and Federal Communications Commission (FCC) [32] UWB for OFF-Body based monopole [33], [34], [36], [40], [42]–[44], [47]–[49], [52], [54], [55], ground plane [57], [58], [63], [68] and ON-Body antennas [71], [74]–[77], [79], [81], [84]–[86]. Finally, the conclusion of the whole article is presented in section IV.

II. UWB OFF-BODY ANTENNA CONFIGURATION

A. MONOPOLE ANTENNAS

Owing to its easy configuration, broad bandwidth and fair radiation efficiency, the planar monopole antenna topology is commonly used in UWB communication systems and classified as the initial topology employed in wearable applications. The accelerated evolution of wireless networking systems has steadily required the need for improvement in antenna designs. Particularly, after the FCC allocated in February 2002, the frequency range from 3.1 GHz to 10.6 GHz for use without the license [32]. Elhabchi *et al.* [33] studied and built an innovative triangular semi-circular monopole antenna fed by CPW for super high UWB band purposes. The proposed antenna uses the FR4 substrate with selected dimensions of (23 × 25 × 1.6) $mm^{3,}$ as shown in figure 1. The proposed architecture has been successfully tested and improved with a broad bandwidth of more than 126 percent, where the UWB frequency spectrum covered the range from 4.9 – 25 GHz with a reasonable reflective coefficient and gain efficiency alongside the radiation patterns which was given in the range of FCC. This arrangement can be a good candidate to satisfy the requirements of the UWB ranges and can be conveniently utilized with the compact configuration of RF microwave systems.

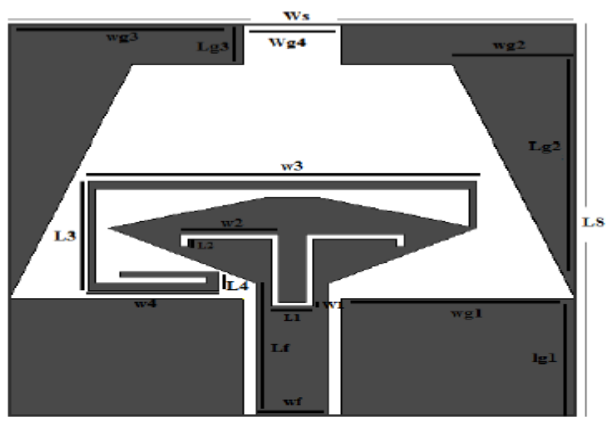

FIGURE 1. Super high UWB CPW-fed antenna dimension [33].

The convergence of state-of-the-art technology in the current connectivity scenario has intensified the common usage of integrated miniaturized computing systems possessing the capacity of communicating and executing specific sensing functions. Mustaqim *et al.* [34] introduced a lightweight and planar UWB antenna built and defined for wearable Internet of Things (IoT) applications for WBANs. The proposed antenna was fabricated using two separate substrates, and the dimensions of the model were defined by (31 × 42) mm for FR4 substrate and (70 × 56) mm for denim textile substrate as shown in figure 2, with patch dimension (22.6 × 17) mm^2. This patch simplifies the architecture such that the current and next generation of IoT devices and WBAN transceiver systems can easily be incorporated with respect to the obtained

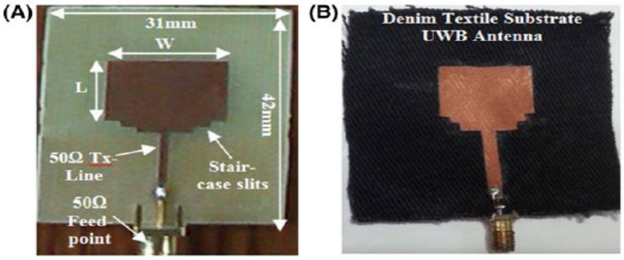

FIGURE 2. Fabricated prototypes of (A) FR4 substrate UWB antenna and (B) denim textile substrate UWB antenna [34].

impedance bandwidth of 7.71 GHz and 7.95 GHz for the substrates respectively.

Fast transfer speeds, cellular networking, broader range implementations, and compactness have become essential criteria for trend-setting UWB wireless communication systems. Accordingly, the UWB antenna that fed by a flangeless regular SMA connector along with the hexagonal patch vertices is presented by Joshi and Singhal [35]. A circumradius hexagonal patch, R =16.5 mm, and a circumradius concentrate hexagonal slot, r_{cut} = 3 mm is designed over a (46 × 46) mm FR-4 substrates as shown in figure 3. The prototype antenna realized (8.3) GHz from 2.3 – 10.6 GHz and (1.6) GHz from 4.9 – 6.5 GHz for impedance bandwidth and WLAN band rejection, respectively. The antenna calculations demonstrate that flange elimination converts a C-band antenna into a UWB antenna. Hereby, the proposed antenna can be a perfect choice for UWB applications.

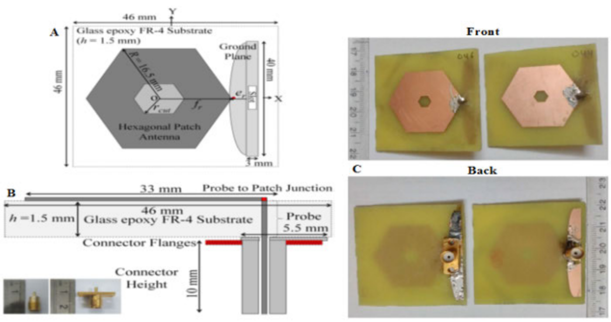

FIGURE 3. (A) Layout, (B) antenna with flange connector, (C) fabrication with and without flange [35].

Nowadays, the predilection for wearable ultra-wideband devices has increased. Additionally, the value of low-cost, versatile, and environmentally sustainable antennas has grown. In view of this, Rahman and Hossain [36] Introduced a wearable UWB antenna fed by a coplanar waveguide (CPW) on fabricated using paper substrate and analyzed the early detection proficiency of the brain stroke. The antenna dimensions and their geometry are addressed along with seven head structural model layers. To reduce the cost, copper nanoparticles are regarded as the radiating elements behalf of silver nanoparticles. A quite thin sheet of paper is known as a substrate to keep the antenna lightweight, portable, low-cost, and sensitive to the area (see figure 4). The antenna displays a coefficient of reflection of −10 dB or less at frequencies 1.91 – 34.45 GHz. The proposed antenna demonstrated reasonable return loss value covered by the frequency range of 1.91 – 34.45 GHz. The presented frequency range specified for Medical Body Area Network (MBAN), Industrial, Scientific and Medical (ISM), UWB concerning 5G and IoT applications at 2.36 – 2.4 GHz, 2.4 – 2.5 GHz, 3.1 – 10.6 GHz respectively. The accepted Specific Absorption Rate (SAR) values alongside the other simulation results confirmed the usability of the proposed antenna in wearable applications.

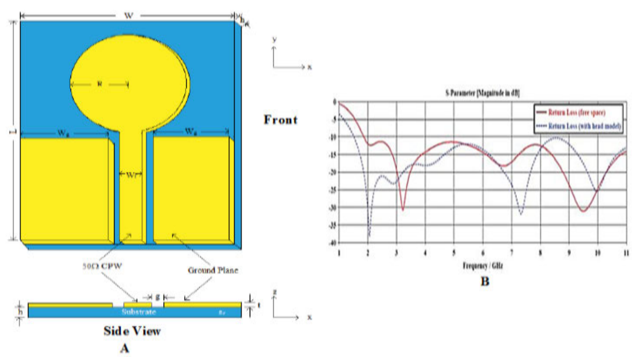

FIGURE 4. (A) Antenna structure, (B) S11 comparison between free space and head model [36].

Moreover, the UWB antenna was designed and fabricated by Rokunuzzaman *et al.* [37] using an inexpensive FR4 substrate with $\varepsilon r = 4.3$ and $h = 1.6$ mm in order to evaluate UWB radiation output near the Hugo head phantom with antenna dimension depicted in figure 5. The antenna functions over a frequency spectrum of 3.1 – 6.7 GHz assessed in terms of the reflective coefficient, E field, H field penetration, and SAR. The results confirmed that the power propagation at lower UWB frequency area inside the human head is more effective.

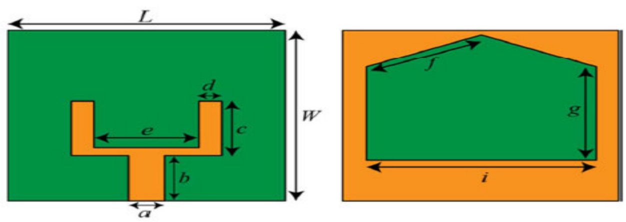

FIGURE 5. Schematic of the UWB antenna [37].

In [38], Khan *et al.* discussed the proximity effect of the U slot UWB antenna on the human body (see figure 6). The proposed antenna used Rogers TMM3 as substrates materials and operates within the bandwidth frequency range of 4.4 – 9.5 GHz and improved the impedance bandwidth by 75% concerning 50 mm distance between the antenna and the proposed human body. The results have proved that the obtained SAR value indicates that thermal absorption in the human body test is more critical in the skin layer compared to the other layers.

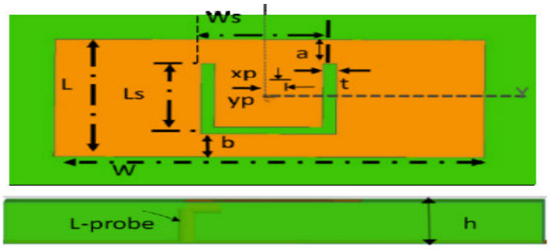

FIGURE 6. UWB slot loaded microstrip patch antenna [38].

In medical uses, microwave imaging has been commonly used to image the interior of human bodies and identify pathogens when they are already evolving in their early stages. Lin *et al.* [39] proposed novel low-profile ultra-wideband full-textile antenna architecture for portable medical imaging systems in the microwave. With this in mind, the antenna provides an easy-to-manufacture monopoly frame constructed of lightweight polyester fabrics and conductive copper taffeta, providing a compact and flexible structure for practical applications that conforms to the curved design of human bodies. The measured results show that the antenna obtained an ultra-wide operational bandwidth of 109 %, acceptable omnidirectional radiation, and an allocated gain of 2.9 dBi across the operating bandwidth. The antenna even retained its performance in the presence of phantoms imitating the tissue when it is bent or working (see figure 7). In comparison, on-phantom measurements suggest that the operating bandwidth and the apparent gain of the antenna when it works in the vicinity of human bodies do not affect. The time-domain return loss of the antenna varies significantly with the size of the deployed component, which highlights the versatility of the antenna for these utilization scenarios in microwave medical imaging.

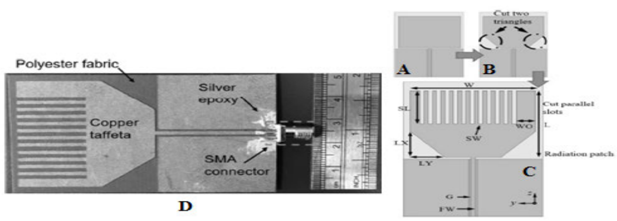

FIGURE 7. (A) Monopole antenna (B) Cut two triangles - bottom (C) Cut parallel - top (D) SMA prototype [39].

Research and production of versatile or foldable antennas in wireless technology are growing owing to their various benefits such as easy to install, highly robust, stretchable, corrosion-resistant, etc. In the scope of band-notched flexible UWB antennas, a band-notched flexible UWB antenna with a rejection band for high-speed WLAN applications is presented by Lakrit *et al.* [40]. The proposed monopole antenna was built on a thin, portable compatible substrate material of thick Teflon sheet with $\varepsilon r = 2.08$, $\delta = 0.001$ and $h = 0.6$ mm and antenna dimension $(42.5 \times 30 \times 0.6)$ mm^3 (see figure 8). A broad impedance bandwidth across UWB was realized in the frequency range of 3.25 – 13 GHz. The results depict strong bending robustness, high gain, and reliable distributed radiation pattern for trivial diversions impedance bandwidth and rejection render the antenna a conventional alternative for UWB communication systems.

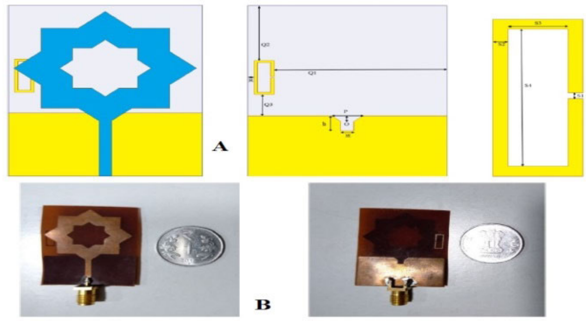

FIGURE 8. (A) Structure of UWB antenna with rejection band, (B) Fabricated prototype of proposed antenna [40].

Antennas are recognized as a device capable of sending and receiving signals. The speed of this sending and receiving process is a challenging interest, particularly when it comes to the rapid development of communication technologies. Accordingly, Saeidi *et al.* [41] demonstrated, addressed, and numerically analyzed the wide, multi and ultra-wideband antennas for wireless communication systems concerning the Martials used in the design comprehensively.

Recently, UWB technology has gained further interest due to the benefits of low power usage, fast data rate, and the potential to create short-range wireless networking links utilizing low-cost and low-energy transmitter/receiver connections. In view of this, Rahmatian *et al.* [42] designed a flat UWB portable antenna with a notched band built for the C channel. The antenna was designed on planar flexible PDMS substrate $\varepsilon r = 2.7$, $\delta = 0.035$ with overall antenna dimensions of (61×74) mm, as shown in figure 9. The antenna is generated by utilizing a split ring slot (SRS) on the radiating patch and avoiding satellite transmission to improve the upper-frequency spectrum. The design is significant for wearable technologies and ideal for off-body applications because the antenna and the body are fully protected from each other, and the operational frequency of the designed antenna is in the range of 3.9 – 10.75 GHz.

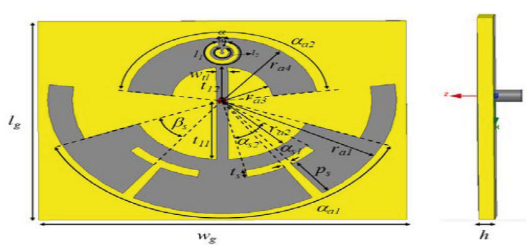

FIGURE 9. Structure of the proposed antenna with detailed geometries [42].

Through the constant development of civilization, citizens have created higher demands for the speed of communication and the results of communication. In view of this, Lv *et al.* [43] proposed a new UWB printed monopole antenna with triple band-notched functionality. The proposed antenna shown in figure 10 is printed on FR-4 substrate with $\varepsilon r = 4.4$, and $h = 1.6$ mm. The antenna bandwidth is expanded by grooving on the linking floor and boosting the impedance transition line about 3 – 11 GHz antenna bandwidth and 114% relative bandwidth. Furthermore, the proposed antenna realized triple band-notched features by etching the complementary split-ring resonators (CSRR) on the patch antenna, etching the symmetric J-shaped slot on the floor, and the spiral slot on the feeding line. Besides, the antenna easily blocked out WiMAX, WLAN, and the X-band downlink frequency portion of the satellite transmission network. Under this act, the whole module can offer promising results in the fields of different UWB applications.

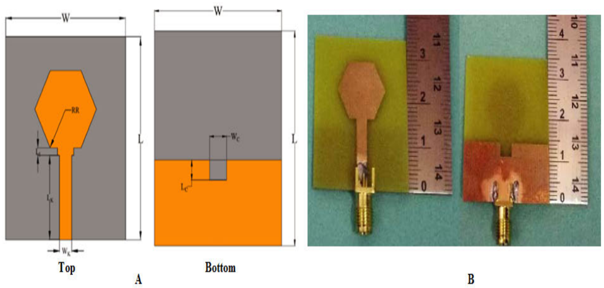

FIGURE 10. **(A) Geometry of the UWB antenna, (B) Fabricated sample of the UWB antenna [43].**

The necessity for wideband wireless connectivity is growing owing to the high data rate delivering more knowledge and the need to help more consumers. Compact quadruple planar UWB antenna attributes of band notch were reported by Devana and Rao [44], mounted on FR-4 substrate material. The use of two inverted U-shaped slots, symmetrical split ring resonator pair (SSRRP), and a through-hole are used to accomplish the quadruple band-notched functionality (see figure 11). The antenna can be recognized as its compact size, realized good impedance bandwidth and covered 4 band notch features specified by frequency ranges of 3.25 – 3.55 GHz, 3.7 – 4.2 GHz, 5.2 – 5.9 GHz and 7 – 7.8 GHz that support WiMAX, C band, WLAN and X band satellite communication respectively. The tests of the proposed antenna were in absolute agreement on the working bandwidth to achieve impedance matching, consistent radiation levels, continuous gain, and community delays. Hence, the antenna can function very well with portable UWB applications.

The UWB antennas are commonly seen in many networking technologies such as high data rate networking, high-resolution radar systems, and wireless image sensing. In this communication [45], a lightweight UWB and broadside radiated antenna is introduced using a folded ground area

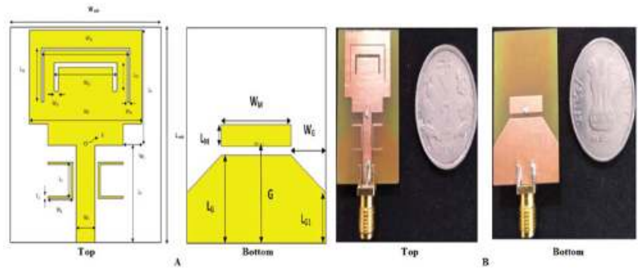

FIGURE 11. **(A) Detailed geometry of the Antenna, (B) Fabricated antenna prototype [44].**

by Kim *et al.* (see figure 12). The antenna doesn't have the PMC barrier needed by the initial Tightly Coupled Dipole Array (TCDA), which allows the designed antenna to enforce and suit impedance conveniently and helps to prevent the ideal TCDA structure from being self-resonant so that the antenna impedance bandwidth could be even broader. However, the UWB coverage does not have a wider bandwidth in this work. The calculated results obtained 130 % impedance bandwidth enhancement with a total gain of 2.33 dBi and good radiation efficiency of more than 89% along with the operation band. Additionally, this antenna is intended to be employed in several of the UWB array antenna applications.

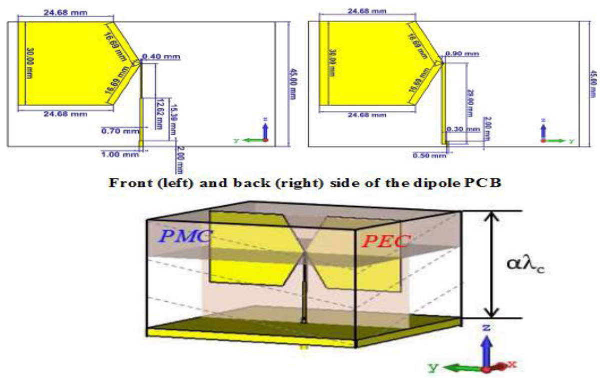

FIGURE 12. **Structure and the impedance characteristic of a unit cell antenna [45].**

Furthermore, Zahran *et al.* [46] presented a compact single-feed, circularly polarized slot antenna that was designed for wideband applications. The antenna versatility was accomplished with the usage of a physically twisting liquid crystalline polymer (LCP) substrate with overall antenna dimensions of $(50 \times 42 \times 0.1)$ mm, as shown in figure 13 and 100% impedance meeting the UWB spectrum of FCC. The final design featured good reflection coefficient, relatively omnidirectional radiation patterns, the large operating frequency bandwidth of 2.6 – 10 GHz, and total gain of axial ratio bandwidth (ARBW) across the whole operating frequency range alongside with encouraging the functionality of the antenna in the time domain for both smooth and bent scenarios.

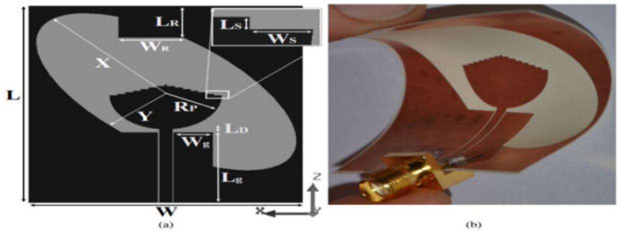

FIGURE 13. Proposed CP flexible antenna. (a) Labeled geometry layout, (b) photograph of the fabricated bent antenna prototype [46].

In [47], the design and creation of a lightweight planar UWB antenna were described by Susila, Rama Rao *et al.* for wireless applications. In order to reach broader impedance bandwidth, the antenna was installed over an FR4 substrate with εr = 4.4 and h = 0.16 cm, classifying the antenna as low profile with full dimension of (32 × 32) mm as depicted in figure 14. The proposed antenna operates in an omnidirectional frequency band 2.9 – 15 GHz with 12.1 GHz bandwidth. Regarding SAR, the measurement of electromagnetic (EM) radiation sensitivity to human tissues is detected while the proposed antenna was positioned near to the ionizing phantom template. The analysis proved that the SAR values are far below the limit of FCC and other safety standards, rendering the proposed antenna a reasonable choice for wireless applications of short-range.

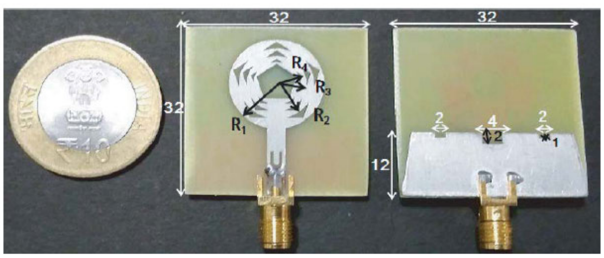

FIGURE 14. Photograph of the Prototype with dimensional details [47].

With the rapid advances of electronic information technology, wireless interface connectivity coverage was expanded from narrowband to broadband. Tan *et al.* [48] introduced a miniaturized planar monopole antenna of UWB with L-shaped stubs of ground aircraft (see figure 15). The provided antenna is capable of realizing UWB efficiency and miniaturization with the L-shaped stubs. The proposed prototype covered the whole UWB and realized impedance bandwidth of 10.1 GHz, firm radiation pattern, miniaturized size, and low-profile antenna type. Such outstanding results make the antenna a perfect choice for realistic UWB applications.

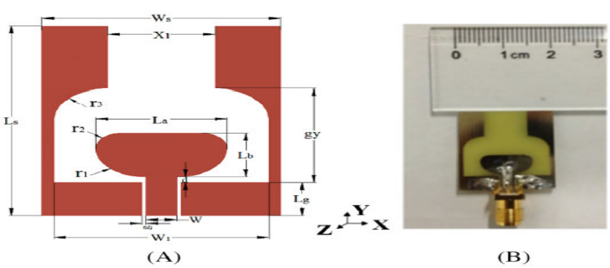

FIGURE 15. (A) Configuration of the proposed antenna, (B) Fabricated antenna [48].

For further miniaturization, the biomedical illustration demonstrates positive outcomes utilizing non-ionizing radiation in multiple applications such as protein characterization and cancer detection. In [49], Zakaria *et al.* presented a design of miniaturized printed elliptical patch antenna used for medical imaging such as skin cancer detection. The antenna is relatively compact with overall dimensions (15 × 15) mm, fabricated by a combination of a Roggers 5880 sheet εr = 2.2, and h = 0.787 mm, PTFE sheet εr =2.55, and h =2.5 mm as a cover, and Indium Tin Oxide (ITO) sheet with thickness = 0.1 μm as shown in figure 16.

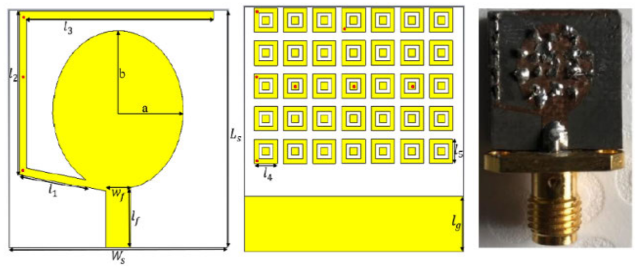

FIGURE 16. Proposed antenna prototype (the red points are shown the shorting point locations) [49].

The designed antenna realized super wide frequency bandwidth range 3.9 – 30 GHz with peak gain and directivity defined by 7.3 dB and 7.78 dBi, respectively. Furthermore, the proposed antenna reached high resolution due to the wideband duty cycle, taking into consideration that 92% of radiation efficiency was satisfied by choosing the ITO layer as a part of the substrates. These promising results classified the antenna to be an ultimate application in the fields of medical imaging and satellite communication systems.

In addition, circularly polarized (CP) antennas have considerable importance in large applications such as Satellite Communications, Global Positioning System (GPS), Radio Frequency Identification (RFID), (WLAN), Real-Time Locating System (RTLS), (UWB) and Microwave Imaging due to substantial characteristics such as multi-path avoidance and transmitter-receiver alignment versatility. Based on this, a circularly polarized UWB Crossed Dipolar Antenna was designed and manufactured by Akbarpour and Chamaani [50]. The outcomes emphasized that by changing the radiator and feeding configuration depicted in figure 17, the impedance and axial ratio were improved. The proposed antenna realized bandwidth ration around (4.1:1) for axial ration and (4.75:1) for the impedance. The antenna used the planar circular symmetric structure to shrink the multi-path effects between the transmitter and the receiver. Furthermore, the transient antenna reaction, which has a significant impact on image restoration, was measured for both near-field and far-field, resulting in favorable fidelity factors for imaging applications. Based on the far-field features, several performances were fulfilled satisfactorily, such as radiation pattern, gain value, and axial ratio.

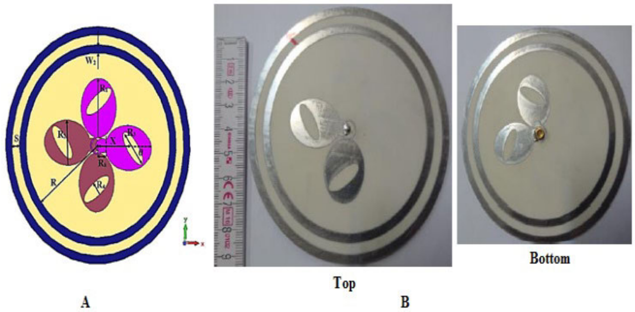

FIGURE 17. Schematic of presented antenna with slots and PSC, (B) Fabricated antenna [50].

According to the review article presented in [51], Del-Rio-Ruiz *et al.* stated that the textile and flexible antennas need careful trade-off between fabrics, topologies of antennas, design methods, and EM and mechanical capabilities. Besides, the analysis revealed the current research work for textile and flexible planar, totally grounded off-body communications antennas, including a novel design guide related to main parameters of antenna efficiency against topologies, feeding methods, conductive and dielectric textile materials, as well as an action under different measurement circumstances. Microwave medical imaging has drawn significant attention in recent years among the numerous applications of the UWB. Wearable technology is a growing area of innovation that can reduce medical mistakes and enhance the standard of patient healthcare. To diagnose skin cancer in a person afflicted by xeroderma pigmentosum disease, Mersani *et al.* [52] suggested a miniature monopole antenna for use in medical imaging to discover the cancerous tumors without contacting the skin concerning the electromagnetic signal radiated towards the human body. The overall dimension of the antenna was defined as shown in figure 18 based on flexible Zelt, tin/copper textile substrate material. The realized results confirmed that the artificial magnetic conductor (AMC) antenna could operate in the frequency range of 8 – 12 GHz with a radiation coefficient of less than −10 dB and obtained SAR value in the limits of FCC standards.

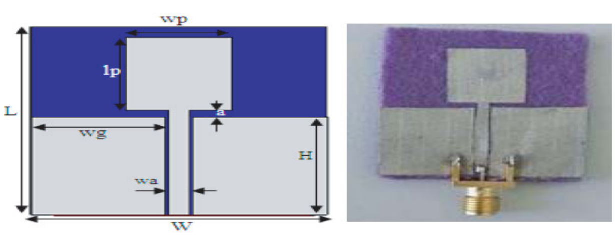

FIGURE 18. Geometry of the patch antenna [52].

The implementation of electro-textiles and smart clothing for connectivity, entertainment, health, and safety recently required the deployment of several technological tools directly onto textile substrates to improve consumer ease and satisfaction. Hereby, an innovative textile (UWB) antenna proposed by El Gharbi *et al.* for portable applications in [53]. 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 (see figure 19). This small size 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.

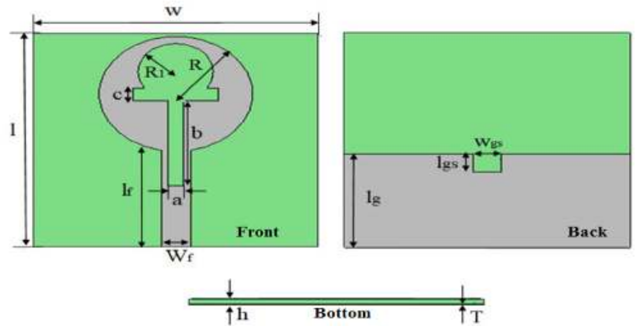

FIGURE 19. Geometry of proposed antenna [53].

Besides, the research discussed the effect of bending on the performance of the antenna. For this experimental analysis seen in figure 20, the proposed textile UWB antenna was used in two separate concave and convex bending conditions. Each location was determined by taking into account the normal bending radius in the human body. The comparison results confirmed 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 is recorded and justified by several potential reasons: the flexibility of the embroidery production system, the influence of humidity and temperature

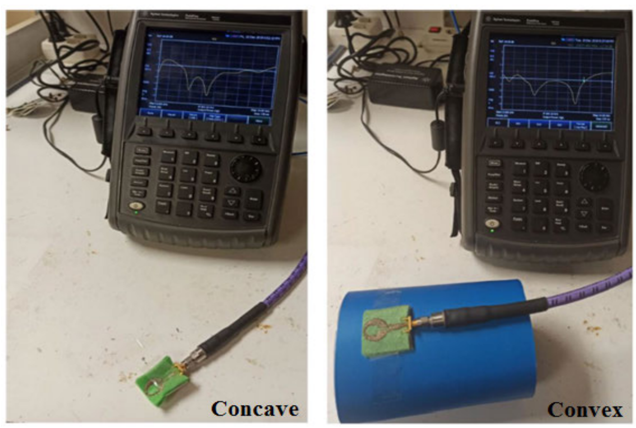

FIGURE 20. Measurement of textile UWB bending antenna [53].

on the successful dielectric permittivity of the felt, the non-uniformity sample thickness (rugosity).

Flexible electronics is an innovative technology that has recently gained tremendous prominence. On the other hand, Wang *et al.* [54] presented a flexible ultra-wideband (UWB) antenna, which uses a polyimide (PI) as the substrate (see figure 21).

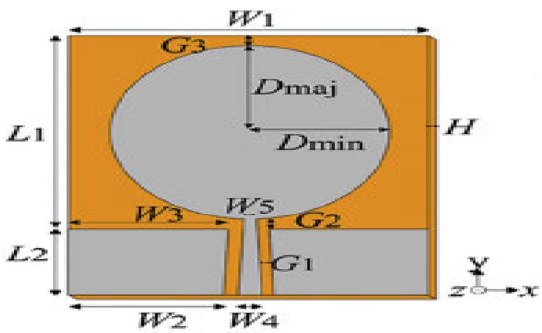

FIGURE 21. Geometry and dimensions of the flexible UWB antenna [54].

The appropriate flexible framework of the UWB antenna was manufactured at room temperature using surface modification and in situ self-metallization technique. The simulated and measured bandwidth of the proposed antenna operates in the frequency range covering 1.40 – 16.40 GHz and 1.35 – 16.40 GHz, respectively. The antenna provides an appropriate range of omnidirectional radiation between 2.45 and 5.2 GHz, allowing the versatile UWB antenna to retain its omnidirectional radiation pattern under bending circumstances, and the shaped silver layer often exhibits outstanding conductivity with PI films. Furthermore, this strategy offers an alternative solution to produce lightweight antennas without costly tools, ventilation conditions, and thermal annealing at high temperatures. In the same trend, Ji *et al.* [55] proposed a flexible antenna printed on Kapton polyimide substrate $\varepsilon r = 3$, $\delta = 0.02$ and $h = 3\ \mu m$ with an overall dimension of (21 × 21) mm used for UWB applications. The proposed antenna covered the UWB range frequency from 2.2 – 11 GHz, as presented in the measured bandwidth in figure 22.

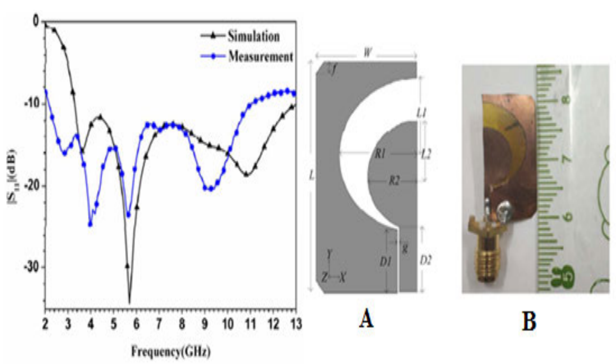

FIGURE 22. Proposed antenna. (a) Antenna configuration. (b) Photograph of the antenna [55].

Wearable wireless devices have drawn growing focus to address the conformal question of portable antennas and fabrics. In [56], a versatile and compact portable CPW-fed antenna based on a highly conductive graphene-assembled film (GAF) and a super-flexible ceramic composite material have been presented by Fang *et al.* (see figure 23). H-shaped slots significantly raise the performance bandwidth of the antenna such that the antenna realized impedance bandwidth of 67 % in the bending period and overall gain of 4 dBi. The CPW-fed system significantly decreases the antenna height and thereby improves the conformal capacity of antenna to the human body as well as its clothing absorption capability. The antenna has UWB characteristics of bandwidth that is resistant to bending abnormalities and alteration in ambient material, rendering it a strong choice for wearable applications.

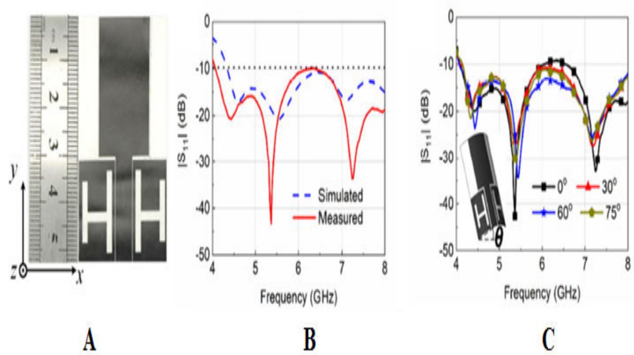

FIGURE 23. (A) Fabricated GAF antenna prototype, (B) Simulated – measured (S11), (C) Measured (S11) on bending angles [56].

B. GROUND PLANES ANTENNAS

A crucial drawback of the planar monopole topology, while being easy and quickly designed for wideband service, is that it does not provide conductive shielding between the antenna and the human body. Because of this, there is a strong possibility that the output of the antenna would degrade significantly when worn on-body, particularly in terms of radiation pattern and quality. While the issue is not solved immediately, some approaches have been suggested to reduce the antenna-body bonding causing deterioration, such as the pattern of radiation. A workaround suggested by Tuovinen *et al.* used anisotropic materials as a substratum while eliminating reduced radiation trends that can impede effective communication [19]. However, the manufacturing operation of such material is still challenging. It is advisable to use topologies of antennas with rear ground planes, to prevent the human body from affecting the output of wearable antennas. One of the easiest and more functional topologies for such a function is the well-known topology for microstrip, composed of a ground plane, dielectric sheet, and radiating area Yan *et al.* [31]. Mostly because of the endogenous resonance function, the new microstrip antenna has a minimal intrinsic bandwidth. Hence, different modifications are required

TABLE 1. Comparison analysis based on (off-body) monopole antenna design.

Ref No.	Substrate	εr	δ	h (mm)	Dimensions (mm)	Very wideband	Frequency Band (GHz)	Application	
								Wearable	Non-Wearable
[33]	FR4	4.3	0.02	1.6	23 x 25	YES	4.9 – 25	×	√
[34]	FR4	4.4	0.019	1.6	31 × 42	YES	2.9 – 11	√	×
	Denim textile	1.67	0.01	1	70 × 56				
[35]	FR-4	---	---	1.5	46 × 46	NO	2.3 – 10.6	×	√
[36]	Paper sheet	2.85	0.05	0.254	67 × 47	YES	1.91 – 34.45	√	×
[37]	FR4	4.3	---	1.6	24 × 22	NO	3.1 – 6.7	×	√
[38]	Rogers TMM3	3.27	---	4	---	NO	4.4 – 9.5	√	×
[39]	Polyester fabric	2.193	0.004	0.08	45 × 40	NO	1.198 – 4.055	√	×
[40]	Teflon sheet	2.08	0.001	0.6	42.5 × 30	YES	3.25 – 13	×	√
[42]	PDMS	2.7	0.035	3.5	61 × 74	YES	3.9 – 10.75	√	×
[43]	FR-4	4.4	---	1.6	35 × 30	YES	3 – 11	×	√
[44]	FR-4	4.3	0.02	1.6	24 × 30	YES	2.86 to 12.2	√	×
[45]	Taconic TLY-5 PCB	2.2	0.0009	0.25	(0.17 × 0.17) λ_{low}	NO	0.72 – 3.43	×	√
[46]	LCP	3.14	3.14	100 μm	50 × 42	NO	2.6 – 10	√	×
[47]	FR4 epoxy	4.4	0.02	1.6	32 × 32	YES	2.9 – 15	×	√
[48]	FR4-epoxy	4.6	0.02	1.6	26 × 20	YES	3.1 – 13.2	×	√
[49]	Roggers 5880 sheet	2.2	---	0.787	15 × 15	YES	3.9 – 30	×	√
	PTFE	2.5		2.5					
[50]	RO4003	3.55	0.0027	0.817	(0.55 × 0.55) λ_{min}	NO	1.6 – 7.2	×	√
[52]	Zelt, tin/copper	1.22	0.016	2	36 × 32	YES	8 – 12	√	×
[53]	Felt	1.2	0.0013	0.7	30 × 30	NO	3.1 – 10.6	√	×
[54]	Polyimide	3.5	0.001	50 μm	52 × 32.6	YES	1.35 – 16.40	√	×
[55]	Kapton polyimide	3	0.02	3 μm	21 × 21	YES	2.2 – 11	×	√
[56]	Ceramic	3.2	---	255 μm	32 × 52	NO	4 – 8	√	×

to increase bandwidth. To extract RF energy and different frequency bands, Elwi *et al.* [57] designed a unique printed circuit antenna using a low profile cylindrical substrate. The structured antenna design, as seen in figure 24, demonstrating that the patch is compatible with (3 × 5) MTM Hilbert inclusions based array printed on a flat, cylindrical polytetrafluoroethylene (PTFE) substrate with antenna diameter =15 mm and the height = 32 mm.

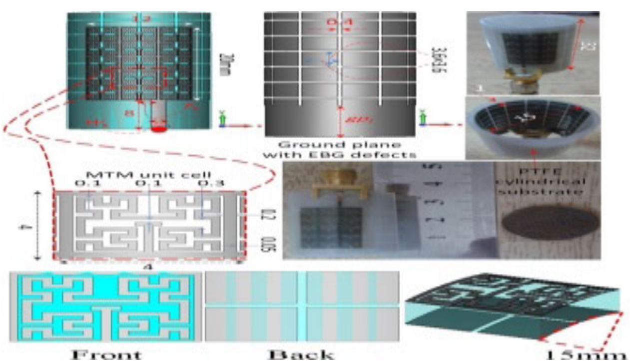

FIGURE 24. Antenna geometrical details in (mm) [57].

The proposed efficiency of the MTM unit cell is configured to attain improved relative constitutive parameters to progress the proposed output of the antenna. Thus, the antenna provides an outstanding equivalent bandwidth from 3 – 17.5 GHz. The developed version offered UWB with an initial independent resonant mode at 3 GHz across the frequency spectrum of 3.77 to 13.89 GHz. Lastly, the average extracted performance DC voltage is tested and located at 5.8 GHz about 4.5 mV. It was noticed that the proposed antenna displays outstanding processing conversion efficiency relative to other reported outcomes.

In [58], Farhood *et al.* designed an ultra- hexagonally shaped microstrip (UWB) antenna incorporated with dual-band technologies. The antenna used FR4 substrate material in the fabrication with an overall antenna dimension of (26 × 30) mm^2, with (h = 1.6 mm and εr = 4.4) using the hexagonal patch on the left side of the network antenna with two folded Capacitive Locked Line Resonators (CLLRs). This hexagonal arrangement was used for the design of UWB technologies. The proposed antenna achieved a reasonable 1.1 – 10.69 GHz bandwidth with voltage-standing-wave-ratio (VSWR) and a return loss less than 2 and −10 dB, respectively, leading the designed antenna to be an optimum choice for UWB applications and dual-band technologies. Regarding the compact design, Amin *et al.* [59] designed of a lightweight four-port Multi-Input-Multi-Output (MIMO) type antenna that functions on 3.1–10.6 GHz over the entire license of free UWB range with overall dimensions of (40 × 43 × 1) mm^3 as shown in figure 25. The proposed single UWB antenna configured using the low cost (20 × 20) mm over FR-4 substrate with $\varepsilon r = 4.4$, $\delta = 0.02$ and h = 1 mm.

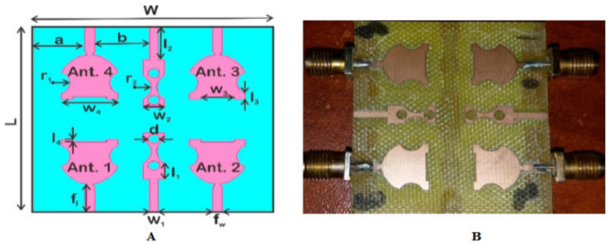

FIGURE 25. **UWB-MIMO antenna, (A) Designed, (B) Fabricated [59].**

The structure of the proposed antenna was unveiled by subfigure 25 such that (figure 25A) shows the four antennas grouped in MIMO setup; (figure 25B) shows the rear view of the fabricated MIMO antenna prototype. The wideband impedance balancing was maintained by different geometry modifications in the patch itself and ground plane, and due to the two distinct isolation mechanisms of parasitic resonators and ground plane with reactive stub setting, an insulation standard of at least 20 dB was reached for the whole unit. The efficiency requirements for diversity suggest the suitability of the proposed architecture for UWB-MIMO applications that contribute to consumer electronics applications for WPAN. Generally, microstrip patch antennas are widely used because of their small sizes, and the unidirectional distributive radiation of circular polarization can be effectively obtained. The bandwidth of patch antennas, though, is minimal, which restricts their usage in UWB applications. Sun [60] proposed a wideband enhancement approach based on a multimode patch antenna study. The resonance frequency of the higher-order modes TM20, TM30, TM40, and TM50 is diminished and coupled with the dominant mode TM10 one by applying sufficient shorting loads to the pad. A compact UWB patch antenna with unidirectional radiation pattern and circular polarization are planned using this bandwidth enhancement process depending on the design of five antenna modules. Using the free-space wavelength at the center frequency (λ_0) to describe the dimension of antenna patch, the size of the patch was specified as (0.5 × 0.5) λ_0 with (0.1) λ_0 height (see figure 26). The Simulated and calculated tests indicate that the proposed antenna reached an 85% bandwidth for S11 and RHCP gain, with operating frequency range 2.2 – 5.5 GHz, which classify the designed antenna as an optimum choice in UWB applications.

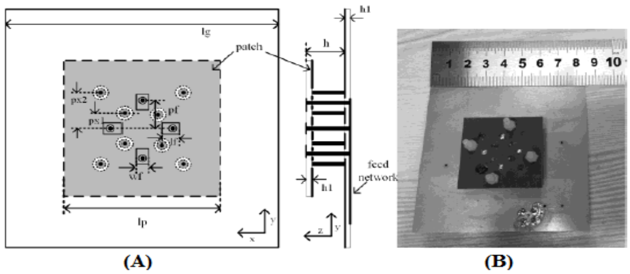

FIGURE 26. **(A) Structure of a final CP UWB patch antenna. (B) Fabricated photo [60].**

Furthermore, Bhanumathi and Swathi [61] designed and fabricated a compact microstrip antenna with overall dimensions of (24 × 36) mm^2. The antenna aspect with a dual-feed line structure was proposed in order to reduce the un-radiating terminal based on the signal interference principle. The proposed microstrip patch antenna was fabricated easily in a compact design and precise construction, as depicted in figure 27.

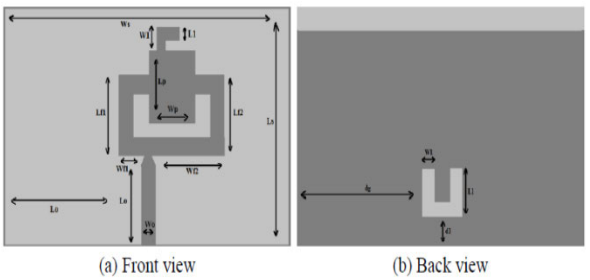

FIGURE 27. **Structure of Inverted L-shaped patch with U-Slot antenna [61].**

The reputation of the narrow bandwidth range given to the microstrip antennas was eliminated by placing an inverted L shape patch on the top of the FR-4 substrate material and etching the limitless ground plane to achieve 28% bandwidth enchantment (see prototype fabrication in figure 28). Moreover, the antenna operated in the frequency band of 4.8 – 7.8 GHz and classified as a perfect solution for UWB applications.

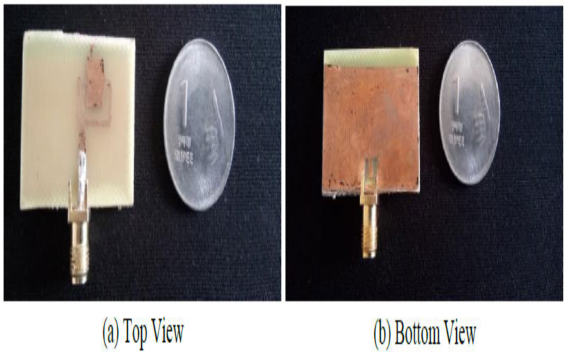

FIGURE 28. **A fabricated prototype of the proposed antenna [61].**

Another work presented by Türkmen and Yalduz [62] to design a compact grid array microstrip patch antenna using RT/duroid substrate $\varepsilon r = 2.2$, $\delta = 0.0009$, and h = 1.57 mm. The proposed antenna can be a suitable choice for ISM bands, WBAN applications, and UWB technologies. An initial strategy to miniaturize a traditional rectangular patch antenna fed with coplanar was presented in [63]. For the optimal UWB connectivity, Vyas, Gautam *et al.* applied the methodology of adaptations in ground plane and antenna radiator configuration (see figure 29). For improved impedance balancing, a basic solution was adopted to install an inverted stub in 'L' form at one of the ground planes of the uneven CPW-fed antenna. The proposed antenna achieved 3.6 dB in the UWB range at peak gain 7 GHz and adequate electrical efficiency, rendering it to be used conveniently in wearable UWB devices.

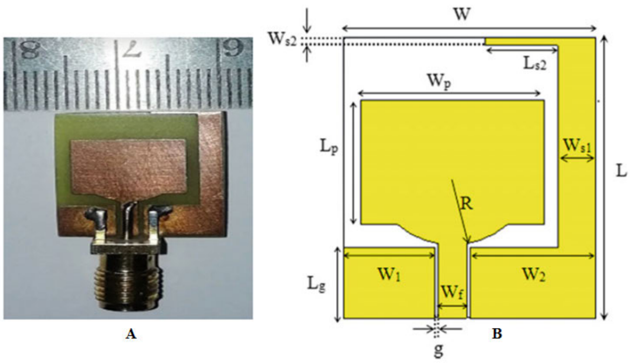

FIGURE 29. (A) Configuration of UWB antenna, (B) Fabricated prototype [63].

Moreover, a compact textile antenna built on microstrip developed to follow the IEEE 802.15.4 Wireless Body Area Network Ultra-wideband (WBAN-UWB) specification is designed and analyzed by Samal *et al.* [64], [65] with overall antenna dimension of (42 × 39 × 3.34) mm (see figure 30) fabricated on a felt textile substrate of $\varepsilon r = 1.45$, $\delta = 0.044$ and h = 3 mm.

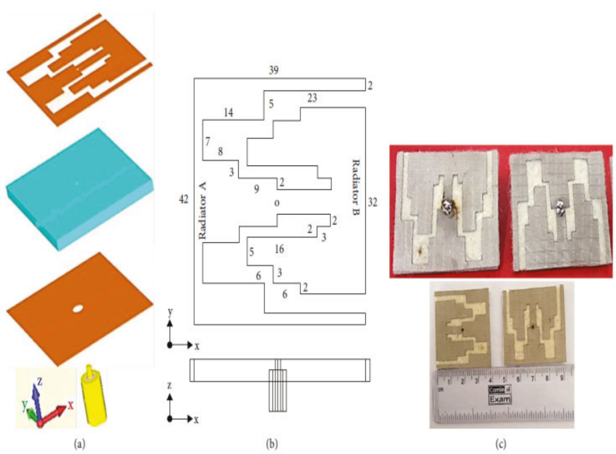

FIGURE 30. Design of the proposed antenna: (a) exploded view, (b) dimensions (in mm), (c) fabricated prototype (top) and fabricated prototype prior to soldering feed (bottom) [64], [65].

The full ground plane, meanwhile, enables the activity of the antenna in the vicinity of the human body with minimum body binding and exposure against it, which promises operational protection. In addition to the mandated low and high band channels of WBAN-UWB, the proposed antenna often worked in five other high band channels, showing a cumulative bandwidth of 3.4 GHz by considering antenna evaluation both in free space and on the body which proved its functionality in both channels with a spatial radiation pattern with realized gains 4 and 6 dB in the XZ axis. UWB antennas must be lightweight, low-cost, and offer reasonable radiation patterns for various applications.

To design the UWB omnidirectional antenna with high gain, Qaddi *et al.* [66] proposed and designed a new UWB antenna for the application of C band satellites. The overall dimension of the proposed antenna was (40 × 40 × 1.6) mm^3 fabricated on FR4 substrate material specified by $\varepsilon r = 4.3$ and h = 1.6 mm, as depicted in figure 31. The designed antenna would span the UWB spectrum from 7.8 – 10.25 GHz for radar applications, as well as the ground station frequency of 6.3 GHz for spacecraft applications, assuming that such a wideband is accomplished using various slot techniques by etching various formed slots into the radiating area, which is satisfied once the constant radiation characteristics with appropriate omnidirectional radiation patterns were achieved.

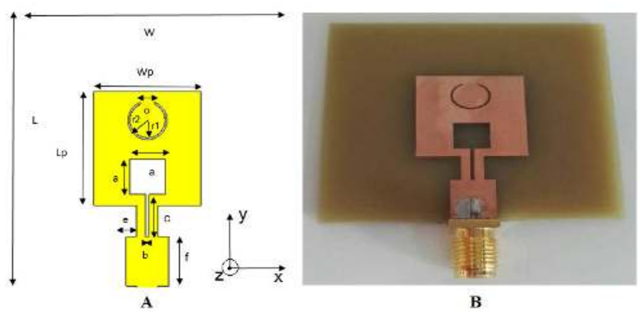

FIGURE 31. (A) Geometry of the proposed UWB antenna, (B) Photograph of the fabricated UWB antenna [66].

Since FCC authorized the usage of UWB frequency, several antenna architectures have been introduced, such as Annual ring antenna, triangular slotted antenna, diamond, and rounded diamond antenna, U-shaped antenna, circular disc antenna, spline antenna, and dual-band antenna. In view of this, a miniaturized fractal antenna is developed and introduced by Dwivedi and Kommuri [67] utilizing Coplanar Wave Guide (CPW) fed and UWB-artificial magnetic conductor (AMC) for ultra-wideband and Successfully integrated applications (see figure 32). The antenna realized overall gain of (3.35) dB and (7.7) dB with and without UWB-AMC, respectively. The architecture indicates that if the amount of iteration rises, then the benefit declines after successive iteration, however, enhanced the bandwidth and reflection coefficient. Nevertheless, the proposed antenna requires further optimization in the flat gain and AMC design dimensions.

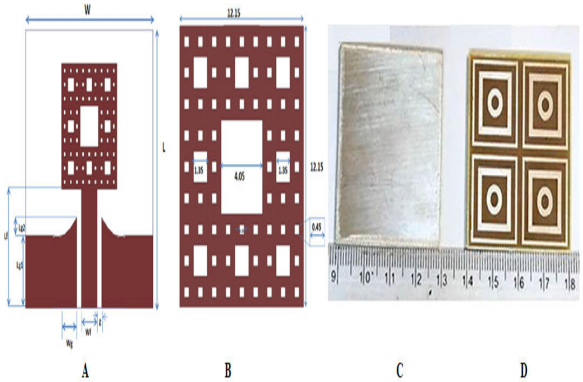

FIGURE 32. (A) Dimension of proposed UWB antenna, (B) Fractal patch, (C) Fabricated PEC, (D) Fabricated AMC [67].

Owing to their dimensional flexibility and design symmetry, wire monopoles with varying geometries and configurations were among the most popular and readily accessible solutions for LF to UHF communications. To ensure high fidelity of the transmitted and received antenna system and in order to realize a good competitor in the ultra-wideband antenna unit, a basic innovative cross-finned configuration of a monopole antenna has been investigated by Ganguly *et al.* [68]. The optimized configuration with a minimum monopole dimension (11 × 22.5) mm was designed on foam strip to operate in the frequency range of 5 – 22.5 GHz to operate in the frequency range of 5 – 22.5 GHz with high fidelity and a peak gain of as much as 1 – 7 dBi and strong co-to cross-polarization isolation 26 – 31 dB across the band (see figure 33).

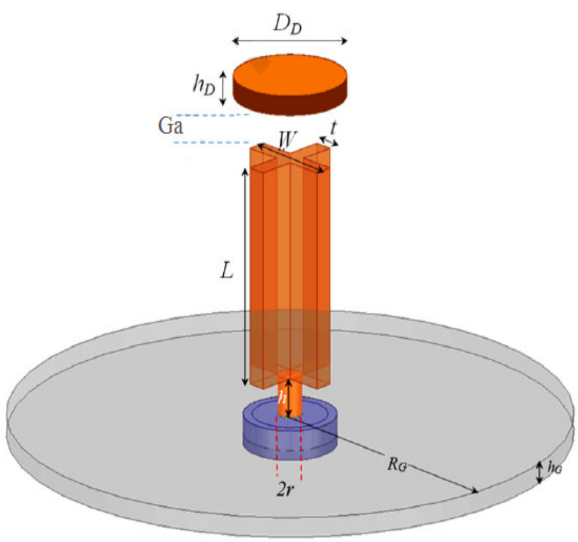

FIGURE 33. Schematic representation of cross finned top-loaded monopole [68].

The proposed design demonstrated desirable transmitting and reception characteristics in the time domain and considered extendable to the upper side up to 32 GHz and the lower side to 1.5 GHz of the microwave spectrum, allowing this commercially feasible configuration to find future applications in the lightweight and miniaturized wireless transceiver systems as in [65], [66]. The portable antenna is a planar antenna constructed of as the substratum textile materials. In [69], For UWB implementations, a planar-printed Antenna with a micro-strip feed line was proposed and evaluated by Baidda *et al.* on five usable portable and implementable materials. The antenna is constructed in the ground plane by four measures and three additional form shifts. The proposed antenna covered the full operational band with 99 % radiation efficiency. The antenna with ARLON AD-320 substratum content showed good sensitivity, and the antenna with FERRO A6 M substratum demonstrates the highest output of radiation. CPW was fed in order to reduce backward radiation, providing improved results for on-body contact and SAR. For higher gain and more directionality, the arrays of such antenna can be implemented. For more clarity, OFF-Body based ground plane antenna configurations were summarized in Table 2.

III. UWB ON-BODY ANTENNA CONFIGURATION

Since wearable antennas are used for on-body contact in WBAN devices, the radiation pattern in the horizontal plane has to be omnidirectional, and the orientation has to be longitudinal for the human site. A vertical monopole with a wide field is thus a strong choice for these schemes. Nonetheless, to maintain practicality, the height should be lowered significantly, and the bandwidth should be increased to accommodate the intended applications. Irene and Rajesh [70] proposed the design of compact microstrip- dual-polarized UWB monopole MIMO antenna for WBAN access point technology. The proposed antenna was designed on FR4 substrate $\varepsilon r = 4.4$, $\delta = 0.02$ with an overall dimension of $(29 \times 58)\ mm^2$ and (1.6) mm thickness, as shown in figure 34.

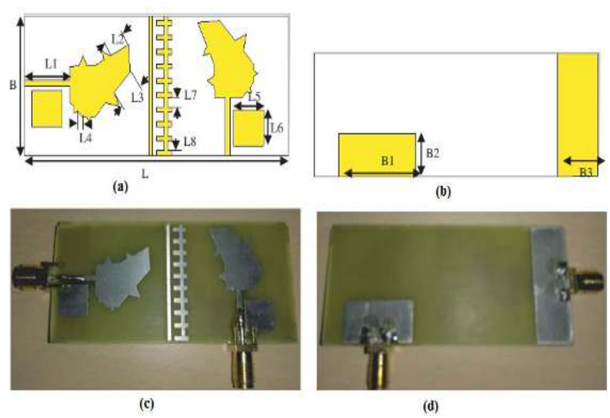

FIGURE 34. UWB MIMO antenna, (a) top layer and (b) bottom layer of the antenna, (c) Front view (d) bottom view of the fabricated antenna [70].

TABLE 2. Comparison analysis based on (off-body) rear ground plane antenna design.

Ref No.	Substrate	εr	δ	h (mm)	Dimensions (mm)	Very wideband	Frequency Band (GHz)	Application	
								Wearable	Non-Wearable
[57]	Polytetrafluoroethylene	2.04	0.0002	1	32 × 15	YES	3.77 – 13.89	√	√
[58]	FR4	4.4	---	1.6	26 × 30	YES	1.1 – 10.69	×	√
[59]	FR4	4.4	0.02	1	40 × 43	NO	3.1 – 10.6	×	√
[60]	F4B	2.65	0.002	0.5	(0.5 × 0.5)λ0	NO	2.2 – 5.5	×	√
[61]	FR4	4.4	---	1.6	24 × 36	NO	4.8 – 7.8	×	√
[62]	RT/duroid	2.2	0.0009	1.57	38 × 50	NO	2.45, 6.25, 8.25, 10.45	√	×
[63]	FR-4	4.4	0.02	1.6	18 × 16	YES	2.7 – 12	√	×
[64]	Felt textile	1.45	0.044	3	42 × 39	NO	3.9 – 4.2	√	×
[65]						NO	6.5 – 9.9		
[66]	FR4	4.3	---	1.6	40 × 40	NO	7.8 – 10.25	×	√
[67]	FR4	4.4	0.0001	1.6	27 × 28	NO	2.5 – 10	×	√
[68]	Foam strip	1.08	---	0.5	11 × 5	YES	5 – 22.5	×	√
[69]	ARLON-AD 320	3.2	0.04	1.75	27 × 31	NO	2.4 – 5.8	√	×
	FERRO A6M	5.9	0.0098			NO	3.1 – 10.6		

The designed antenna has strong insulation with the incorporation of Modified Serpentine System (MSS), serving as a decoupling unit (DU) recognizing that the antenna was obliquely polarized in the range of 6 – 10.6 GHz. It operates in the range of the UWB frequency band. The proposed antenna offered reduced coupling. Improved bandwidth impedance concerning the Electromagnetic Band Gap (EBG) ran to realize wide impedance bandwidth in UWB, large isolation, and fractional bandwidth of 106% with omnidirectional radiation pattern. The Envelope Correlation Coefficient (ECC) is equivalent to zero, and the power loss is 0.264, which reflects the complexity characteristics of the proposed antenna. In [71], a lightweight epsilon-shaped (π) ultra-wideband (UWB) antenna was designed and investigated by Singhal *et al.* for dual-wideband circularly polarized (CP) applications. The form was engraved to the FR-4 substrate $\varepsilon r = 4.3$, $\delta = 0.025$ with overall dimensions (20 × 20) mm^2. The design offered 97.02% impedance bandwidth through 10.4 – 30 GHz with ARBW for two bands as 6.45% and 38.50% for (26.25 – 28.00) GHz and (13.30 – 19.64) GHz respectively. For Wireless Local Area Networks (WLAN) and Ultra-wideband (UWB) implementations, a low-profile, wireless antenna with a monopole based radiation design was introduced by Zheng *et al.* [72]. The total physical dimension of the antenna is (15.8 × 15.8 × 8.5) mm concerning the electrical dimension of (0.24 × 0.24 × 0.061) λ0. The proposed antenna offered omnidirectional radiation pattern characteristics over 2.4 – 13 GHz operating frequency range. Tan *et al.* [73] introduced a miniaturized planar UWB slot antenna with dual-polarization MIMO with overall antenna dimensions (32 × 22) mm^2 printed on inexpensive FR4-epoxy substrate $\varepsilon r = 4.6$, $\delta = 0.02$ and h = 0.8 mm. The efficiency of the UWB impedance was obtained using phased slots of one-quarter of wavelength. The antenna presented several benefits such as UWB dual-polarization efficiency, consistent radiation patterns, low profile, steady gains, compact size, and operating frequency range of 3.05 – 10.61 GHz. All these benefits classified the antenna to be suitable for UWB applications. However, the performance might further be enhanced using additional structures (see figure 35).

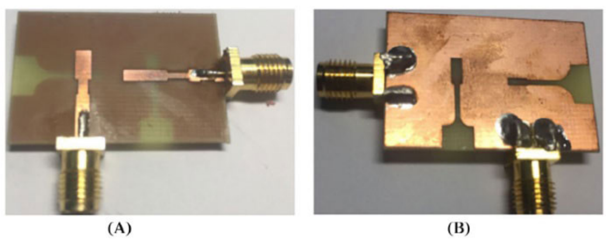

FIGURE 35. Photograph of the fabricated antenna: (A) front view, (B) back view [73].

Owing to technological advancement, wireless communication systems have improved many creases. Shahid *et al.* [74] introduced a microstrip patch antenna for (UWB) applications. The antenna has been designed for different substrates, and a comparison among the different substrates is performed. The FR4 substrate is a solid fiber, Rogers RT duroid 5880 is bendable with a smaller size, and versatile is even Kapton Polyimide. The optimum bandwidth is obtained with compact Rogers RT duroid 5880. As a result of this, the flexible substrate with higher bandwidth is the considered substrate (see figure 36).

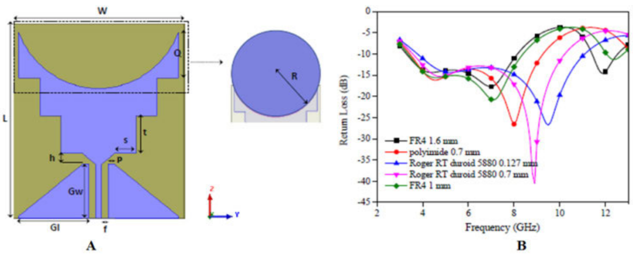

FIGURE 36. (A) Antenna design, (B) The S parameter plot [74].

An antenna printed on an ultra-thin flexible substrate shows characteristics of low profile, lightweight, versatile bendability, and compatibility for tools in various sizes. Zhang *et al.* [75] proposed a novel UWB antenna built on a transparent substrate, which is 70 μm thick. To get broad bandwidth, CPW feeding and unequal height ground planes were employed. The proposed antenna contains a patch fed by CPW with a hybrid form. The ground planes at opposite ends of the feeding line have different heights to improve the bandwidth of antennas. The simple and low-cost printed circuit board (PCB) is the etching technique used in the fabrication process (see figure 37). The produced antenna has robust measured bandwidth with acceptable gain in flat and bent situations due to considerable bandwidth in the simulation phase. The proposed antenna showed strong output after bending, with a low profile, broad bandwidth, and reliable frequency band, which can be applicable in foldable WWAN terminals, WBAN devices, and medical sensors.

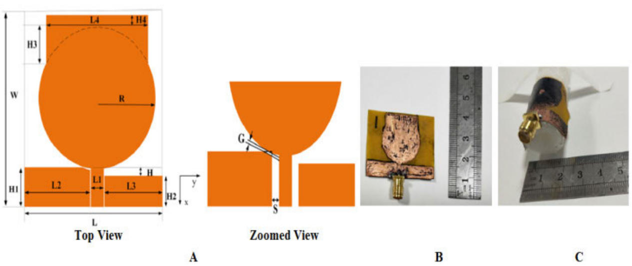

FIGURE 37. (A) Configuration of proposed antenna, (B) Fabricated antenna, (C) Bent antenna [75].

The antenna plays a vital function in making sure a WBAN network works. A WBAN antenna can be mounted on a human body, the effect of wearer on the transient characteristics should be included in the design of the antenna. Hereby, Yang *et al.* presented a low-profile, UWB antenna for WBAN [76]. The antenna starts from top-to-bottom with horizontal substrate, two vertical orthogonally positioned substrates, and a metalized ground plate constructed of regular FR-4 substrates with a thickness (1) mm with a metalized ground plate made of copper sized (80 × 80) mm. The new antenna combines the features of both the monocone and the printed antenna such that the produced design is light in the weight, simple in fabrication, and promises wideband with omnidirectional radiation patterns. The height of the antenna of (0.05) λ_0 with the optimized patch shape has enhanced the impedance bandwidth about 162%, and 2.5 – 24 GHz frequency range was achieved. Therefore, the effect of the human body on the proposed antenna was negligible, and the time-domain activity of the low-profile UWB antenna was checked. The results concerning system fidelity indicate success in transmitting and receiving pulse signals.

Owing to its uses in a wide variety of fields such as health surveillance, patient recording, emergency systems, frontline survival, recreation, navigation, wearable computing, and so on, WBANs has recently become an important branch of research. For wireless body area network applications, UWB low SAR flexible metasurface-enabled wearable antenna was introduced by Yalduz *et al.* [77]. The metamaterial (MM) structure-based antenna was built and produced on a jeans textile substrate in a size (58 × 80 × 1) mm^3 as shown in figure 38 knowing that (MM) structure is fabricated on flexible felt textile substrate with (91 × 105 × 3.6) mm and 7.9 mm thickness to reduce the value of SAR and increase the efficiency of the antenna. Furthermore, the ethylene-vinyl acetate (EVA) foam substrate is placed as a separator to prevent any electrical contact between the antenna and MM.

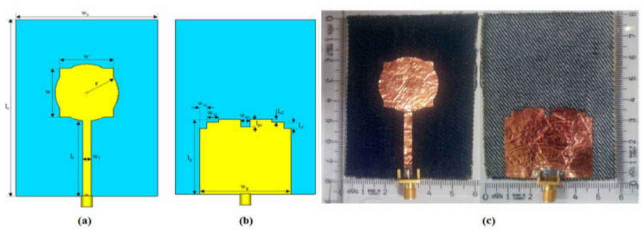

FIGURE 38. Configuration of the proposed antenna with (A) Front view, (B) back view, (C) Fabricated antenna front and back views [77].

Accordingly, this development increased impedance matching, high gain, radiation pattern, and a wide operating frequency of 3.5 – 12.4 GHz with increased peak gain by 98% for (MM)-based antenna. The maximum SAR value with (MM)-based antenna positioned on-body is reduced by 97% compared to the SAR value without (MM), this emphasizes that the overall SAR value is less than the European safety bounds for 10g human body tissues. Under this act, the designed antenna would be a perfect solution for safety wearable applications.

Within the study proposed in [78], the benefit of a solid, lightweight, and monopole-based construction was considered by Das *et al.* for wearable antenna applications to counteract the impact on antenna characteristics of the body bending, tissue crumpling, and textile washing. The designed antenna was fabricated on Rogers RO4232 substrate $\varepsilon r = 3.2$, $\delta = 0.0018$, and h = 1.52 mm with overall antenna dimension (75 × 63 × 1.52) mm^3 as depicted in figure 39.

The antenna realized (111.4) % and (45.61) % for impedance bandwidth and ARBW, respectively. The measurement of this planar antenna on body output validates its applicability under the body-worn environment. It was found

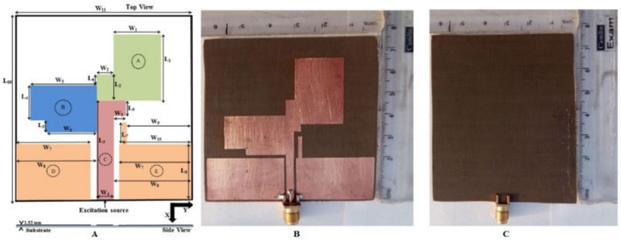

FIGURE 39. The proposed antenna, (A) Geometry, (B) Prototype Front View, (C) Prototype Back View [78].

that the overall volume of radiation consumed by the body type is limited to a peak SAR value.

Noteworthy, UWB antennas are incredibly competitive for low transmission energy, high data rate, high image quality, relatively high characterization. Such features render them appealing to interaction with UWB. Accordingly, Pannu and Sharma [79] proposed a single port, miniaturized UWB antenna design shown in figure 40. The antenna offers a basic configuration consisting of a rectangular patch and a defective field. The irregularities in the ground plane have a significant effect on the whole UWB on the −10 dB bandwidth. The bandwidth was further increased by adding a changed tapered feed line with respect to the slit patch. Owing to these features, the antenna can be a good candidate for various wireless applications.

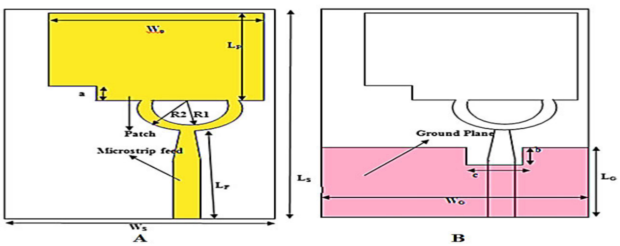

FIGURE 40. (A) Proposed geometry highlighting patch, (B) Geometry of ground plane [79].

The ranges of UWB are not only becoming a significant testing sector for radar systems. However, they have been applied to Body Area Networks (BAN) devices, particularly medical applications such as Wireless Capsule Endoscopy. In light of this, Kissi *et al.* [80] defined an improved antennal structure (see figure 41). The antenna has proved to be a successful choice for applications on Body Area Networks. A study based on frequency and time domains comparison of the existing grounded system was performed. Various antenna structures have been checked on the abdomen and back of the actual human subjects, especially at the navel stage. The results indicate that the antenna should be used to connect with UWB signaling for Wireless Capsule Endoscopy in compliance for IEEE 802.15.6.

The antennas that cover the UWB range are excellent competitors for certain short-range networking and WBAN applications. In [81], Di Natale *et al.* proposed a configuration

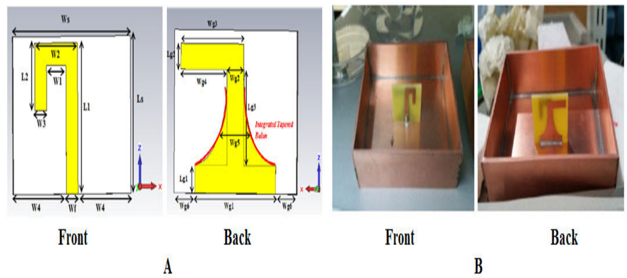

FIGURE 41. (A) Structure of the "Grounded" UWB antenna, (B) Antenna prototype of the studied UWB antenna [80].

of an all-textile adjustable antenna for UWB applications with a bandwidth consistent with the UWB FCC standards. In all instances, the antenna can even serve as a monopole over a ground plane or as a microstrip patch preserving UWB functionality. In monopole and directive microstrip topologies, the determined radiation pattern includes a better behavior at lower frequencies to be quite omnidirectional. However, In the case of microstrip topology, the radiation pattern loses stability at higher frequencies, but a reorientation can make more changes in the layout. UWB technology has the benefits of high communication efficiency, fast data rate, and low cost. However, it also has the drawbacks of multi-path fading and weak reliability; so that an innovative means called MIMO technology has been suggested to solve the problems.

In another work, Liu *et al.* [82] proposed a lightweight (MIMO)-based ultra-wideband (UWB) antenna with dual band-notched characteristics for wearable applications. The proposed antenna was fabricated on Rogers 5880 substrate $\varepsilon r = 2.2$, $\delta = 0.0009$, and $h = 0.787$ mm with overall antenna dimensions of (50 × 50) mm2 (see figure 42).

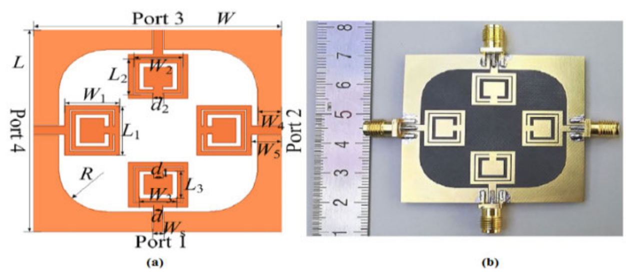

FIGURE 42. The proposed Antenna, (A) Geometry of the dual band-notched UWB, (B) Fabricated photograph of the antenna [82].

The etching separate SRR slots can obtain dual band-notched properties on the radiation patches at core frequencies between 3.5 and 5.5 GHz. The designed antenna works effectively between 2.2 and 10.4 GHz, with (3.1 – 4.1) GHz and (5.0 – 5.85) GHz notched bands, respectively. Furthermore, the antenna offered stable radiation patterns, low ECC, gain smoothness, and compact antenna design leading this antenna to be an appropriate choice for wearable applications.

TABLE 3. Comparison analysis based on (on-body) common antenna design.

Ref No.	Substrate	εr	δ	h (mm)	Dimensions (mm)	Very wideband	Frequency Band (GHz)	Application	
								Wearable	Non-Wearable
[70]	FR4	4.4	0.02	1.6	58 × 29	NO	3.1 – 10.6	√	×
[71]	FR4	4.3	0.025	---	20 × 20	YES	10.4 – 30	√	×
[72]	Standard SMA probe	---	---	---	(0.24 × 0.24) λ_0	YES	2.4 – 13	×	√
[73]	FR4-epoxy	4.6	0.02	0.8	32 × 22	NO	3.05 – 10.61	×	√
[74]	Roger RT Duroid 5880	2.2	2.2	0.127	16 × 26	YES	~ 3.6 – 11	×	√
[75]	Kapton polyimide	3.5	---	70 µm	30.4 × 38	YES	3.06 – 13.5	√	×
[76]	FR4	---	---	1	80 × 80	YES	2.5 – 24	×	√
[77]	Jeans textile	1.7	0.026	1	58 × 80	YES	3.5 – 12.4	√	×
	EVA foam	1.2	0.005	3.2	91 × 105				
[78]	Rogers RO4232	3.2	0.0018	1.52	75 × 63	NO	1.28 – 4.5	√	×
[79]	FR4	4.4	0.02	1.6	17 × 25	YES	2.1 – 15.8	×	√
[80]	Agilent 8720ES	---	---	---	89 × 60	NO	3.75 - 4.25	√	×
[81]	Denim	1.82	0.045	0.6	---	YES	1.8 – 16	√	×
[82]	Rogers 5880	2.2	0.0009	0.787	50 × 50	NO	2.2 and 10.4 3.1 – 4.1 5.0 – 5.85	√	×
[83]	FR4	4.3	0.025	0.8	14.90 × 33.12	NO	> 3.1GHz	√	×
[84]	Non-woven	1.15	---	5	23.5 × 22	YES	4.3 – 16.25	√	×
	Cotton	1.65		1			4.1 – 16.9		
	FR4	4.4		1.6			4.4 – 17.75		
[85]	FR4 epoxy	4.4	0.017	1.6	8 × 27.5	YES	2.8 – 12.6	×	√
[86]	FR4	4.4	---	0.8	Volume = 3625 mm^3	YES	3.45 – 28	×	√
	Rogers RT/Duroid 6010	10.2	0.003						

Furthermore, a compact size rectangular slot antenna needed for centric applications of the ultra-wideband body was introduced by Danjuma *et al.* [83]. The antenna is fabricated on the FR4 substrate under the specification of (εr = 4.3, δ = 0.025, and h = 0.8 mm) and overall antenna dimension (14.90 × 33.12) mm as shown in figure 43.

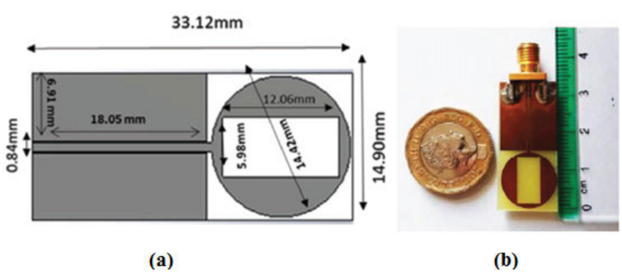

FIGURE 43. The Proposed Antenna, (A) Geometry model, (B) Physical implementation of the proposed antenna [83].

The antenna realized the best results in terms of efficiency, gain, and bandwidth enhancement, particularly when the rectangular slot affixed in close contact with the human body. The proposed antenna was a robust choice for centric applications in wireless body technologies due to the compatibility shown between the ON and OFF body measurements. In [84], a compact and UWB CPW-fed square slot antenna was featured for wearable applications by Varkiani *et al.* The antenna sized (23.5 × 22) mm^2 is fed by a semi-polygon feed line surrounded by grounded aircraft and fabricated on cotton fabric as substrate material, which is realized 13.1 GHz bandwidth from 3.2 – 16.3 GHz concerning the fractional bandwidth (FBW) of 135% (see figure 44).

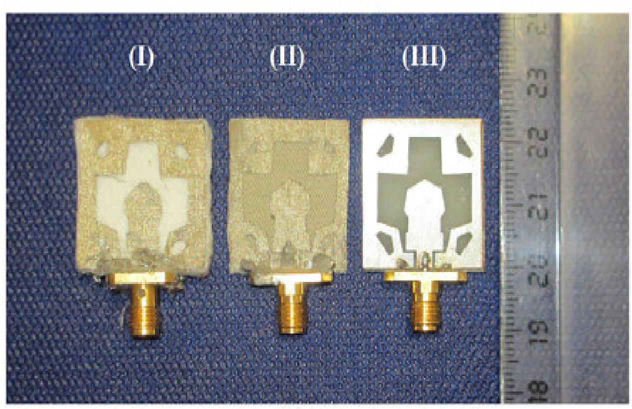

FIGURE 44. The fabricated antennas, (I) non-woven substrate, (II) cotton substrate and (III) FR4 substrate [84].

The proposed compact antenna was tested in OFF-body and ON-body conditions using two additional substrates with different dielectric constant identified by FR4 and non-woven. The antenna affixed ON-body showed less efficiency than OFF-body reduced radiations on the body, frequency shifts, and bandwidth reduction. On the chest, the frequency band coverage in FR4 based antenna demonstrated better output than the rest of the other antennas, knowing that the entire frequency ranges were shifted back than the range of (in air) test.

Furthermore, a compact printed monopole antenna in the UWB G-shaped type with reconfigurable band-notched characteristics is displayed by Toktas and Yerlikaya [85]. The G- shaped antenna has been demonstrated in a compact size of (8 $\times$ 27.5) mm^2 fabricated on low-cost double copper-sided FR4 epoxy substrate $\varepsilon r = 4.4$, $\delta = 0.017$, and h = 1.6 mm. The band-notched reconfigurability dominated the antenna based on pin diode in the patch leads the antenna to operate in the frequency range 2.8 – 12.6 GHz during ON diode state and turns to ordinary radiation during OFF state. The antenna promised higher features, reliable gain, acceptable omnidirectional pattern, compactness with UWB applications.

Owing to FCC opens the frequency band from 3.1 to 10.6 GHz for industrial usage, UWB connectivity devices gain enormous interest in wireless networking because of many benefits, including easy equipment setup, fast data transfer speeds, wide accuracy coverage, low-cost and low power consumption. In accordance to [86], a new lightweight dielectric resonator UWB antenna in the T-shaped form was introduced and analyzed by Zitouni *et al.* the UWB dielectric resonator antenna (DRA) with improved bandwidth is accomplished covering 156.12%, Ku and K band frequency ranges by feeding DRA with a stepped scanned monopole antenna using L-shaped tuning stub, a slot in the partial ground plane and a parasite strip inserted at the bottom of the substrate (see figure 45). Moreover, this antenna also realized a reasonable radiation pattern, steady peak gain, an almost constant community delay in the operational bandwidth, low expense, and compact layout.

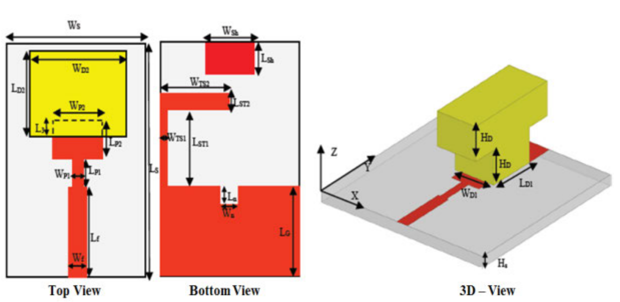

FIGURE 45. Geometry of the proposed UWB DRA [86].

IV. CONCLUSION

UWB development has opened up a window of opportunities for WBAN solutions, and many WBAN implementations offer a low cost with an effective solution. Wearable UWB developments are anticipated to advance quickly in more realistic implementations and to develop in the immediate future as a significant area of consumer wireless electronics. The paper demonstrated and investigated both wearable and non-wearable UWB antenna designs and applications for ON-Body and OFF-Body communication techniques. Furthermore, the paper examined and evaluated antenna designs to determine various characteristics that influence the output of an antenna and efficiencies such as small shapes, omni-directional radiation patterns, bending factors, and types of substrates with respect to their measurements and other characteristics that rule the patch such as relative permittivity (εr), loss tangent (δ) and thickness (h) of the dielectric materials. Throughout this study, a range of wearable and Non-wearable UWB antenna prototypes are listed and accompanied by the analysis of (ON-OFF) body channel studies. Finally, the review process addressed several open challenges which are summarized as follows:

1. The loss tradition and high loss tangent of the flexible substrates that decay the performance of the antenna.
2. The massive sizes of the imaging systems that need significant printing areas are Illogical.
3. The bending capabilities of the flexible materials in various degrees in the woven wearable devices considering the efficiency of the antenna in specific bending scenarios.

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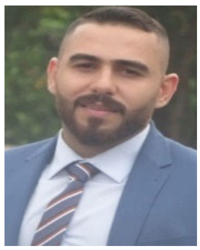

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