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TOPICAL REVIEW

Recent Advancement of Wearable Reconfigurable Antenna Technologies: A Review

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ABSTRACT Wireless Body Area Network (WBAN) technology is gaining popularity in personal communication owing to the expanding improvement in wireless technology. Wearable antennas are utilized in various WBAN applications including personal healthcare, entertainment, military, and many more because of their attractive characteristics and the potential for integrating lightweight, compact, low-cost, and adaptable wireless communications. A wearable reconfigurable antenna will allow a single antenna to operate at multiple resonant frequencies, radiation, polarization or a hybrid between them, by using single or multiple active switching devices for signal transmission and reception in different parts of human body, rather than using multiple antennas. Over the years, several review papers were reported on wearable antennas which discussed the requirements and issues of wearable antennas in terms of their design, fabrication, and measurement. Currently, the WBAN technology employs a single wearable reconfigurable antenna to perform multiple functions in different parts of human body. Recently, a significant amount of research has been conducted in the area of wearable reconfigurable antennas for WBAN applications. This paper presents a comprehensive review of the requirements and analysis needed for wearable reconfigurable antennas such as Specific Absorption Rate (SAR) for on-body analysis, investigation of antennas under bending conditions, reconfigurable techniques and reconfigurable performance metrics.

INDEX TERMS Wireless body area network, wearable antenna, wearable reconfigurable antenna, specific absorption rate, bending condition, reconfigurable techniques, performance metrics.

I. INTRODUCTION

Wireless health monitoring of the elderly requires that the components such as sensors and antennas needed for such monitoring fit into the daily routines of the elderly [1]. The devices to be worn on body must be useful, comfortable, non-invasive, and obstructive. One such technology is the WBAN and the requirements are gradually increasing. The world population has grown rapidly due to medical advances and the number of elderly people who need more attention is increasing. One of the most crucial components of today's health care is monitoring patients' vital signs such as temperature, blood pressure, and heart rate. Due to the current advancement in technology, there are several solutions for extracting information about patients' behavior and detecting potential anomalies in health parameters. For a long period of time, people have suffered from health issues. Illnesses may bring a lot of stress and agony. Patients must visit the hospital every time they seek medical care since conventional healthcare services necessitate well-trained experts and

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massive monitoring equipment [2]. On the other hand, wearable electronics provide quick, distant, smart and compact features which shall allow a single antenna to operate at different frequencies and also can be worn in different parts of human body [3]. Wearable devices simplify and enhance human needs when it comes to healthcare. Numerous usages of flexible electronic devices are depicted in Figure 1. To enable wireless connectivity in today's information-oriented culture, flexible electronic systems require the integration of flexible antennas operating in certain frequency bands [4].

A large number of reconfigurable antennas based on active switches, such as PIN diodes, varactors and RF MEMS have been reported in recent years [6], [7]. These antennas were often built on a non-flexible substrate and could be reconfigured in terms of resonant frequencies [8], radiation patterns [9] and polarization [10]. However, a single antenna that is wearable with different radiation patterns, frequencies, polarization and conformal to human body is preferred. In contrast, the number of practical reconfigurable wearable antennas has been limited. This is mainly due to the difficulties of establishing electrically and mechanically stable connections between rigid electronic components and flexible textile conductors [11]. Previous research has reported on a few practical wearable reconfigurable antennas [12], [13], [15]. To meet the requirements of WBAN, the antennas must be compact and reliable [16]. Reconfiguration of a wearable antenna is related to the ability of the antenna to change its radiation pattern, frequency and polarization depending on the applications. A wearable reconfigurable antenna is a feasible solution in WBAN [17], [18]. In addition, it also saves space in addition to enhanced performance. Thus, based on these appealing characteristics and attractive features, wearable reconfigurable antennas have gained a lot of interest and a huge effort has also been made in recent years to integrate the antennas in WBAN [19], [20], [21].

This paper presents a review of the requirements and analysis for designing a wearable reconfigurable antenna. Similarly, conductive material selection, appropriate flexible material choice, fabrication techniques and analysis for a wearable antenna design are also discussed. Moreover, the reconfiguration mechanisms and performance metrics requirement for a reconfigurable antenna are discussed. The review is divided into a few parts. Part I focusses on the requirements and analysis needed for a wearable antenna design. Part II focusses on the mechanisms and performance metrics required for designing a reconfigurable antenna. Finally, a review of the reconfigurable wearable antenna is presented and an open conclusion for more research in the future is made.

II. REQUIREMENTS FOR WEARABLE ANTENNA DESIGN

The perspectives of recent publications on the technology of wearable devices encompass various wearable systems. WBAN combines both personal body components and the space surrounding the user to ensure human comprehensive information [22]. To meet the expectations of WBAN, many techniques are employed. The use of conductive materials as radiating elements, substrates and fabrication techniques has an impact on the performance of wearable antennas [23], [24].

A. CONDUCTIVE MATERIAL

Textile antenna design requires an investigation that necessitates the understanding of electromagnetic characteristics of the conductive material such as permittivity and loss tangent [25], [26]. Textile material can be classified as conductive, non-conductive, or both [27], [28]. The radiating part is designed from conductive material while the substrate is made from nonconductive material [29]. Flectron, Zelt and pure copper are examples of conductive materials while silk, felt and fleece are examples of substrates made from a non-conductive material. In [30], proposed a four purely textile patch antenna at 2.4 GHz. Zelt and spacer fabric were used as the conductive material. The substrates are flexible so that the antenna could be deformed. The conductive material used as the radiating element in designing and fabricating the wearable antenna as shown in Figure 2.

The positions on human body on which the wearable antenna can be placed are also limited. The performance of an antenna might be affected when a conductive material is used to design a wearable antenna because the material absorbs fluids [31]. Research was conducted in [32] which uses a conductive woven fabric type with a surface resistance and thickness of 0.05 Ω/square and 0.125 mm respectively.

B. SUBSTRATE MATERIALS

Designing a wearable antenna and choosing the right substrate is critical since several properties of the materials influence the antenna's behavior. For example, the permittivity and thickness of the substrate have a large impact on the antenna's bandwidth and efficiency. The use of textile material as a substrate in wearable antennas necessitates characterization of its properties such as electrical, mechanical, chemical, optical, thermal, and surface roughness. [33]. In [34], proposed a microstrip patch antenna at 2.4 GHz using different flexible substrates. The design utilizes an inverted U-shape on the radiating patch. Table 1 shows various performances of the antenna using different flexible substrates.

In [35], presented a design with a low-cost and flexible direct-write printed inverted-F antenna on an ultra-low-cost paper-based organic substrate. The substrate has a dielectric constant of 3.4 and a loss tangent of 0.065, indicating that it is a high-loss type which can be seen in Figure 3.

A flexible bow-tie wearable antenna using polyethylene naphthalate (PEN) was reported in [36]. Kapton polymide and Polyethylene Terephthalate (PET) were also used as flexible substrates because of their stable electrical and mechanical properties with a thickness of 0.05 mm and 0.1 mm [37], [38].

This section explains how Polymide, Epoxy, PEN, and RT Duroid flexible materials have a significant influence on

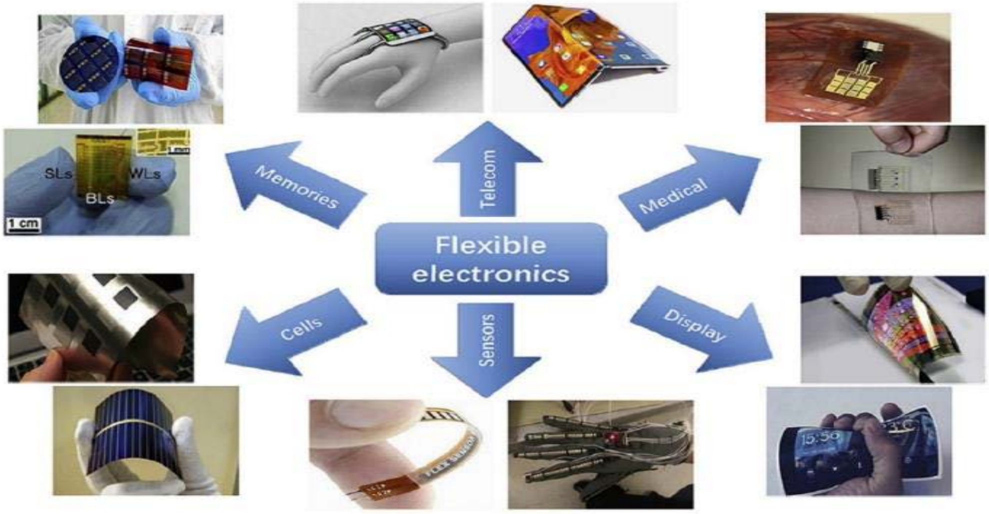


FIGURE 1. Application areas for Flexible electronics [5].

TABLE 1. Comparison of different flexible substrates [34].

Substrate	Dielectric Constant	Loss Tangent	S_{11} (dB)	Gain (dB)
PDMS	2.68	0.04	-34.1	3.2
Epoxy	4.2	0.02	-24.4	3.3
Polyethylene	2.25	0.001	-20.0	6.3
Polyamide	4.3	0.004	-25.6	5.2
RT Duroid	2.2	0.0009	-26.0	5.8
Teflon	2.1	0.001	-30.0	6.78

antenna design. Furthermore, such substrates are commercially available and cost-effective. Furthermore, according to this research, Teflon and Polyethylene substrates with U-shape etching slots on the radiating patch have outstanding bandwidth and gain.

C. FABRICATION TECHNIQUES OF WEARABLE ANTENNAS

Another essential factor in designing a wearable antenna is the fabrication techniques, which can be influenced in part by the flexible materials used in its development. This is because different fabrication processes necessitated the use of different materials in the antenna design. There are different types of fabrication methods in wearable antenna design including copper tape, conducting spray technique and inkjet-printing fabrication technique. The conductive inks are of different types which include silver, gold, and copper which has an impact on the printing quality. The features of the substrate, such as thermal properties, are also significant for the printing quality [39], [40].

In [41], the research work uses different fabrication techniques for the fabrication of their wearable antenna. The use of copper tape was recognized as the easiest technique as compared to woven copper thread and conductive spray as it can be applied directly on the substrate which can be seen in Figure 6.

In [42], presented a multilayered polyester fabric with an E-shaped microstrip patch antenna for Wi-MAX applications. The polyester fabric contains a high-tech polyvinyl alcohol (PVB) coating and a 91-degree angle of hydrophobic behavior. The root mean square (RMS) roughness of uncoated polyester fabric was 341 nm. The RMS roughness of the PVB-coated polyester fabric was 15 nm, and the proposed antenna arrangement is shown in Figure 7. The fabricated antenna resonate at 3.37 GHz with a return loss of 21 dB and a maximum measured gain of 3.6 dB was achieved. The most challenging aspects of designing a textile antenna were ensuring that the textile substrate had the proper thickness, surface uniformity and water wettability.

III. ANALYSIS NEEDED FOR WEARABLE ANTENNA

Reflection coefficient, radiation patterns, gain and antenna efficiency are the characteristics used to evaluate the performance of antennas performance [43]. Moreover, planar antennas are flat and thus, it is unnecessary to analyze their bending behavior. On the other hand, a wearable antenna necessitates the analysis of other aspects to ensure the antenna's performance when it is worn on and off body. Other measurements that must be performed while assessing a wearable antenna design are included in the next sub-section.

A. SPECIFIC ABSORPTION RATE (SAR) AND ON-BODY MEASUREMENT

Issues about the health impacts of radiation, as well as regulations across the globe have motivated researchers to investigate the quantity of power that the human body receives regularly. The measurement of SAR is critical when designing a wearable antenna since the antenna works near various parts of human body. The amount of power absorbed

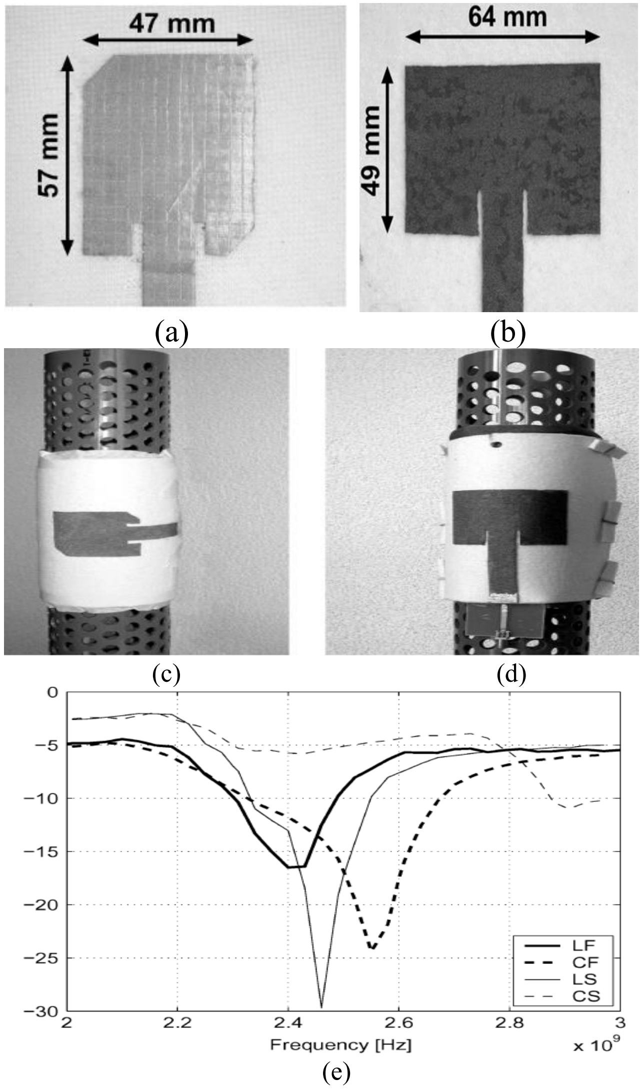


FIGURE 2. Proposed wearable antenna using conductive material as the radiating element: (a) LF antenna (b) CS antenna (c) bent in the x-axis (d) bent in the y-axis (e) measured S_{11} [30].

by biological tissue when exposed to electromagnetic radiation is characterized by the value of SAR. The SAR level should be kept under 1.6 W/kg per 1 g tissue for the Federal Communication Commission (FCC) standard and under 2 W/kg per 10 g tissue for the International Commission on Non-Ionizing Radiation Protection (ICNIRP) standard [44], [45].

The SAR computation is provided in Equation 1 as follows:

$$\mathrm{SAR} = \frac{\sigma E^2}{\rho} \tag{1}$$

where σ is the conductivity of human tissue, E is the electric field intensity and ρ is the density of human tissue, Figure 8 and Table 2 show the model and characteristics of human tissue.

In [47], presented a lightweight latex structure. It integrates a terminal radiation wearable antenna with an artificial

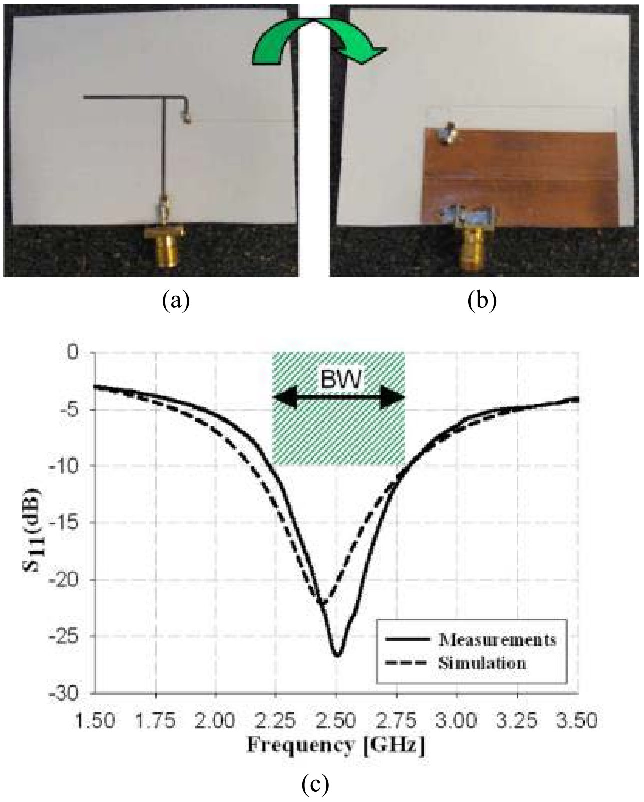


FIGURE 3. Photographs of the fabricated antenna using paper-based organic substrate (a) front side (b) back side (c) measured S_{11} [35].

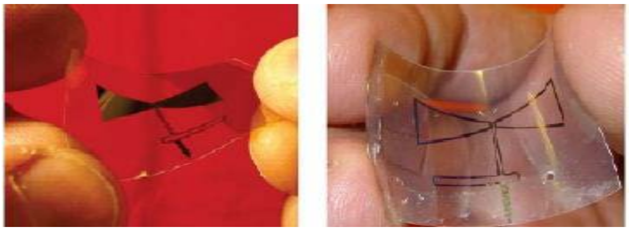


FIGURE 4. Wearable Antenna Printed on a PEN Substrate [36].

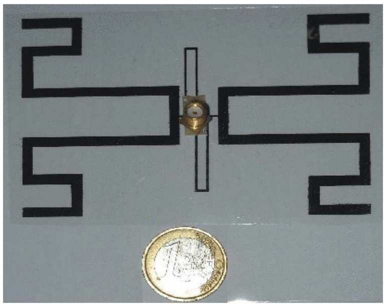
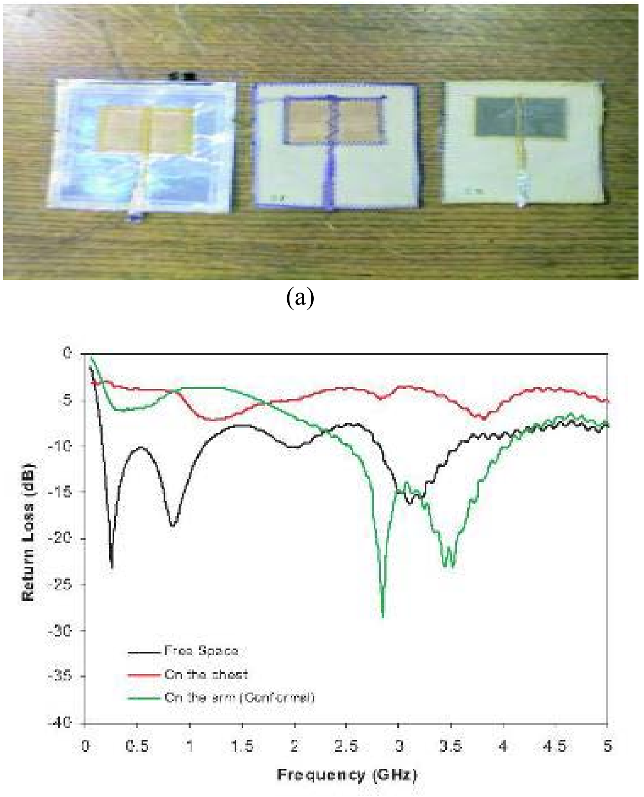


FIGURE 5. Wearable Antenna Printed on a PET Substrate [37].

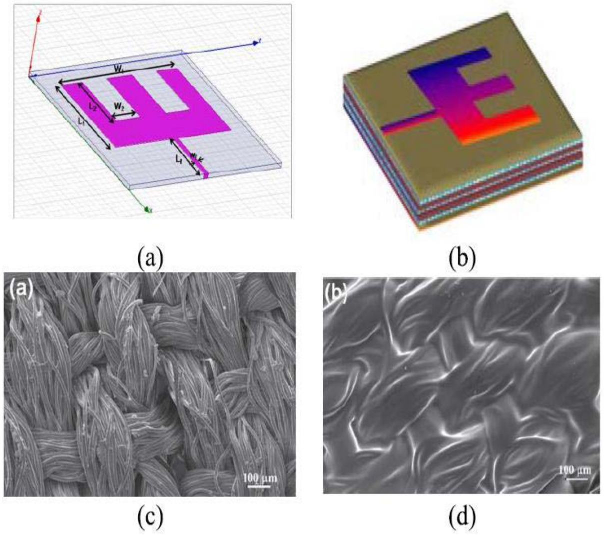
magnetic conductor (AMC) surface to decrease back radiation. The proposed wearable device has an improved efficiency of 78-97% which minimize the human body's collected radiation using WBAN applications. The antenna



(a)

(b)

FIGURE 6. Fabricated wearable antennas (a) from left to right using copper tape, woven copper thread and conductive spray (b) measured return loss [41].



(a) (b)

(c) (d)

FIGURE 7. The layout of the E-shaped antenna (a, b) and uncoated, coated polyester fabric's cross-section respectively (c, d) [42].

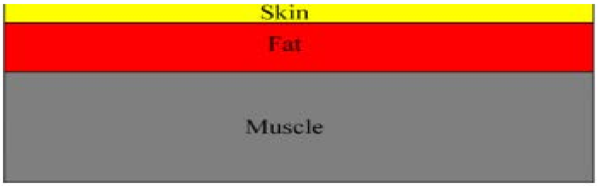
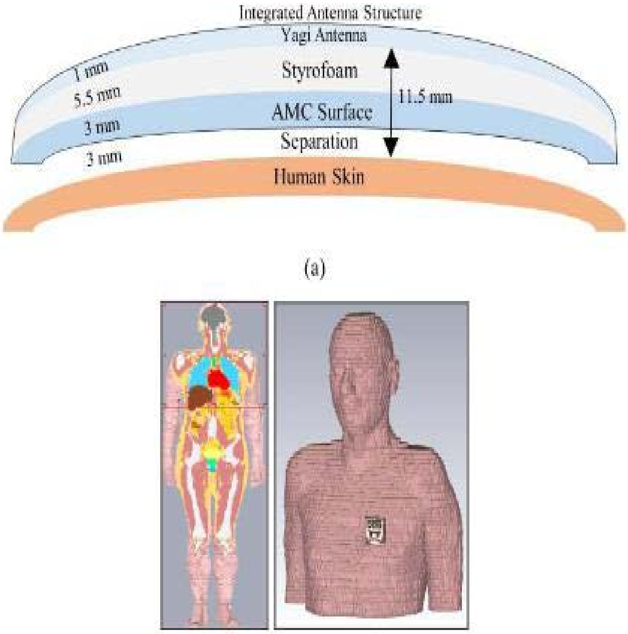


FIGURE 8. The layers of human tissue [46].

TABLE 2. Characteristics of human tissue [46].

Layer	Permittivity (F/m)	Conductivity (Ωm)	Mass Density (kg/m^2)	Thickness (mm)
Skin	35.11	3.72	1100	2
Fat	4.95	0.96	910	5
Muscle	48.48	4.96	1041	20

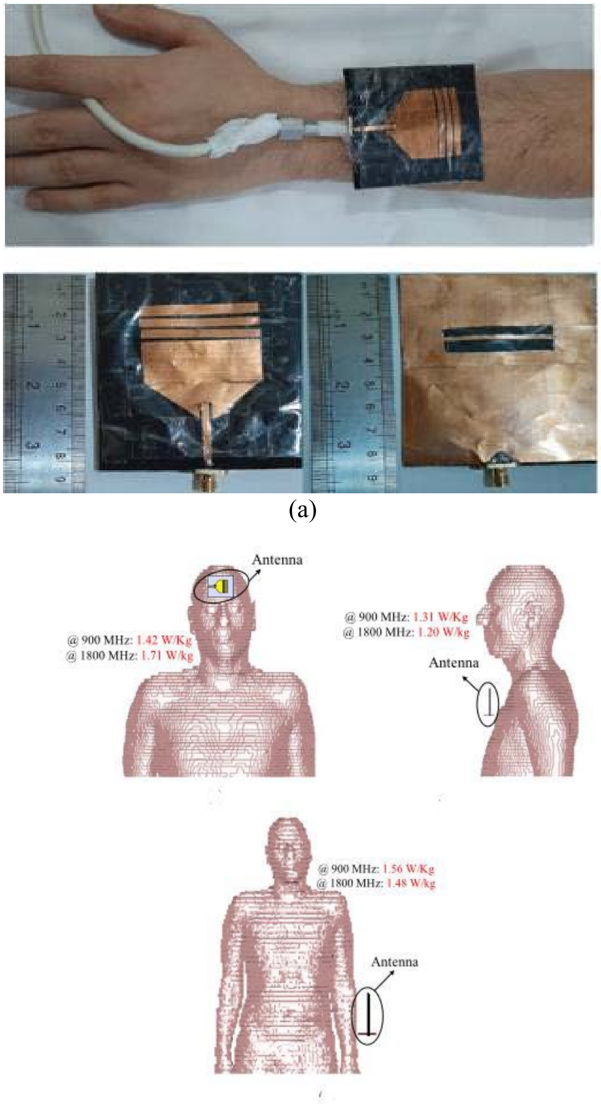


(a)

FIGURE 9. A proposed antenna placed on human body [47].

proposed was initially refined and produced on a printed circuit board to validate the design before being constructed over latex for a genuine human on-body all-flexible arrangement. The −10-dB bandwidth of 45 MHz between 2.425 to 2.47 GHz and gain of 0.12 dBi was measured using Yagi–Uda antenna with D-AMC reflector. The value of the SAR level achieved was 0.714 W/kg which is less than 1.6 W/kg of 1 g of tissue.

In [48], designed and fabricated a multiband wearable antenna for telemedicine applications that use Defected Ground Structure (DGS) in rectangular parasitic elements. The antenna has a dual-band capability which is suitable for Global System for Mobile Communications (GSM) applications. Standard rubber is deployed as a flexible substrate. The proposed portable antenna has a dimension of 70 × 85 × 1.64 mm^3 with a gain of 7.46 dB and 8.13 dB at 0.9 GHz and 1.8 GHz. The observed radiation efficiencies are 91%



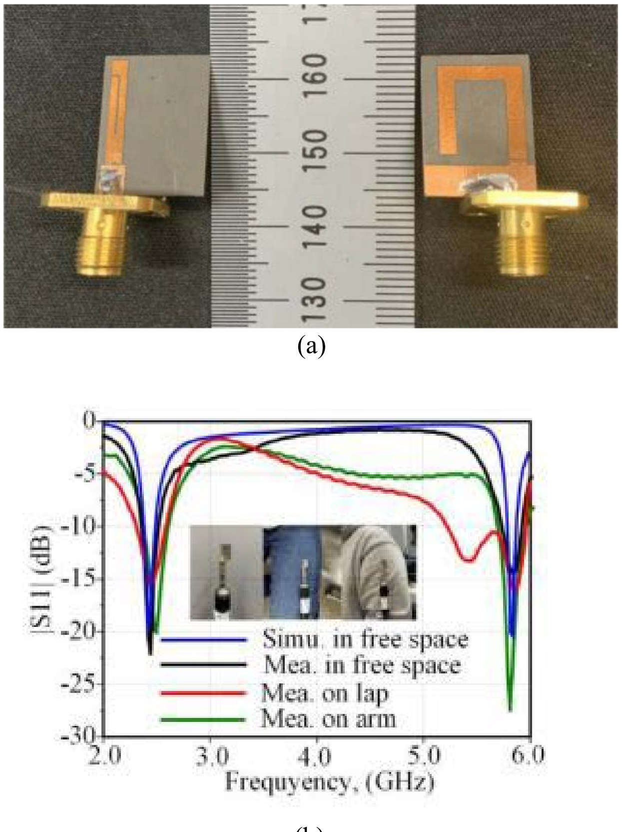
(a)

(b)

FIGURE 10. Photographs of the fabricated antenna (a) on human body, front side and back side (b) Simulated 1 g SAR at 0.9/1.8 GHz [48].

and 94% on a normal phantom, the values of SAR are 1.2 and 1.81 W/kg, on each operating frequency.

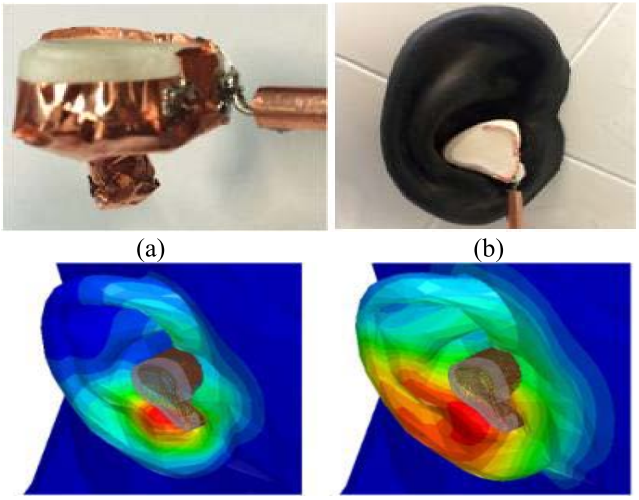
Multiple beam-forming antennas were also investigated to improve the efficiency of wearable antennas in a multi-path fading environment [23], [24]. A textile antenna based on Substrate-Integrated Waveguide technology was proposed in [51]. The antenna was entirely made of textiles. The textile antenna's functionality was examined in free space, and subsequently on the body. On-body performance was achieved by simulating the antenna in the near vicinity of human tissue model that comprises thick skin, thick fat, and thick muscle. At 2.45 and 5.5 GHz, the computed SAR was 0.056 W/kg and 0.067W/kg, respectively. On the body, measurements must also be performed to determine the performance of the wearable antenna at various locations on human body [26]. The positions of wearable antennas may change based on the antenna's applications. Wearable antennas might be constructed to be worn on the chest, arm, or back of the body, among other places. A dual-band wearable antenna was designed and fabricated in [53] at 2.45 GHz. The antenna has a size of 0.15λ × 0.1λ × 0.004λ. The proposed



(a)

(b)

FIGURE 11. Photographs of the (a) fabricated wearable antenna (b) measured S_{11} [53].



(a)

(b)

(c)

(d)

FIGURE 12. Photographs of the (a) fabricated antenna (b) fitted into the human ear (c) 1 g of FCC (d) 10 g of FCC tissue [54].

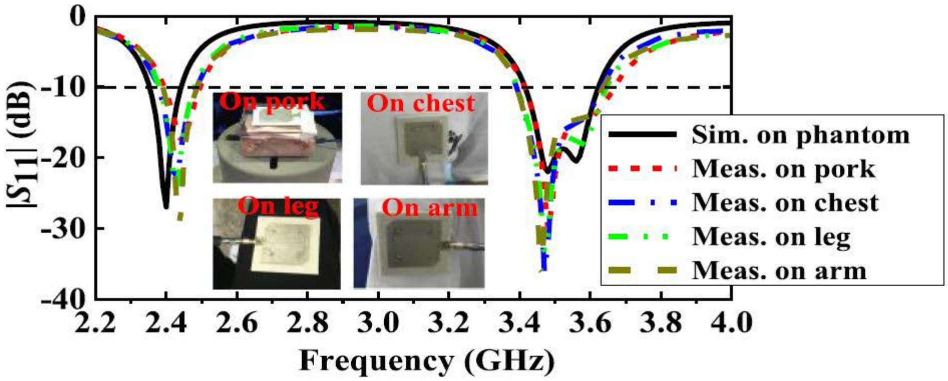


FIGURE 13. Measured reflection coefficient on different Structures [57].

TABLE 3. Performance analysis of previous wearable antenna based on SAR/On-body measurement.

Ref	Size $(\lambda_0)^3$	Freq. (GHz)	Material /ε_r	Gain (dBi)	SAR (W/kg)	Radiation Efficiency (%)	Fractional Bandwidth (%)	Polarization/ Flexibility
[47]	0.4 × 0.4 × 0.076	2.45	Latex / 3.2	0.12	0.714	78	1.84	Linear/ Yes
[48]	0.21 × 0.26 × 0.0005 @ 900 MHz	0.9 1.8	Rubber / 3	7.46 8.13	1.31 1.20	96.2 98.1	8.6 54	Linear/ Yes
[58]	0.56 × 0.3 × 0.013	2.45	RT Duroid 5880 / 2.2	6.88	0.244	76	4.88	Linear / Yes
[59]	$\pi \times 0.228^2 \times 0.026$	2.45	FR-4 / 4.3	4.2	0.55	60.7	3.67	Linear/ No
[60]	0.58 × 0.51 × 0.009 @ 3.5 GHz	3.5/5.7/10.2	FR-4 / 4.3 RT Duroid / 2.2	8	0.10	89	153	Linear/ Yes
[61]	0.4 × 0.4 × 0.02 @ 1.575 GHz	1.575 2.45	Kevlar / 1.66	1.98 1.94	0.78 0.71	73.6 83	7.6 5.5	Circular, Linear / Yes
[62]	0.11 × 0.12 × 0.0004	2.45 5.8	Polymide / 3.5	-4.1 2.33	0.7 0.71	48.4 35.7	16.3 8	Linear / Yes
[51]	0.26 × 0.34 × 0.001 @ 2.4 GHz	2.4 5.8	Felt / 0.044	2.0 5.6	0.056 0.067	55 60	6.54 11.5	Linear/ Yes
[63]	0.62 × 0.62 × 0.0008	2.45	Rogers 3850 / 2.9	6.584	0.0072	38.84	25	Linear / Yes
[53]	0.15 × 0.1 × 0.004 @ 2.45 GHz	2.45 5.85	RT Duroid / 2.2	2.1 3.5	0.919 0.118	86 91	23.3 6.5	Linear / Yes
[64]	0.5 × 0.3 × 0.028	2.45	Rogers 3003 / 3	6.2	0.15	Not Given	5.5	Linear / Yes
[54]	0.19 × 0.1 × 0.022	2.45	Plastic / 2.4	6	0.891	70	6.1	Linear / Yes
[65]	0.77 × 0.51 × 0.07	5.5	Wood felt / 1.2	6.7	0.43	77	17.1	Linear / Yes
[57]	0.56 × 0.56 × 0.016 @ 2.38 GHz	2.38 3.5	Wood Felt / 1.2	1.38 7.7	0.722 0.533	82 95	0.4 7	Linear, Circular / Yes
[66]	1.08 × 1.08 × 0.0008	2.4	Polyester / 2.8	8.53	0.07	Not Given	14.5	Linear / Yes
[67]	0.275 × 0.549 × 0.04	2.5 5.5	Felt substrate / 1.22	Not Given	Not Given	Not Given	11.6 13.2	Linear / Yes

antenna achieved a maximum gain of 2.1 dBi and 3.5 dBi at 2.4 GHz and 5.8 GHz respectively. The achieved impedance bandwidths are as follows: 5.7% (2.4-2.54 GHz) and 3.78% (5.72-5.94 GHz).

A wearable antenna system operating at 2.4 GHz was presented in [54]. The system was built for an ear-hearing instrument application on a lossless material. An impedance bandwidth of 149 MHz was obtained by using a slot radiator. The wearable antenna was built on a cavity-backed design. The radiation pattern is demonstrated by a measuring study in free space and on a specific anthropomorphic mannequin (SAM) head with ears. Moreover, to achieve the highest

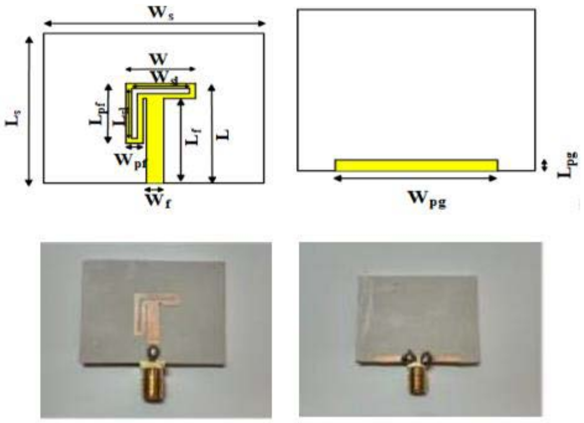


FIGURE 14. Geometry and prototype of the proposed antenna [77].

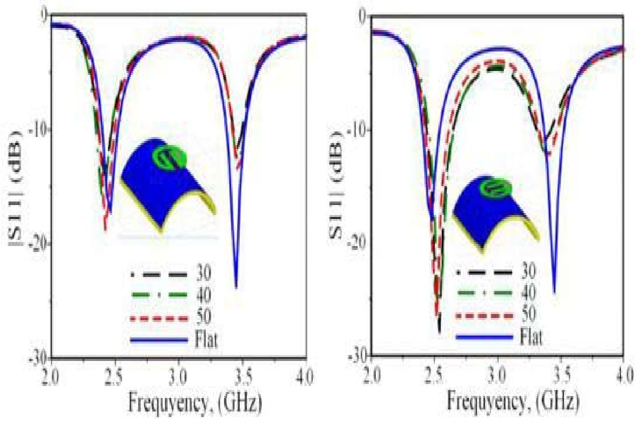


FIGURE 15. Bending effects on the proposed antenna [78].

on-body route gain, the antenna is largely twisted and is located normally on the head surface. WBAN applications consist of the following modes namely, in-body, on-body and off-body modes which are essential in designing wearable antennas [55], [56].

Similarly, a wearable antenna working in dual-band for body-centric communications was proposed in [57] which uses felt as the substrate. The measured results in different scenarios of pork, chest, leg, and arm correspond well, indicating a strong resistance to the effect of the living organism. On average, the measured impedance bandwidths of the antenna in several locations of the human body are 4.1% (2.385–2.485 GHz) and 7% (3.400–3.645 GHz). As shown in Figure 13. The values of SAR are 0.722 and 0.533 W/kg at 2.38 GHz and 3.5 GHz which are less than 1.6 W/kg of 1g of tissue. Therefore, careful monitoring of SAR is required when designing a wearable antenna. Table 3 summarizes the performance of previous wearable antennas. The current SAR minimization approaches are the focus of this section. SAR has a significant impact on a wide range of applications. In most cases, the EBG, AMC structure is strongly recommended for lowering SAR value.

A wireless communication device's location and direction on the body can have a significant impact on its performance. The signal strength changes significantly as the antenna direction is changed [68]. This implies that antenna direction is an important factor in determining wireless communication device performance. Moreover, additional design challenges such as bending and radiation can be mitigated to a certain degree by optimal antenna placement on or near the human body; the wearable antenna bending effect is an important design aspect [69], [70]. The effects of changes in the distance between the human body and communication devices should be negligible for wearable devices [71].

B. BENDING INVESTIGATION

Bending is an important feature for a flexible antenna since it may bend and crumple during practical application. In addition, to reduce body coupling, a wearable dual-band antenna with an artificial magnetic conductor (AMC) structure on the back is proposed in [61]. The antenna reflection coefficient was found to be better conserved during Y-axis bending than during X-axis bending. Work in [72] presented an important conclusion on the bending impact of antenna performance with varied dielectric constants for substrate, showing that the substrate with dielectric constant similar to air ($\varepsilon_r = 1$) had stable performance. [73] investigated the effect of varying substrate thicknesses from 2 mm to 10 mm on bending conditions. This shows that the level of the bending needed by the antenna varies according to the user as a fixed value of bending radius could not provide a definite performance [74], [75]. Whenever an antenna is subjected to bending along its dimensions, the resonant frequency might be shifted. As such, bending conditions must be addressed when designing a wearable antenna as it may affect the antenna's performance. Wearable devices require a consistent performance with different bending radii [76].

TABLE 4. Comparison of the simulated and measured frequencies under different bending conditions [77].

Diameter, d (mm)	Simulated Resonant Frequency (GHz)	Measured Resonant Frequency (GHz)
50	2.45 5.8	2.60 5.83
80	2.45 5.8	2.51 5.71
100	2.45 5.8	2.90 5.73

The study in [77] designed and fabricated a compact, semi-flexible dual-band antenna for Industrial, Medical and Scientific (ISM) purposes with a modified ground plane and operating frequency bands of 2.45 GHz and 5.8 GHz. The proposed antenna was fabricated with dimensions of 30 × 38 mm^2, and the bending investigation was conducted over a vacuum cylinder by varying the diameters from 50 mm, 80 mm and 100 mm, which was the average diameter of a human arm.

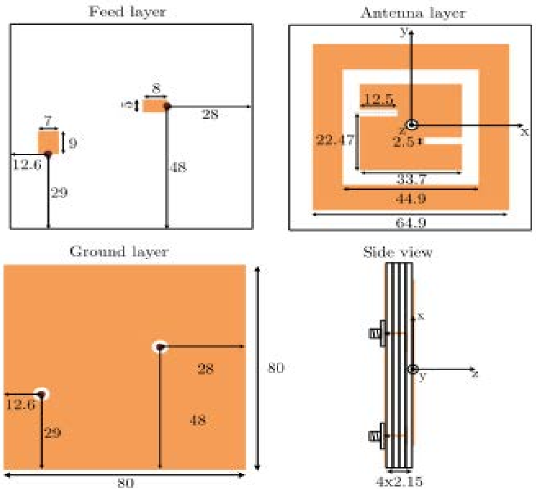


FIGURE 16. Antenna geometry (three metallic fabric layers separated by felt) [80].

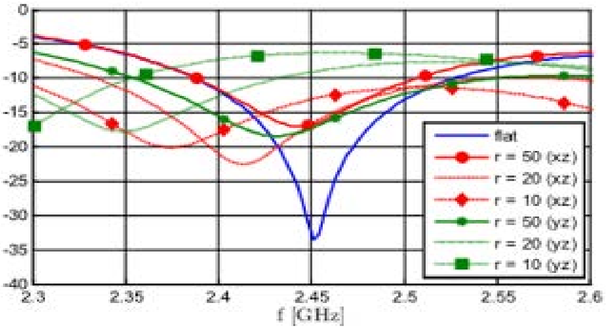


FIGURE 17. Reflection coefficients of the proposed antenna on different bending conditions [80].

In [78], proposed a wearable dual-band antenna for 2.45/3.45 GHz for off-body communication. A conductive textile was connected to a felt substrate in the proposed antenna. The functionality has been validated and demonstrates agreement in both free space and phantom body environments. At each frequency band, the measured impedance bandwidths on the human body are 5.76 % and 4.7 %. The measured gain are 5.1 and 8.6 dB in the operating bands.

Similarly in [79], proposed the design and performance comparison of a dual-band wearable antenna on different simulation tools. Operating frequencies of 2.4 GHz and 5.6 GHz were chosen. The dual-band wearable antenna was designed on a felt substrate which achieved reflection coefficients of −23.64 dB at 2.41 GHz and −16.02 dB at 5.43 GHz using CST suite and −21.85 dB at 2.41 GHz and −15.14dB at 5.43 GHz using HFSS simulation. However, different bending investigation was carried out on the dual-band wearable antenna which shifts the resonant frequencies.

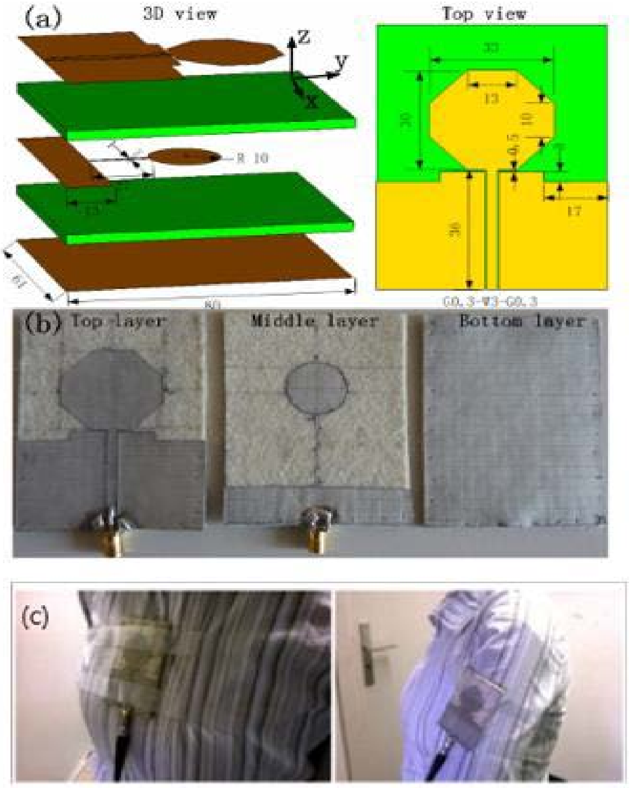


FIGURE 18. Optimized dimensions in millimeters of the OSUA. (a) stacked layer configuration and top patch (b) from left to right: fabricated top, middle and bottom metallic layers (c) OSUA on-body measurement setup with the antenna placed on the chest and the arm respectively [82].

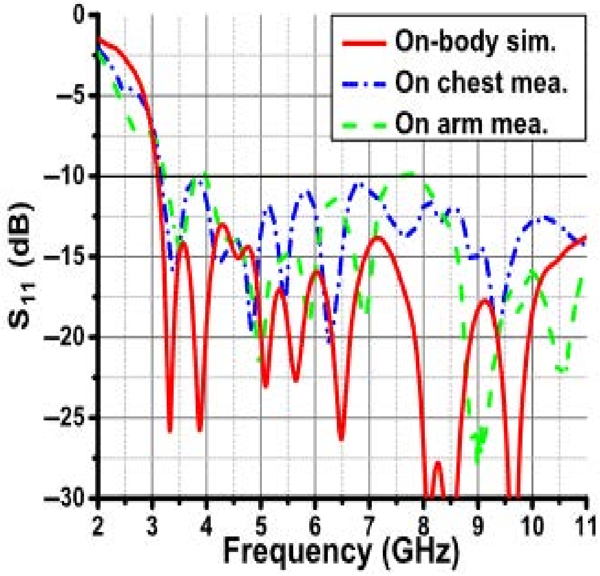


FIGURE 19. Simulated and measured reflection coefficients of the OSUA placed on the chest and the arm respectively [82].

In [80], presented a wearable textile antenna for WBAN applications that operate in the 2.45 GHz of ISM band. A microstrip ring was used to create on-body mode, whereas a small twisted microstrip patch put within the ring achieved the off-body mode. Both antennas were fed individually but shared a similar ground plane and were made entirely from textiles, allowing easy integration into the user's clothing.

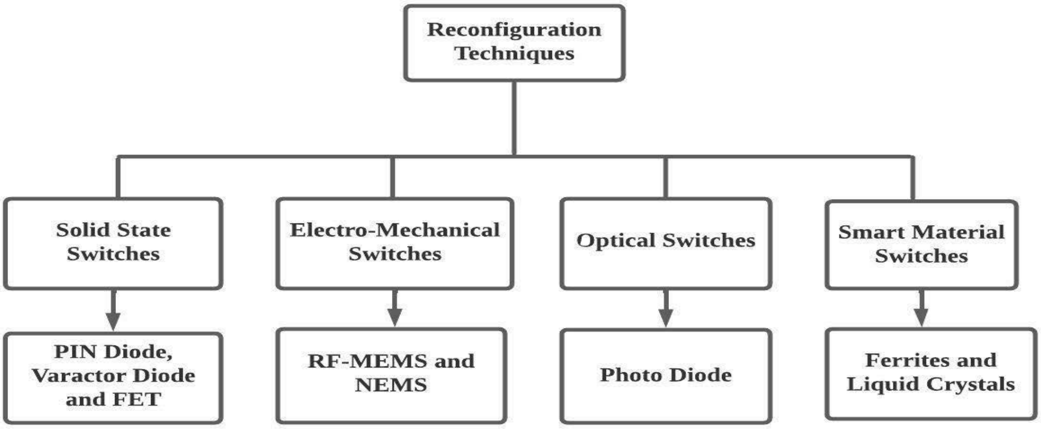


FIGURE 20. Different techniques used for antenna reconfiguration [92].

TABLE 5. Advantages and disadvantages of different techniques used for antenna reconfiguration [92].

Switch Type	Advantages	Disadvantages
PIN Diode	• Easy to design at a low cost • Reliable to use • Applicable between 10 MHz to 100 GHz • Low losses	• High power handling capacity • An extremely large amount of DC bias Voltage • High turning speed • Blocking capacitors limit usable bandwidth
Varactor Diode	• Control the amount of current flow • Easy to integrate with antenna design • Uninterrupted turning	• Has a limited dynamic range • Nonlinear in nature • Biasing circuit is complex to design
FET	• Does not require a bias tee and blocking capacitor to isolate DC bias from the RF signal • Has high switching speed (<10ns) • Low cost	• Isolation deteriorated at higher frequencies • Nonlinear at higher frequencies • High insertion loss
RF-MEMS/NEMS	• Linear in nature • Low noise figure • Low power consumption • Good isolation	• Slow switching • High cost when designing • High actuation voltage
Photo Diode	• Low resistance • Linear in nature • Better frequency response	• Poor temperature stability • Low sensitivity • Requires offset voltage
Ferrites and Liquid Crystal	• Low power consumption • No radiation emission • Zero geometric distortion	• Slow response time • Expensive to design • Restricted viewing angles

Through calculations and measurements, the antenna was tested in free space and mounted on the phantom. The textile antenna was situated in the middle of the phantom for the on-phantom arrangement, with a 4 mm open hole in between the antenna and the phantom. The simulated and measured gain of the textile antenna on the phantom was 4.2 dBi and 4.1 dBi for on-body, 5.8 dBi and 5.3 dBi for off-body respectively.

Presently, antennas incorporated into garments are attracting attention because they can make use of conductive materials that are already present in clothing. As a result, the authors in [81] developed a multi-band flexible antenna for WLAN applications. Jute cloth was used to construct the proposed antenna. The antenna operates in the 2.4/5.2/5.8 GHz WLAN bands. The textile antenna achieved a gain of 2.57 dBi and 4.06 dBi at 2.3 GHz and 4.7 GHz respectively. However, there was a shift in the resonant frequency when subjected to a different angle. A stacked structure textile antenna operating between a frequency range from 3.1 to 10.6 GHz was presented in [82]. The measured on-body system reliability ratings are 95% to 97% at 1 m. For UWB applications, eight-coplanar construction was adopted. The substrate layer is adjusted for the monopole structure's effect by acting as a reflector. On-body S-parameter performance was assessed on a human body with different bending positions. The octagonally shaped UWB antenna (OSUA) was installed in a separate location, notably the chest and arm.

Human body tissue vicinity has a significant impact on performance factors such as impedance bandwidth, radiation pattern, efficiency, and gain [83], [84].

The following are the benefits of employing a full ground plane:

- lowering the device's sensitivity to the human body by lowering backside radiation directed at the human body.
- Improving impedance matching and efficiency for on-body applications.
- Achieving low SAR.
- Reduce device coupling and energy dissipation to the body as the device radiates mostly in the normal direction when a full ground plane is employed [85].

This section provides an overview of how bending affects the performance of wearable antennas. Other issues with these antennas that must be addressed with the bending effect include dielectric properties and radiation characteristics near human skin. Even though textile antennas are intended to be bent or conformed to a specific direction during the activity, a wide range of bending conditions are required to investigate changes in bending-dependent structure. As a result, in all instances, the resonant frequency differed slightly from the operating resonant frequency. Due to the popularity of body-worn antennas, textiles and lightweight materials can be used for mechanical deformation, such as folding. Wearable antennas should be as symmetrical as possible to minimize their impact when bent in a variety of orientations.

The next part shall focus on the reconfigurable mechanisms and performance metrics for the design of a reconfigurable antenna which is needed when designing a wearable reconfigurable antenna.

IV. REQUIREMENT FOR RECONFIGURABLE ANTENNA DESIGN

Using a single or multiple active switching devices, a reconfigurable antenna can change its bandwidth, frequency, radiation, and polarization characteristics, a reconfigurable antenna can be a promising option to increase the ease of wearable antennas while also saving small space close to the body [86], [87]. It is also possible for reconfigurable antennas to use RF switches. This in return increases its bulkiness and renders it inappropriate for operating close to the body Moreover, because of the limited space around the body, it is difficult to insert multiple antennas for different applications, with the trend of wearable devices wearable antenna design is becoming more severe because WBAN requires an increased number of frequency bands for its wireless applications. The primary need for wearable antennas is portability, compact size, and reliability [88]. The next subsection shall explain the reconfigurable mechanisms and performance metrics when designing a reconfigurable antenna.

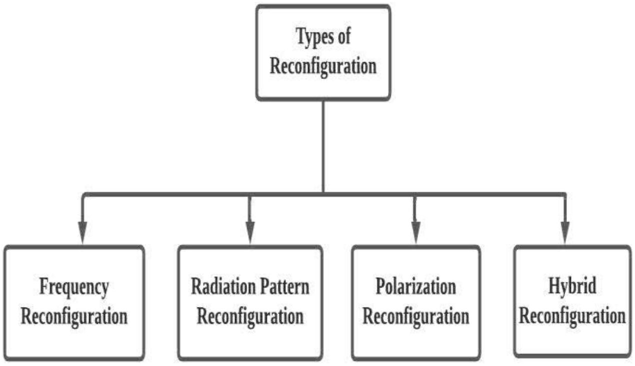


FIGURE 21. Various types of reconfiguration mechanisms [92].

A. TECHNIQUES FOR RECONFIGURABLE ANTENNA

Different approaches for introducing reconfiguration characteristics in an antenna system have evolved over the decades, as seen in Figure 20 and Table 5. One such technology makes use of solid state switches (PIN diodes, Varactor diodes and FET), electro-mechanical switches (RF-MEMS and RF-NEMS), smart material and optical switches to change the length of the radiating structure [89].

Antennas that use photoconductive switches for reconfiguration are referred to as optically reconfigured antennas [90]. Material reconfiguration refers to the employment of certain types of materials (with ferroelectric and ferromagnetic characteristics) such as liquid crystals and ferrites to generate reconfigurability in antenna design. However, the approach used to introduce reconfigurability is determined by the applications of multifunctional antenna [88], [89]

B. RECONFIGURABLE PERFORMANCE METRICS

The frequency of operation, radiation pattern, polarization and hybrid reconfiguration of an antenna can be utilized to satisfy the growing need for wearable electronics [93]. The most widely utilized reconfigurability is the operating frequency because it is the simplest attribute to change. RF and microwave communication systems mostly use PIN diodes as the switching device due to their appealing qualities such as minimal insertion loss, excellent isolation, low power management, and inexpensive cost [94], [95]. Figure 21 shows different types of reconfiguration mechanisms.

1) FREQUENCY RECONFIGURATION

Frequency-reconfigurable antennas allow a single antenna to operate at different frequencies. This form of reconfiguration mechanism is extensively used in RF communication systems such as multiband mobile devices [8]. These frequency reconfiguration antennas allow for the continuous modification of one or more resonant frequencies, and frequency reconfiguration is frequently accomplished physically or electrically by changing the antenna size with switches [96], [97]. A dual-band reconfigurable antenna was designed and fabricated in [98]. The proposed antenna resonates at 2.43 GHz and

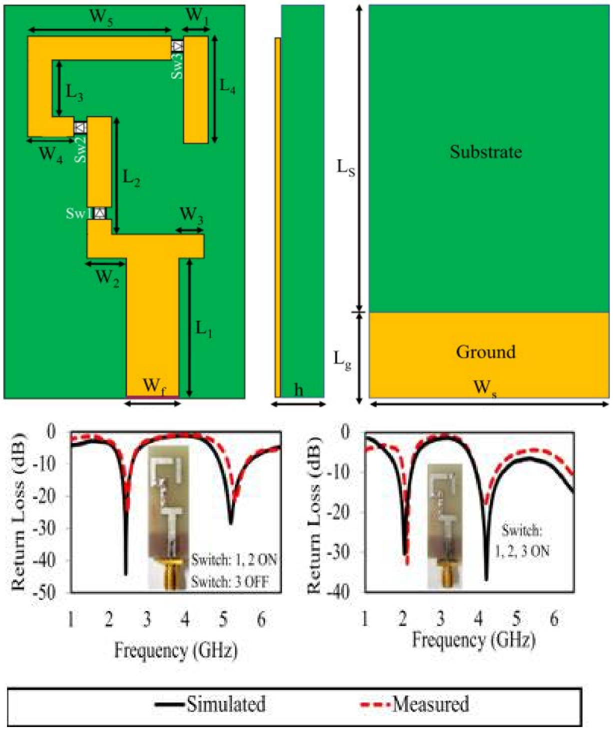


FIGURE 22. Dimensions and reflection coefficient of the antenna [98].

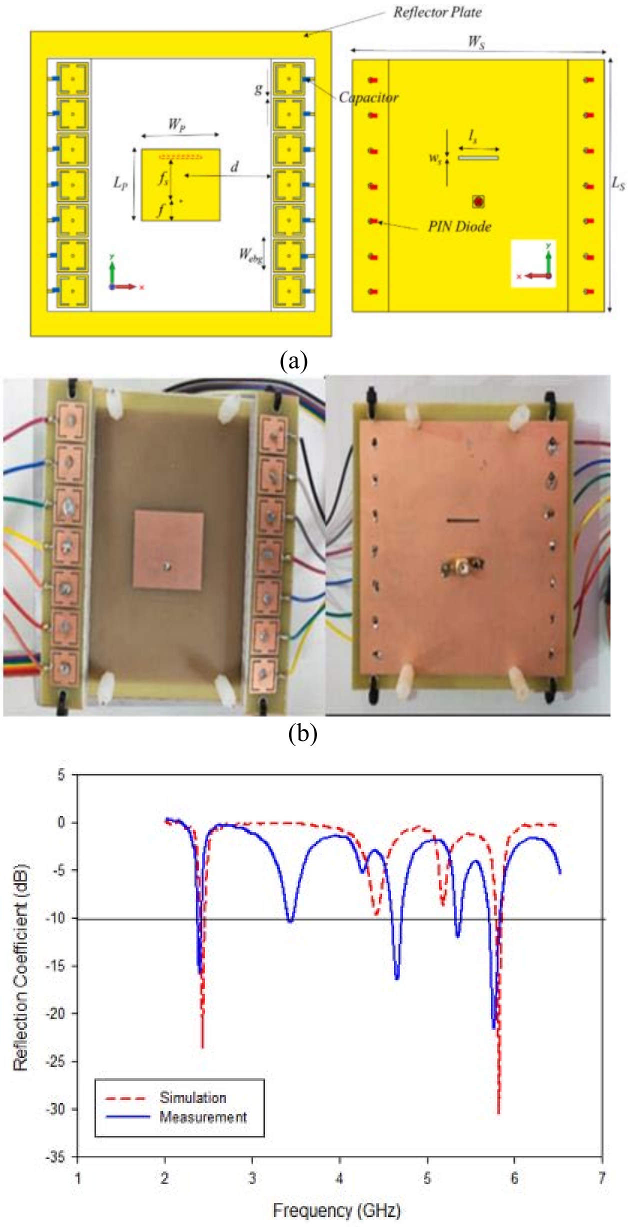
4.14 GHz. The dimension of the proposed antenna is 33 × 16 × 1.6 mm^3 and a PIN diode was used. The prototype reconfigurable antenna range from 2.1 to 5.2 GHz.

The study in [99] presented a dual-band reconfigurable antenna with an EBG structure for beam steering configurations. The proposed antenna structure was designed, analyzed, and fabricated using an FR-4 substrate which resonates at 2.45 GHz and 5.8 GHz. A PIN diode was used to reconfigure the two frequency bands. A percentage bandwidth of 2.46% was obtained between 2.41 GHz and 2.47 GHz and 1.38% between 5.76 GHz and 5.84 GHz.

Similarly, the article [100], proposed a small-size V-shaped frequency reconfigurable antenna that is used for ISM and WLAN band applications with dimensions of 16 × 16 mm^2 and can be switched from one frequency band to another. The proposed antenna employs two strips of 0.25 mm and 4.5 mm in length and width respectively. The experimental and simulation results show a maximum and minimum antenna gain of 6 dBi at 5.3 GHz and 3.4 dBi at 4.66 GHz were achieved.

In [101], the authors designed and fabricated a PIN diode frequency reconfigurable antenna. In the ON state, the antenna operates at 2.686 GHz and 5.164 GHz. while in the OFF state operating frequency of the antenna is 5.302GHz. the power supply was turned off when a voltage of 12V DC was applied to the antenna to produce a current of 10mA flowing through the PIN diode.

In [6], proposed a varactor-loaded frequency reconfigurable antenna. The design is a combination of a band pass within a 50-microstrip feeding line and a dual-sided Vivaldi antenna. The proposed antenna exhibits a filtering function, the frequency of the design antenna changes from 6.2 to 6.5 GHz, with no extra interferences.



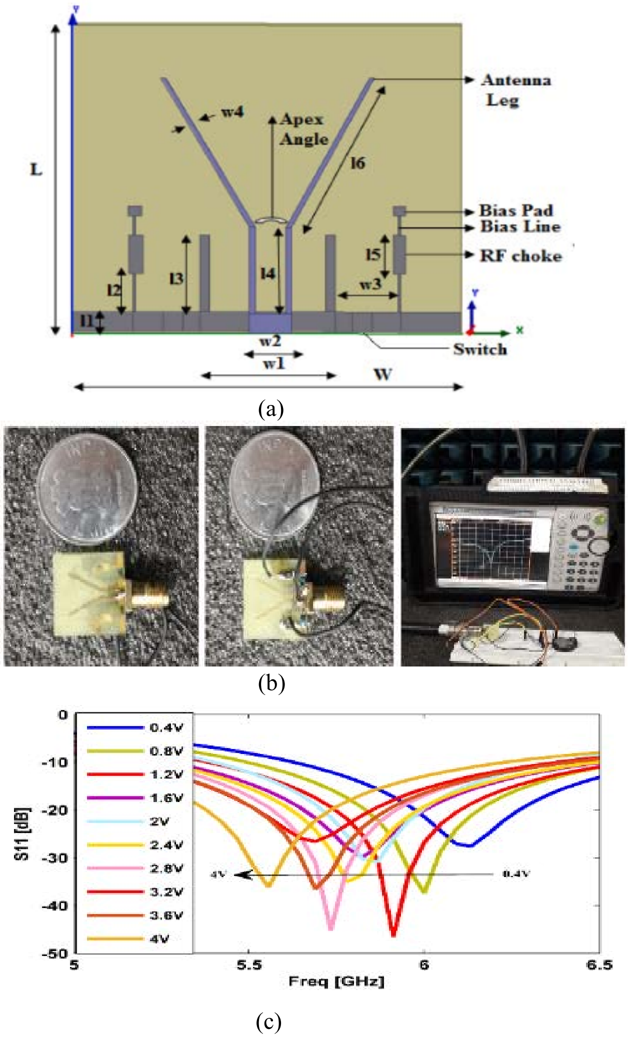
(a)

(b)

(c)

FIGURE 23. Photographs of the (a) geometry of the antenna (b) fabricated prototype (c) measured S_{11} [99].

In [7], investigated the performance of a multiband Sierpinski fractal antenna with a triangular form. RF-MEMS switches were also employed to regulate the antenna components. Also in a study presented by [102], some associated study on RF-MEMS switches with microstrip antenna was carefully carried out. A low-voltage RF-MEMS switch contact with frequency tuning capacity was designed to drive reconfigurability utilizing a rectangular microstrip antenna coil. Micro-fabrication was employed to optimize the

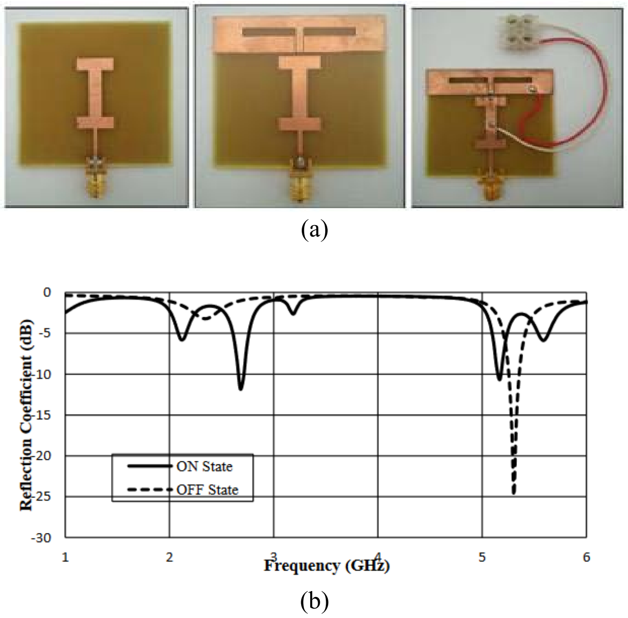


(a)

(b)

(c)

FIGURE 24. **Photographs of the (a) geometry of the antenna and dimensions (b) prototype and measurement setup (c) measured S_{11} [100].**



(a)

(b)

FIGURE 25. **Photographs of the (a) fabricated proposed antenna (b) measured S_{11} in the on and off state [101].**

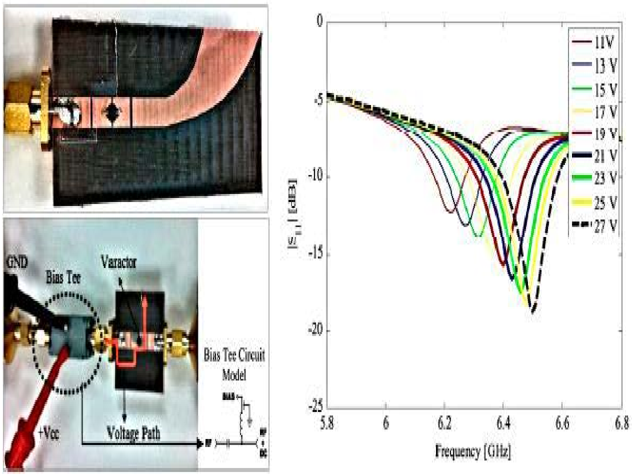


FIGURE 26. **Fabricated antenna and Reflection Coefficient of the antenna [6].**

electromechanical design, and results were obtained utilizing RF simulations. Another work in [102] proposed a compact micro-strip antenna with two FET switches. The biasing used in the switch was easy and had no negative influence on antenna performance, FET has low insertion loss which does not affect radiation pattern. The antenna operates at multi-band frequencies. The gain increased by 20% when compared to UWB operation, but the efficiency remained noticeably the same. Similar work on frequency reconfiguration was proposed in [90] using an optically controlled switch. Four conductive silicon switches were used to reconfigure the antenna. As the light illuminates the switch, it behaves as a short circuit conductor in the ON state, and it acts as an insulator when there is no light beam in the OFF state. The frequency reconfiguration was accomplished by changing the structure or ground of the inner component of the antenna by flexibly merging different slender ring portions using optically controlled switches. Table 6 provide performance comparison of different frequency reconfigurable antenna designs together with challenges. MEMS has the advantage of good isolation, low noise figure, linear in nature better impedance bandwidth and low power losses compared to PIN diodes or varactors. However, when compared to different RF switches, it has a high control voltage, a slow switching speed, and a high design cost.

2) RADIATION PATTERN RECONiFIGURATION

One of the most essential technologies for beam steering applications is radiation pattern reconfiguration. Radiation reconfigurability enables the antenna to vary the radiation pattern while keeping the operating frequency and other properties constant. This form of reconfiguration results in better coverage and greater data because it directs the main

TABLE 6. Performance comparison of different frequency reconfigurable antenna designs together with challenges.

Ref	Type of antenna	Number of switches	Number of frequency bands	Challenges
[6]	Vivaldi antenna with varactor loaded	1 Varactor diodes	10	Very high ohmic losses
[7]	Sierpinski fractal antenna with a triangular form	2 RF- MEMS	2	Requires filters to remove noise and have poor isolation between switches
[99]	Microstrip patch antenna	3 PIN diodes	6	Low gain combined with greater reconfigurable features and a smaller structural size
[100]	Reconfigurable antenna with EBG structure	14 PIN diodes	2	Parasitic loading and cavity effect by the EBG causes a decrease in the impedance bandwidth of the antenna
[101]	V-shaped reconfigurable antenna	2 PIN diodes	5	Reconfigurable features with trade-offs due to the size of the patch
[102]	Patch antenna with partial ground	1 PIN diode	2	Narrow band but covers less bandwidth.
[103]	Microstrip patch antenna	FET	4	Results degraded due to high insertion loss

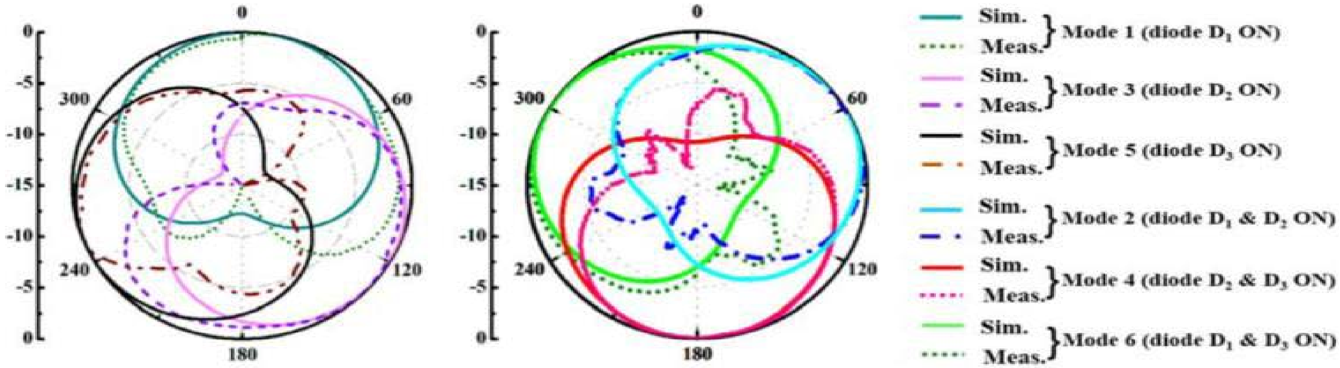


FIGURE 27. The radiation pattern of the antenna for different radiating modes at 2.4 GHz [9].

lobe in useful directions, pattern reconfiguration can reject interference when the direction of the signal is different from its direction and its arrival [103], [104].

A planar reconfigurable antenna on a hexagonal radiator of the Alford loop type was presented in [9]. The size of the antenna was $0.47\lambda_0\times 0.47\lambda_0\times 0.012\lambda_0$. Impedance matching was allowed when the bottom ground plane was tapped. The radiation pattern was regulated by switching three PIN diodes. The antenna observed 4.16% (2.35-2.45 GHz) of the fractional Bandwidth, and the beam steers in six directions encompassing the whole azimuthal plane: 0°, 60°, 120°, 180°, 240°, and 300°. The antenna has a gain of 2.66 dB and an efficiency of 75%.

Similarly in [105], proposed a circular radiating planar antenna with a reconfigurable radiation pattern. To achieve reconfigurability, the reconfigurable antenna made use of a PIN diode. Five parasitic patches coupled to a circular patch made of five PIN diodes with a width of 0.4 mm were used for the design of the antenna. The proposed antenna supplied five different types of radiation patterns with changes in diode conditions as shown in Table 7.

3) POLARIZATION RECONFIGURATION

Polarization reconfiguration can modify the antenna polarity left-hand circular (LHCP) or right-hand circular (RHCP), linear and vertical/horizontal polarization. This type of arrangement improves communication reliability and robustness while also giving an extra degree of freedom. Polarization is achieved by acting on the phase and direction of the supply voltage to maintain the resonant frequency and radiation pattern. It signifies that modifying the orientation of the E-field will affect the polarization of the antenna without affecting the resonant frequencies or the form of the radiation pattern [106]. Authors in [107] proposed a polarization reconfigurable C-shaped monopole antenna. The antenna uses silicon photonic switches for reconfiguration. Between the patch and feed lines are two optical silicon switches. To improve

TABLE 7. Modes of operation of the proposed pattern reconfigurable antenna [105].

Mode	PIN diodes					Resonant Frequency (GHz)		Beam Direction		Gain (dB)	
	D_1	D_2	D_3	D_4	D_5	EMC	ELC	EMC	ELC	EMC	ELC
Mode 1	ON	ON	ON	OFF	OFF	≈ 5.41	≈ 5.42	14°	18°	6.66	6.04
Mode 2	ON	ON	OFF	OFF	ON	≈ 5.49	≈ 5.5	32°	29°	5.08	4.31
Mode 3	OFF	OFF	OFF	OFF	OFF	≈ 5.17	≈ 5.15	90°	89°	5.65	5.37
Mode 4	ON	OFF	OFF	ON	ON	≈ 5.49	≈ 5.5	149°	151°	4.87	4.31
Mode 5	OFF	OFF	ON	ON	ON	≈ 5.40	≈ 5.42	166°	161°	6.68	5.93

Equivalent Linear Circuit models of PIN diode (ELC), Equivalent Metallic Conductors of a PIN diode (EMC)

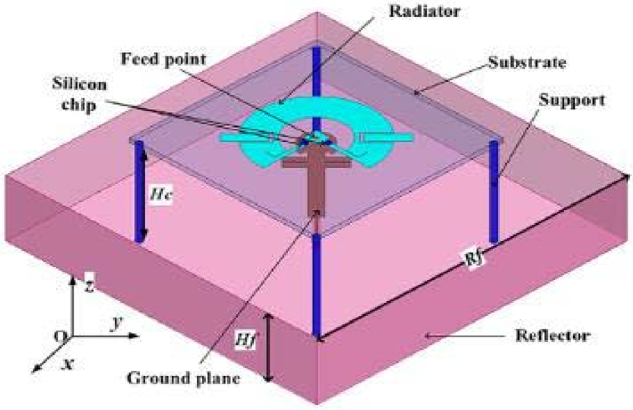


FIGURE 28. Proposed polarization reconfigurable antenna [107].

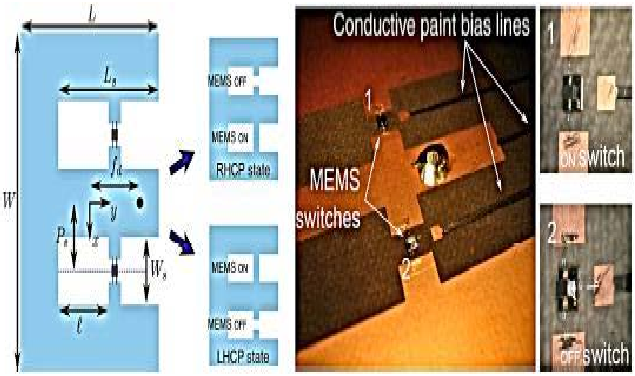


FIGURE 29. Proposed polarization reconfigurable antenna using MEMS [108].

the impedance matching and increase axial ratio (AR) performance a rectangular slot with dual L-shaped slots in symmetric order was employed. The proposed antenna has three polarization modes: LP, LHCP, and RHCP. The performance of the three-polarization mode was shown in Table 8.

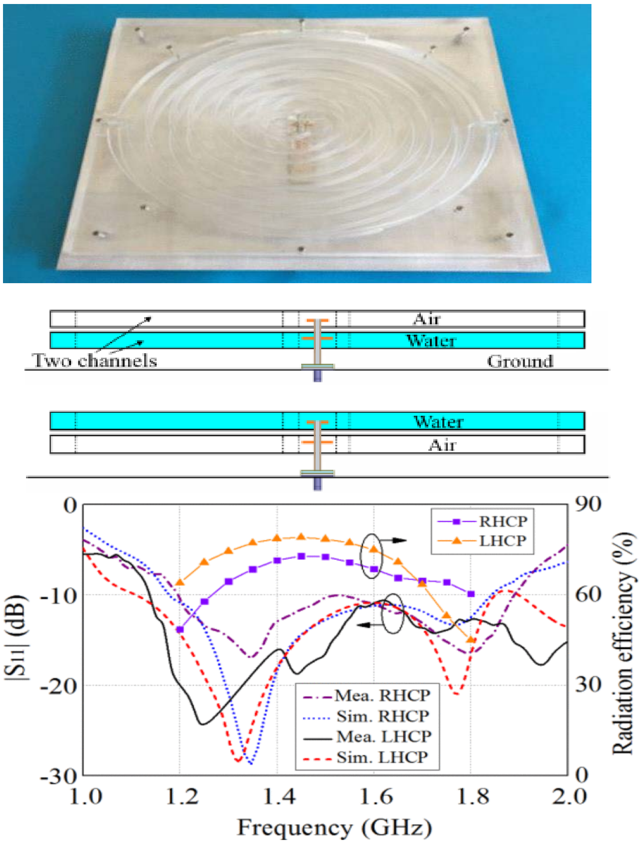


FIGURE 30. Fabricated polarization reconfigurable antenna, simulated and measured results obtained [10].

One of the characteristics of a polarization reconfigurable antenna was investigated in [108] which has an E-shaped radiation patch feed with a coaxial probe. MEMS switches were used across the E-shaped patch slots to achieve different polarization and wide impedance bandwidths, when one switch is turned on and the other is turned off, the RHCP and LHCP features are obtained.

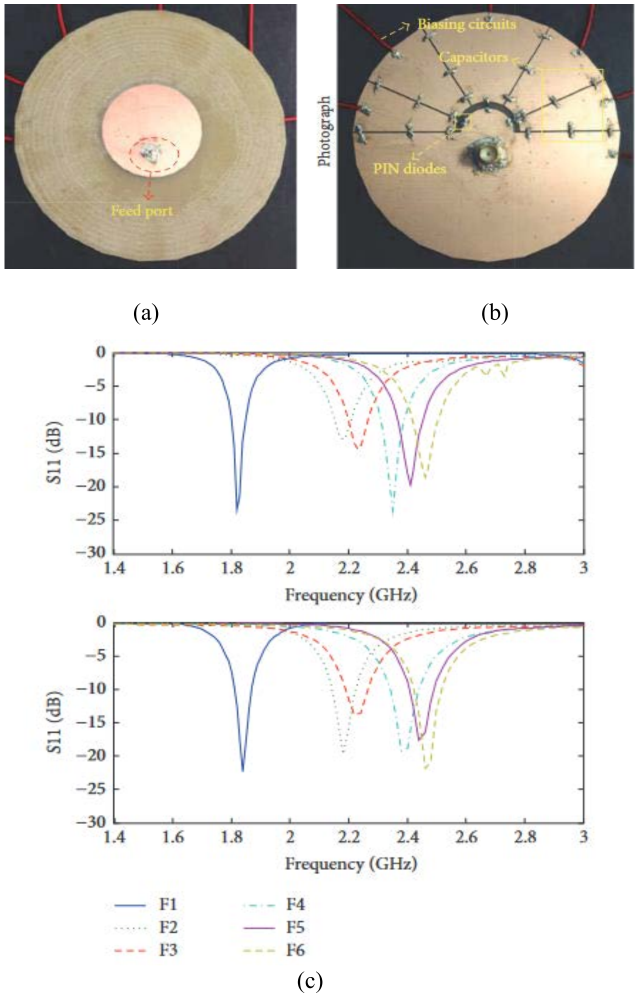


FIGURE 31. Photographs of the fabricated antenna (a) front side (b) back side (c) measured S_{11} [111].

TABLE 8. Performance of the three polarization modes [107].

Mode	SW_1	SW_2	Gain (dBi)	3dB AR BW (%)
LP	ON	ON	9.5	-
LHCP	ON	OFF	8.9	53.7
RHCP	ON	OFF	8.9	63.1

Another polarization reconfigurable antenna was reported in [10] using smart material. The proposed work uses a spiral antenna radiator with a stripline as the feeding technique. to achieve the LHCP/RHCP two water channels were mounted in the ground plane. However, to switch between the two polarization the water flow must be controlled along the water channel. As such the antenna operates between 1.2-1.84 GHz bands.

4) HYBRID RECONFIGURATION

Hybrid reconfiguration combines either frequency, radiation pattern, or polarization in the same reconfiguration. Among the frequent combination is frequency/radiation pattern since it is required for various applications and the requirement to guide the beam at the same time [109], [110]. Study in [111], designed an arc-shaped circular patch frequency-radiation pattern reconfigurable antenna for multiband wireless communication applications. Five PIN diodes were mounted on the arc-shaped slot. The result of the proposed antenna resonates from 1.82 GHz to 2.46 GHz, which was achieved in (1.71-1.88 GHz), (2.11-2.20 GHz), (2.3-2.4 GHz) and (2.4-2.48 GHz). This design achieves an area reduction of over 55%.

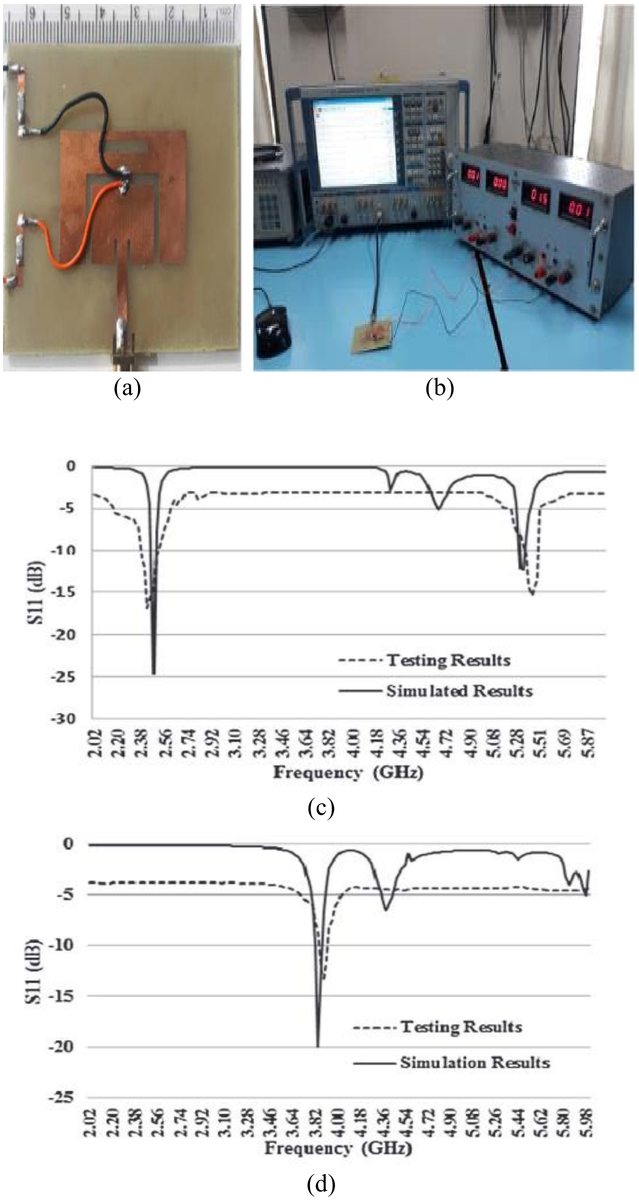


FIGURE 32. Photographs of the (a) fabricated prototype of the antenna (b) measurement setup (c) measured S_{11} on state (d) measured S_{11} off state [113].

A study in [112], designed a multifunctional frequency/polarisation reconfigurable rectangle antenna that is small and compact. The antenna's frequency was reconfigurable

TABLE 9. Comparison of the reconfigurable antenna with multiple antennas [114].

Characteristics	Multiple Antennas	Reconfigurable Antennas
Usage application	• Single-band antenna can only accommodate one frequency of wireless service.	• A single antenna accommodates multiple wireless services.
Space requirement	• Requires more space	• Minimal space requirement
Complexity in the frond-end	• Filter specification is loose, and the front-end is simple.	• Filter specifications can be reduced, but a complicated reconfigurable front end is required.
Radio performance	• Excellent	• Acceptable performance, additional loss introduced by switches.
Diversity features	• Each antenna has to operate with a different frequency, polarization, and radiation pattern.	• Can provide diverse features of frequency, polarization, and radiation pattern.
Radio coexistence	• There is little space between antennas and as such, there is a strong coupling between radios.	• Degraded due to simultaneous operation, since the antenna only supports one service at a time.
Cost	• The increased number of cables contributes to most of the cost.	• The price of a low-loss, low-power-consumption RF MEMS switch is high. However, there are alternative options for less expensive switching devices.

using PIN diodes with truncated corners and switching properties suited for linear to circular polarisation. Narrowband and dual-band modes were achieved for the four switching states. The dual-band mode is achieved by using an upper L-shaped device with two diodes. The antenna's circular polarisation was introduced by the bottom L-shaped components. Similarly [113], presented a rectangular patch antenna with frequency/pattern reconfigurability. The proposed antenna layout employed an inverted U-shaped patch surrounded by a normal patch. A PIN diode was added between the slot that divides the two patches which results in different resonance frequencies. A rectangular slit is also carved in the U-shaped inverted patch which gives the ability to modify its radiation pattern. Biasing lines are positioned distant from the radiating patch of the designed antenna.

The above section presents a thorough investigation and analysis of several design techniques and performance metrics for reconfigurable antennas. The reconfiguration approaches studied are categorized as solid-state switches, optical, electro-mechanical switches and smart material reconfigurable systems. different types of reconfigurable antennas with different integration applications are explored, as well as their properties. Geometrical reconfigurability is required for the implementation of several capabilities such as radiation pattern, polarisation, and frequency reconfiguration. The reconfiguration methods introduce levels of complexity that may have unanticipated consequences. The optimal reconfiguration technique depends on the requirements of the application. Table 9 lists the comparison solution of using a reconfigurable antenna instead of multiple antennas.

The next sub-section presents a thorough investigation and analysis of several design techniques and performance metrics for wearable reconfigurable antennas.

V. WEARABLE RECONFIGURABLE ANTENNA

WBAN is a current research field, particularly in the healthcare field, because it allows for cost-effective and uninterrupted monitoring of patients across a large variety of accessibility [115], [116]. A network of body sensors is linked to a communication device, which collects data and sends it to a health care facility [117]. Moreover, ensuring adequate radiation properties while maintaining low levels of SAR is a difficult undertaking. Furthermore, a single antenna that is flexible, with different radiation, frequency, polarization and conformal to the human body is preferred [25]. However, these effects are affected by the individual's body composition and the location of the antenna on the body. The mobility of the human body results in dynamic channels that necessitate changing radiation, operating frequency and polarization to provide the optimum connection quality as the person moves to address these issues, wearable reconfigurable antennas can be used [11], [118].

Even though wearable reconfigurable antennas are greatly desirable for wearable applications, there is a lack of them in the open literature. This is due to the difficulties in establishing reliable textile-to-electronics connections, to compensate for the negative effects of bending, different environmental variables such as temperature and humidity, and interactions with the human body on their performance, reconfigurable antennas can adjust their radiation properties such as resonance frequency and radiation patterns. [119]. Currently, a few reconfigurable antennas for wearable applications have been proposed. However, most of them have wearability restrictions owing to mechanical inflexibility and/or stability due to the materials and electrical component connections. For example, in [120], Fitbit®Flex wearable device, a radiation pattern reconfigurable monopole/loop antenna implemented in FR-4 was presented. Figure 33 depicts this. The antenna has a robust soldered connection between the copper conductors and the electronic components, but the mechanical inflexibility of the materials limits the antenna to this Fitbit®gadget.

In [121], presented a flexible frequency reconfigurable antenna. Due to the use of a textile substrate and a copper tape conductor, this antenna has a high degree of flexibility. However, copper tape is not a good conducting material for wearable devices because it is easily irreversible due to external pressures, which is poor for antenna performance and stability. A further significant reason for not using coper tape is that it cannot be soldered on the textile substrate, which is required to provide a strong connection for the lumped components. The connection between the textile conductors and the lumped components would be unstable if the conductive cloth was used instead of copper tape in this design due to their highly different physical properties.

A study in [122], proposed a radiation pattern reconfigurable wearable antenna concept based on metamaterial structure. The antenna has good conformability since it is made of felt as a substrate and conductive cloth as a conductor. The theoretical validity of pattern reconfigurability between broadside and Omni-directional in the 2.4 GHz ISM band was verified using two prototypes, with and without a connecting line that simulates the ON and OFF states of a PIN diode. It is expected that properly connecting a real PIN diode between two pieces of cloth with dependable and lasting performance would be quite difficult. Once used by a human, the antenna and its lumped components are more likely to be exposed to external stresses that shorten the connections' endurance.

In [123], proposed a wearable antenna with polarization reconfigurability. To provide three reconfigurable polarizations, PIN diodes were mounted on the portions of the proposed patch antenna. The average gain at the three polarizations achieved by the proposed antenna was 5.96 dBi operating at 2.4 GHz. The components of the antenna proposed are composed of a wearable substrate and have an overall dimension of 70 mm × 70 mm × 4 mm. Four switchable PIN diodes connect four areas on the top of the substrate to the main radiator.

A reconfigurable circular polarized textile antenna was designed and fabricated in [12]. The circular polarization of the proposed antenna was achieved by creating a rectangular patch and adding a slotted ground plane. However, by altering the slot size with three embedded RF PIN diode switches, frequency reconfigurability was achieved. Based on the seven switch configurations, the antenna was switching in the following frequencies: (1.57 GHz, 1.67 GHz, 1.68 GHz, 2.43 GHz, 2.50 GHz, and 2.55 GHz) with a gain of 4.8 dBi.

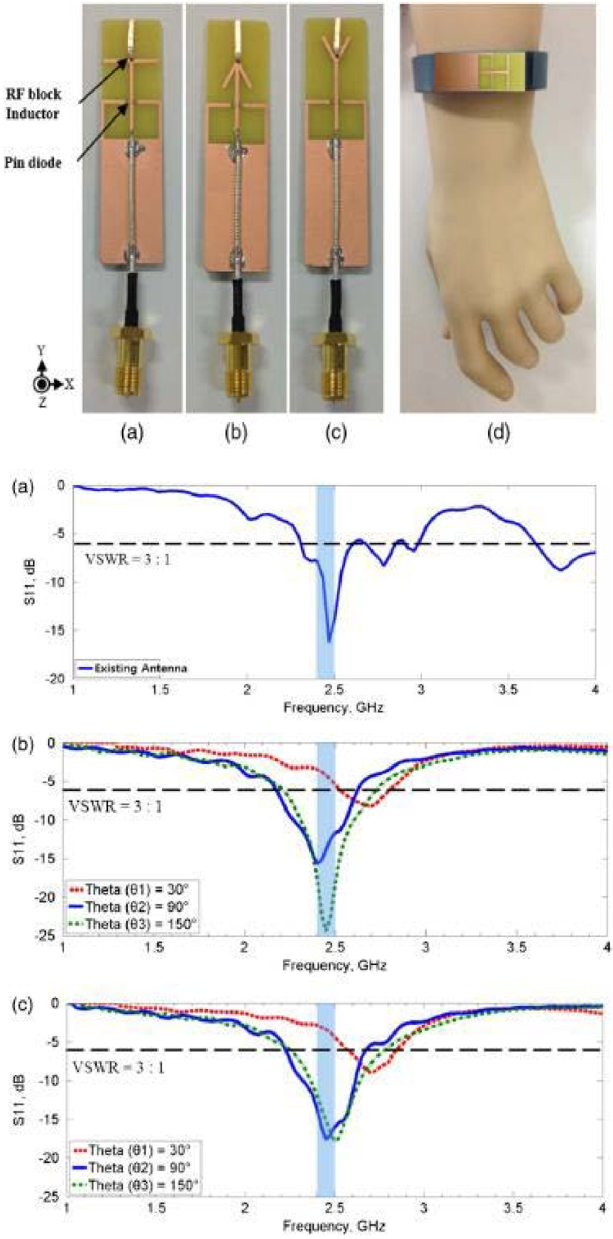
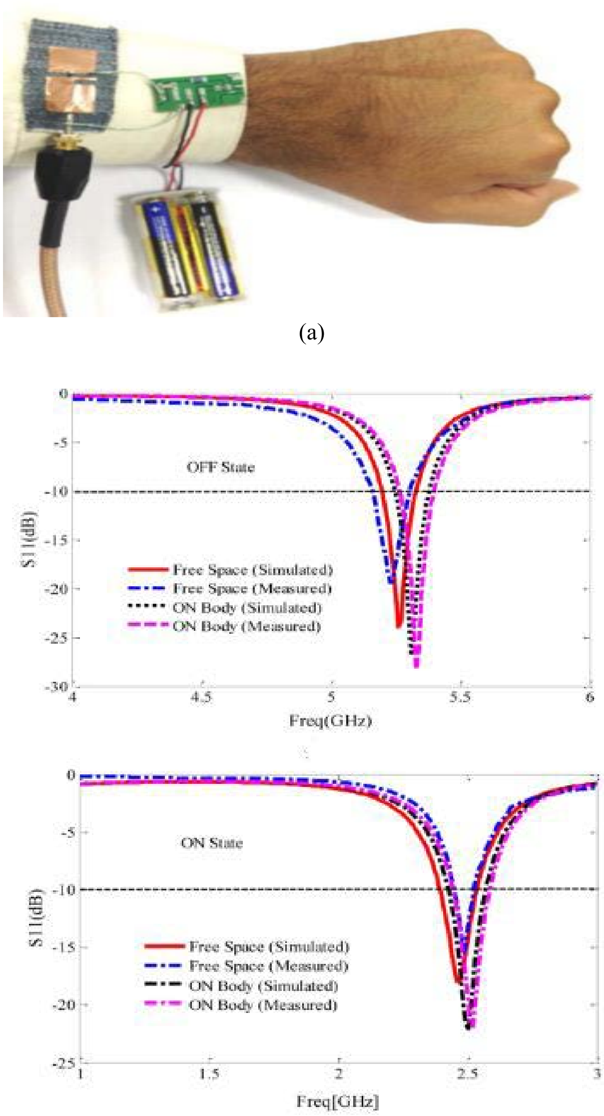


FIGURE 33. Photographs of the rigid reconfigurable antenna (a) CASE1 (b) CASE 2 (c) CASE 3 (d) applied antenna on Fitbit (e) measured S_{11} [120].

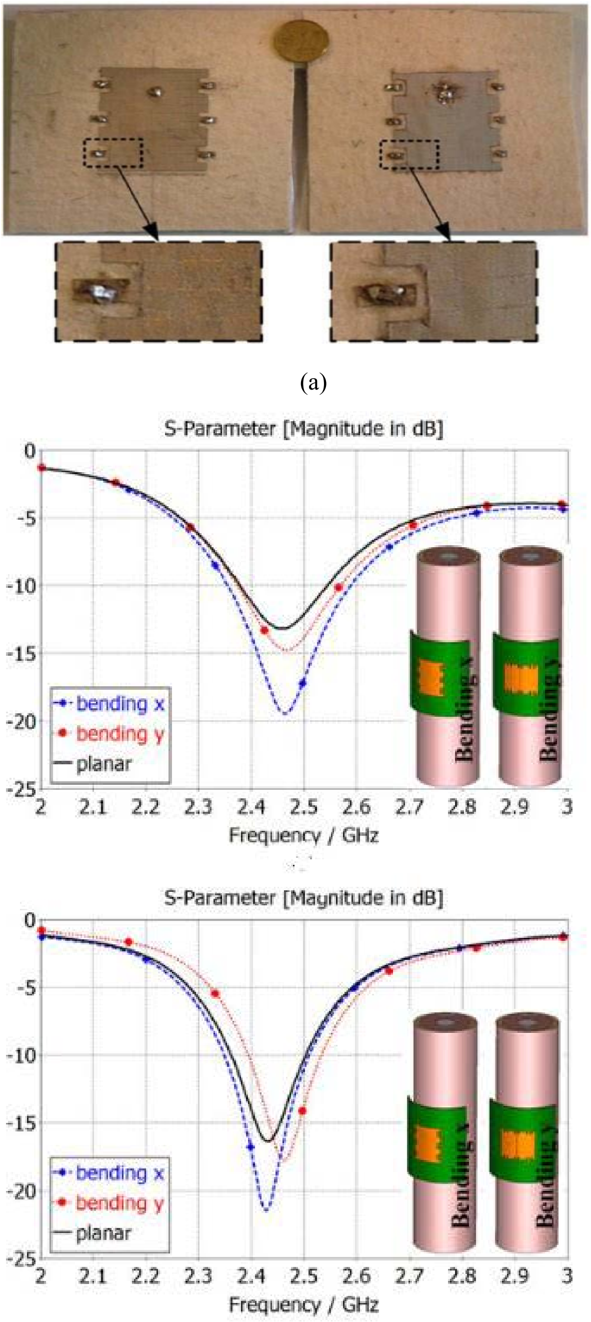
A reconfigurable wearable antenna was designed on a fabric substrate [124]. The proposed antenna may be suitable for frequency reconfiguration to function in the 5G mid-band (3GHz – 5.5GHz). Five switching elements were used at preset intervals to prevent two radios from transmitting from the same antenna at the same time. For simulation



(a)

(b)

FIGURE 34. **Photographs of the (a) proposed antenna mounted on a human wrist (b) measured S_{11} in the off-and-on state [121].**



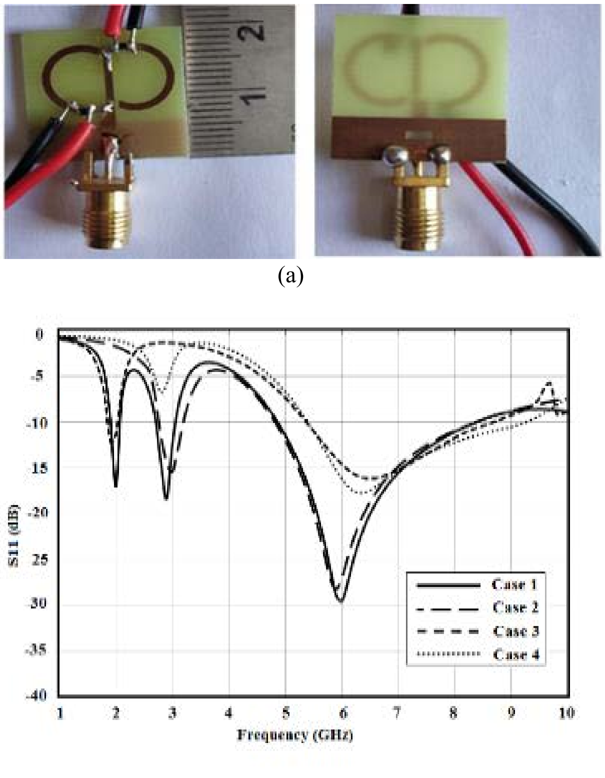
(a)

(b)

FIGURE 35. **Photographs of the (a) fabricated antenna (b) measured S_{11} in different bending conditions [122].**

purposes, element switches act as 5000 k ohm resistors when turned OFF and 1 k ohm resistors when turned ON. The proposed antenna could be used as a tracking device in military applications, monitoring performance at frequencies ranging from 3 to 5.5 GHz. This antenna can also be utilized for Wi-Fi (2.4 and 5.4 GHz), satellite communication, and 5G mobile communication.

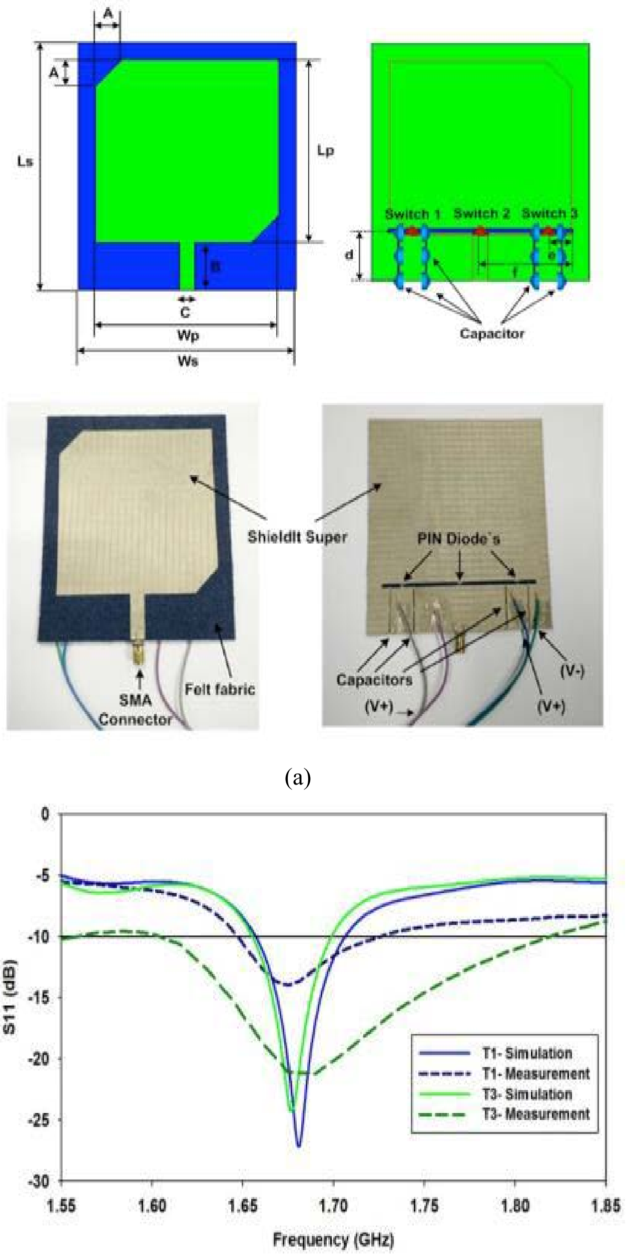
A reconfigurable beam steering antenna on a wearable textile substrate was simulated, measured, and compared to a loop antenna's omnidirectional performance [125]. The two antennas were set to operate in the WLAN 802.11a frequency band (5.725–5.85GHz). The reconfigurable antenna was designed to direct the path of the beam. To achieve beam-steering capabilities, the antenna employs two PIN diodes. The maximal beam directions of three states (states 0, 1, and 2) were steerable in the YZ-plane (h = 2^0, 28^0, and 326^0, respectively). With an overall half-power beam width (HPBW) of 102^0, the peak gain was measured to be 5.9-6.6 dBi. In terms of communication efficiency, total radiated power (TRP) and total isotropic sensitivity (TIS) measurements show that the reconfigurable beam steering antenna outperformed the loop antenna. the SAR values of the reconfigurable beam steering antenna on the body were below



(a)

(b)

FIGURE 36. Photographs of the (a) antenna prototype (b) measured S_{11} [123].



(a)

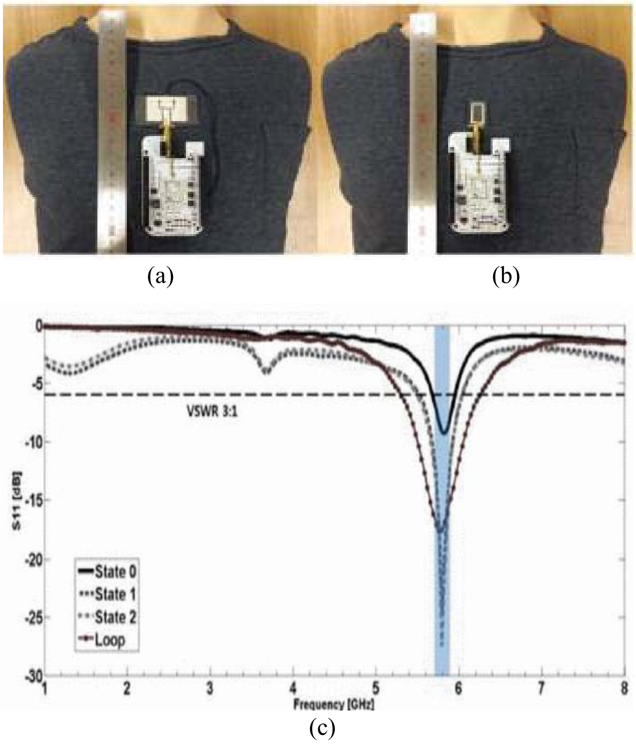
(b)

FIGURE 37. Photographs of the (a) geometry and prototype of the proposed reconfigurable antenna (b) measured return loss [12].

0.979W/kg (1 g tissue) in all states when the input power was 0.04W (16 dBm) which met the FCC standard.

In [126], presented a wearable reconfigurable textile antenna with a wide frequency tuning range. A coplanar reconfiguration component is incorporated into the textile-based planar inverted-F antenna (PIFA) providing frequency agility. The reconfiguration component is comprised of a small flexible printed circuit board (PCB) with tuning circuitry and commercially twisted buttons that act as an electronic-to-textile interface. Using this module fitted with a varactor diode and a seamless transition from a quarter-wave to a half-wave patch resonant mode, the frequency reconfigurability of the PIFA is investigated and parametrically optimized for optimum tuning range. A fabricated prototype, as predicted by computations, has a very large tuning range of roughly 70% (or one octave) with constantly focused radiation properties. The larger and mechanical stability of the reconfigurable antenna in various on-body and bending configurations validate both the antenna tuning concept and the viability of the proposed coplanar reconfiguration module.

A study in [127] proposed a compact frequency reconfigurable antenna for wearable applications and conformal surfaces. The antenna is made up of a stub-loaded circular radiator that was created on a 0.254 mm thick commercially available RT5880 flexible substrate. Combining stub loading with slot etching methods offers the features of compactness, frequency reconfigurability, large impedance bandwidth and constant radiation pattern with structural conformability. Two PIN diodes were employed for achieving frequency reconfigurability. The antenna operates in a variety of significant commercial bands, including S-band (2 GHz– 4 GHz), Wi-Max (3.5 GHz and 5.8 GHz), Wi-Fi (3.6 GHz, 5 GHz, and 5.9 GHz), 5G sub-6-GHz (3.5 GHz and 4.4 GHz – 5 GHz), and ITU-band (7.725 GHz – 8.5 GHz), along with the additional advantage of structural conformability. Furthermore, a comparison of the proposed wearable antenna's performance with state-of-the-art wearable antennas in terms of compact



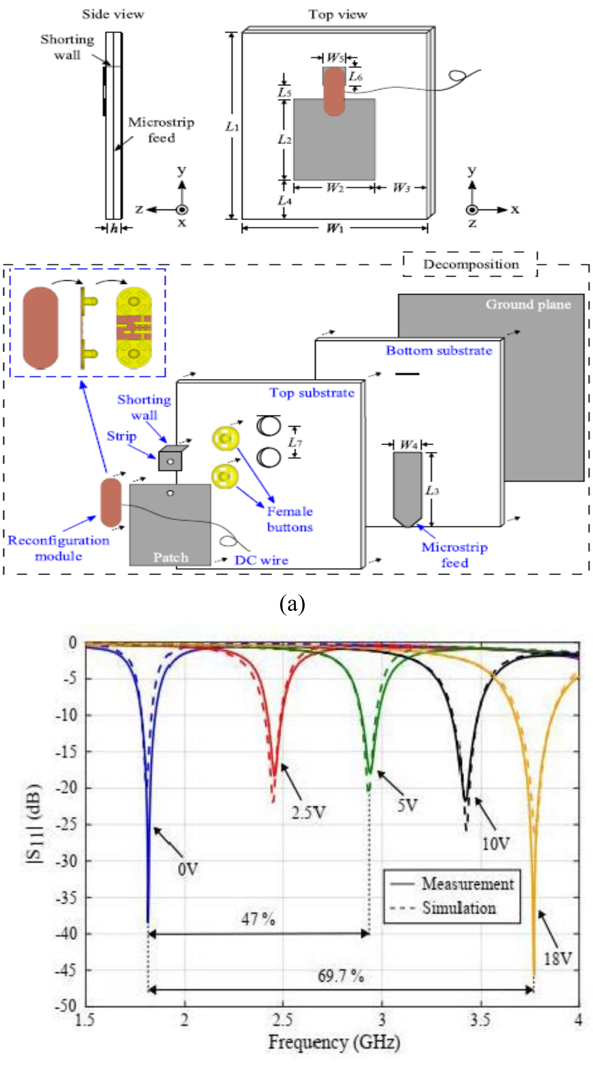
(a) (b)

(c)

FIGURE 38. Photographs of the (a) wearable reconfigurable beam-steering antenna (b) loop antenna (c) measured S_{11} [125].

size, frequency reconfigurability, and the number of operating bands demonstrates the proposed antenna's uniqueness and potential applicability in wearable applications.

Internet of Things (IoT) is a platform on which devices can interact and collaborate. A wearable reconfigurable antenna for IoT applications was proposed in [128]. The proposed antenna has a dimension of 40 mm × 55 mm, which is suitable for small-scale applications. Three PIN diodes were used to achieve four different operating frequencies. Roger 6002 was used as the substrate with a dielectric value of 2.94. The resonant frequency is found between 2.5 GHz to 14.9 GHz.



(a)

(b)

FIGURE 39. (a) Structure of the proposed frequency-reconfigurable flexible antenna (b) measured return loss [126].

A flexible antenna with a compact frequency and pattern reconfigurability for wearable applications was presented in [129]. A triangular monopole antenna with a semicircular stub has formed a frequency and pattern reconfigurability by connecting and disconnecting two inverted L-shaped stubs with PIN diodes. Once either of the stubs is connected to the radiator, a relative phase difference occurs at both ends of the radiator, causing the electromagnetic radiations to change direction and allowing pattern reconfigurability. Furthermore, the reactive load formed by the stubs has changed the overall length of the antenna, allowing for frequency reconfigurability. The antenna has a compact size of 40 × 50 × 0.254 mm^3 with achieved operational bandwidth of 1.65 GHz to 2.51 GHz, an average gain and radiation efficiency of more than 2.2 dBi and 80%, and an E-plane pattern reconfigurability of 180^0 also achieved. The frequency of the proposed antenna can be changed from 2.1 GHz to 1.8 GHz by switching the states of both diodes to OFF and ON, respectively.

A dual-band dual-polarised antenna for on-/off-body WBAN applications is presented in [130]. The proposed antenna is operating at 2.45 GHz with circular polarisation and 5.8 GHz with vertical polarisation in the ISM bands. Due to its broadside radiation pattern, the TM_{11} mode was used for off-body mode in the first band, while the TM_{02} mode was used for on-body mode in the second band due to its monopole-like radiation pattern. The proposed antenna's structure is made of felt textile material with a dimension of 100 × 100 × 2 mm^3 and consists of a circular patch with eight slots. The maximum SAR value at 2.45 GHz is 0.042 W/kg, and at 5.8 GHz is 0.09 W/kg, both of which are well below the industry standard of 1.6 W/kg for 1g of

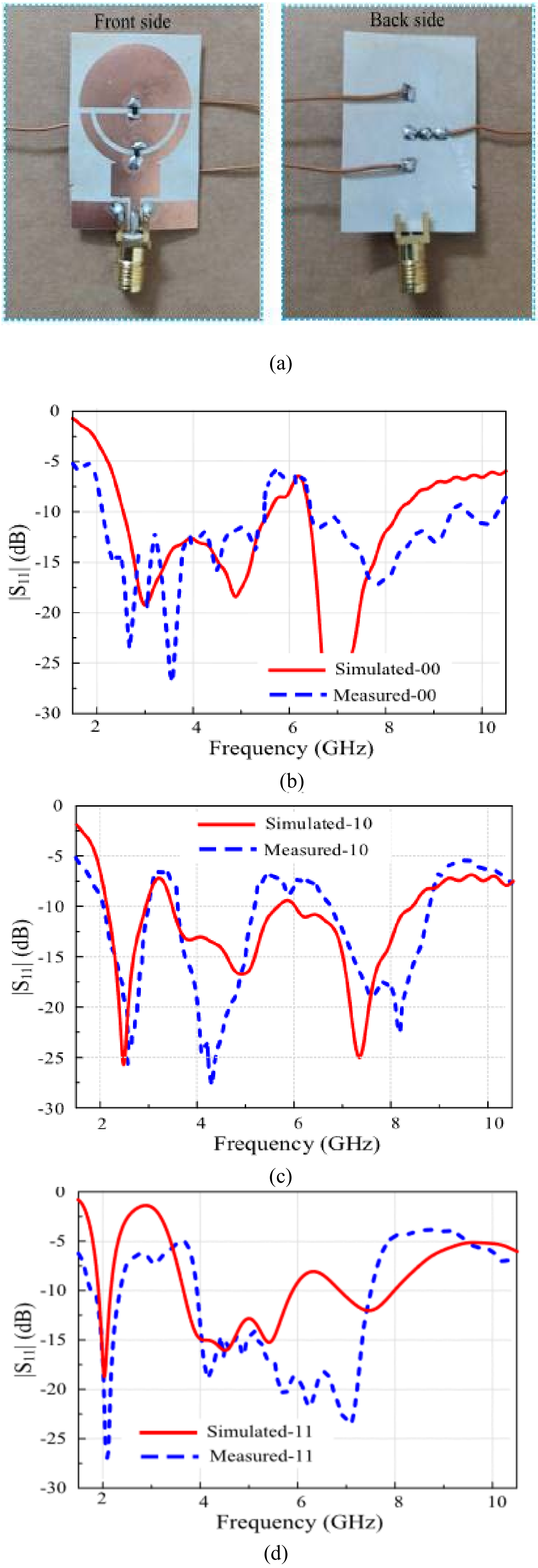


FIGURE 40. Photographs of the (a) fabricated prototype of the proposed reconfigurable antenna and measured return loss (b) case-00 (c) case-10 (d) case-11 [127].

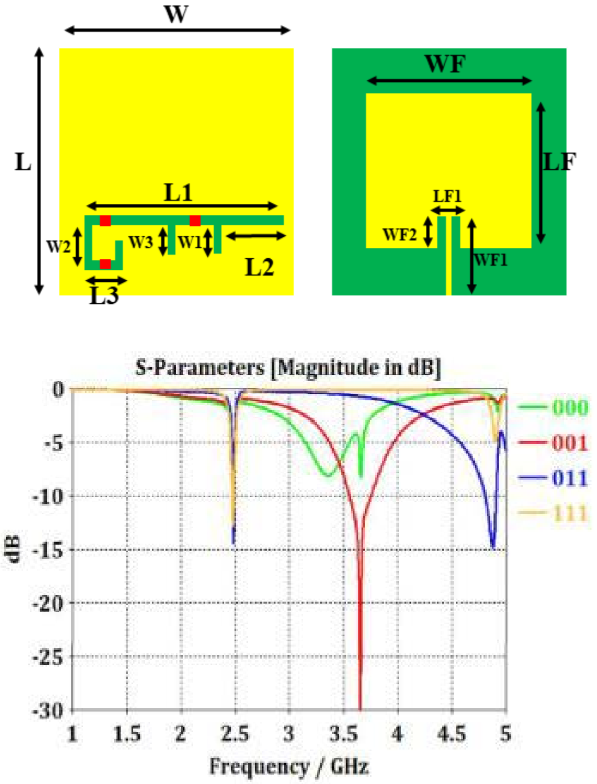


FIGURE 41. (a) Back and front view of the proposed antenna (b) proposed antenna S_{11} at different switching states [128].

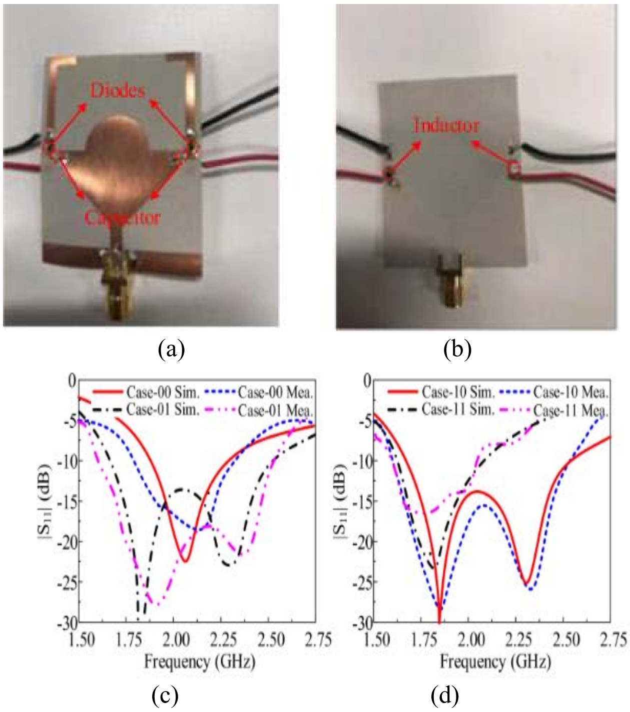
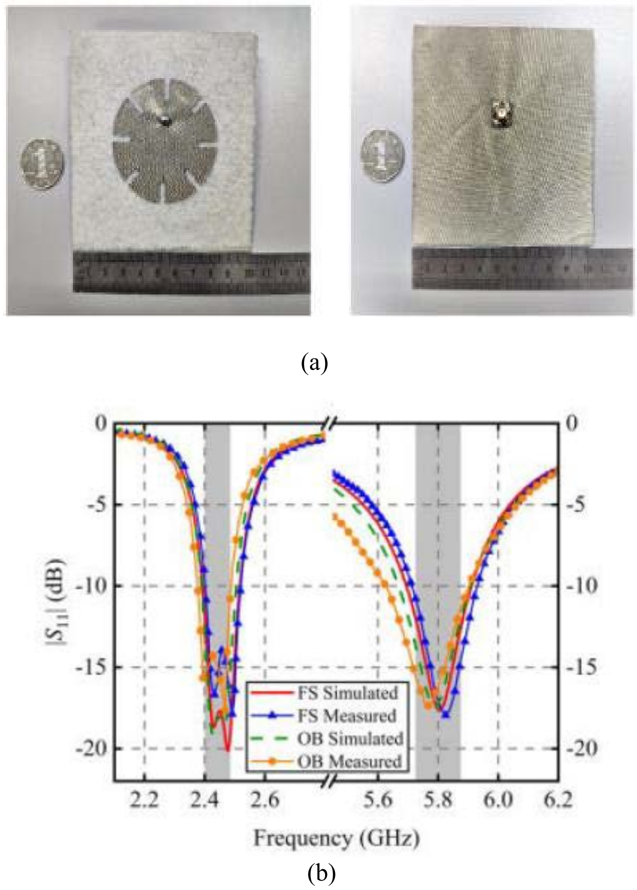


FIGURE 42. Photographs of the (a) front side fabricated prototype (b) back side fabricated prototype and measured return loss (c) case-00, case-01 (d) case-10, case-11 [129].

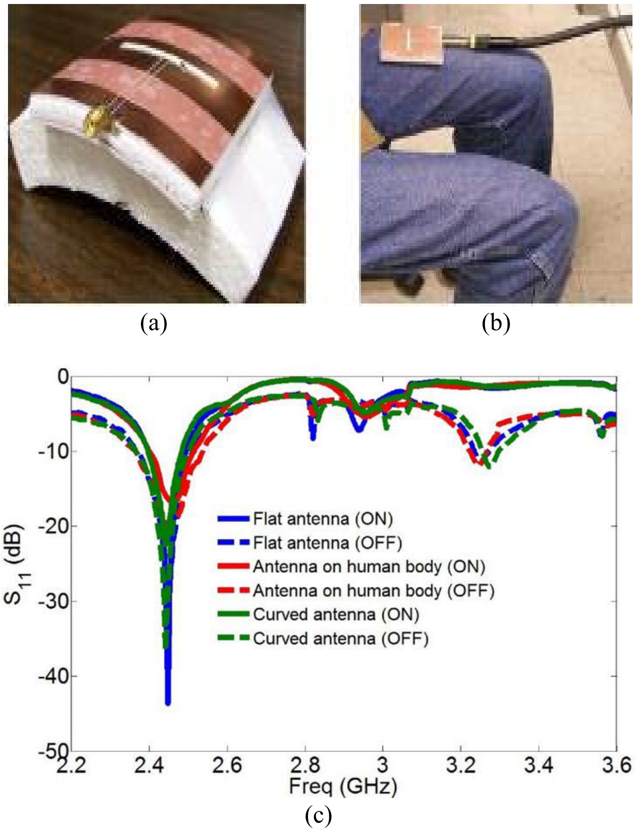
tissue. The obtained results demonstrate that the proposed polarisation reconfigurable antenna can be used in WBAN applications.



(a)

(b)

FIGURE 43. **Fabricated dual-polarized textile antenna's prototype (a) comparison between simulated and measured S_{11} (b) [130].**



(a)

(b)

(c)

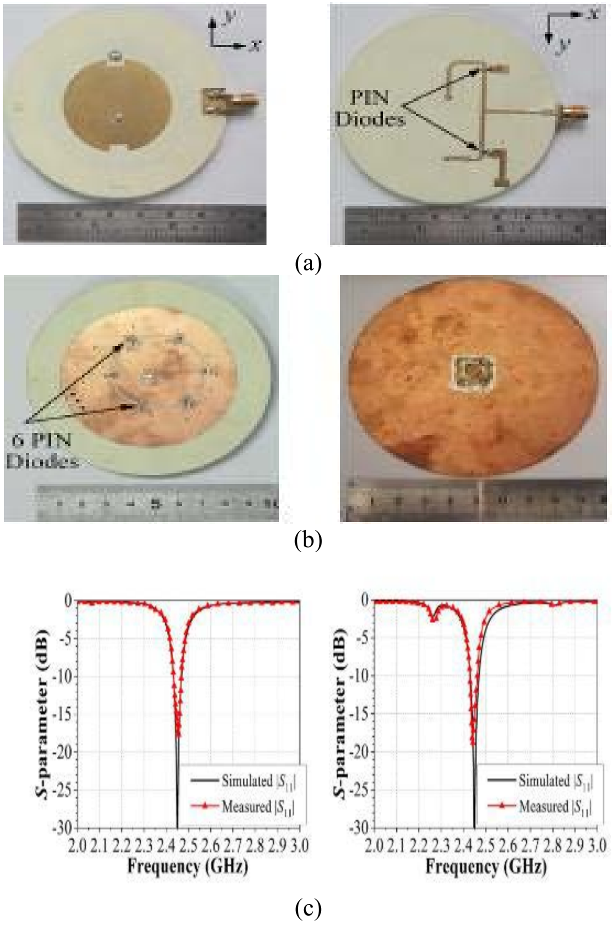
FIGURE 44. **Photographs of the (a) curved antenna's structure (b) antenna placed on human body (c) measured S_{11} [131].**

A wearable flexible reconfigurable folding slot antenna is presented in [131]. The antenna is composed of a folded slot and a stub that can be reconfigured by turning a PIN diode on and off, which changes the stub's radiation properties. The slot and stub have different operating frequencies and polarisation. To increase the antenna's radiation performance and lower the SAR, a polarisation-dependent AMC surface is merged with the proposed antenna. The antenna is designed and fabricated on a flexible substrate. After utilizing the AMC, the level of SAR is lowered.

A study in [103], proposed two pattern-reconfigurable wearable antenna designs, each with a distinct reconfiguration technique. One directional antenna and one Omni-directional antenna are perfectly incorporated into the initial design. An adjustable ring slot on a circular patch is carved in the second design. Both systems are pattern-reconfigurable when using PIN diodes Both the wearable reconfigurable antennas provide reconfigurable Omni-directional/directional radiation patterns and are suited for on/off-body connections in body-centric wireless communications (BCWC) applications.

A reconfigurable wearable repeater antenna (RWRA) for WBAN applications was proposed in [132]. By controlling the status of PIN diodes which are the repeaters, in on-body and off-body modes, the RWRA operates in triple mode. To reduce the profile and improve the coupling strength between the RWRA and an implantable antenna, the antenna is fed by a single port on the side rather than the bottom. The dimension of the antenna is $\pi \times 28 \times 4.8$ mm^3 at 2.45 GHz. The RWRA is measured on minced pork to verify its performance. The radiation patterns are omnidirectional with vertical polarisation on the on-body and broadside polarisation on the off-body, with a measured maximal gain of 1.2 and 5.4 dBi, respectively.

In [133], presented a frequency reconfigurable circularly polarised jute textile antenna that operates in the ISM bands. The antenna topology is based on a semicircular structure. The conductivity is achieved by brush-painting with copper paint. The patch structure is rehashed on the opposite side of the substrate, against the ground, with a rotation turn of 180^0. On the bottom side of the ground plane, two BAR64-03W PIN diodes switches are placed between a semi-elliptical structure and a rectangular structure. The antenna operates at different operating frequencies by controlling the state of the switches. Furthermore, the antenna has an accomplished axial ratio (AR) of less than 3 dB for all four switching states for resonating frequencies. At 2.4, 3.5, 5.8, and 5.9 GHz, the reconfigurable circularly polarised jute textile antenna has a



(a)

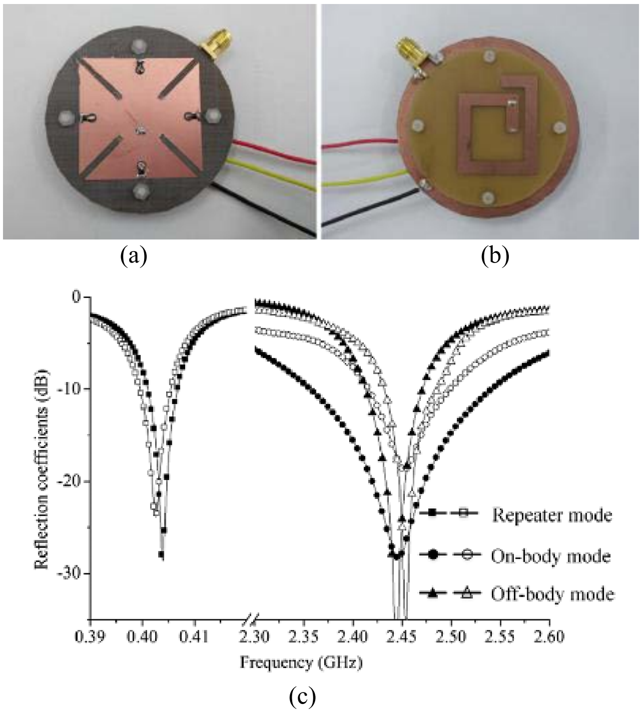
(b)

(c)

FIGURE 45. **(a) Photographs of fabricated antenna A (b) photographs of fabricated antenna B (c) measured S_{11} of antenna A and B [103].**

peak gain of 4.93, 5.67, 8.86, and 10.07 dBi (Wi-Fi, WiMAX, ISM, WLAN).

A low-profile multiband microstrip patch antenna with pattern reconfiguration was proposed in [134], The proposed antenna appropriate has both omnidirectional and directional radiation characteristics which are suitable for WBAN. The antenna's radiation patterns were switched using six PIN diodes. The percentage bandwidths obtained at operating frequencies of 0.915, 2.38, 3.5, and 5.8 GHz are 2.89, 1.68, 2.85, and 2.16, respectively. Peak gain and total efficiencies obtained for OFF mode at the same operating bands are 3.22/4.27/4.65/4.82dBi,82/85/87/89% and 1.12/1.80/2.44/2.68 dBi, 65/67/71/74%, respectively. The path loss model is evaluated using the transmission link between the antennas on the human body. This is suitable for WBAN applications because the LOS path is 30 to 45 dB and the NLOS is 50 to 80 dB.



(a)

(b)

(c)

FIGURE 46. **Photographs of the (a) front side prototype (b) back side prototype (c) measured S_{11} of the implantable antenna [132].**

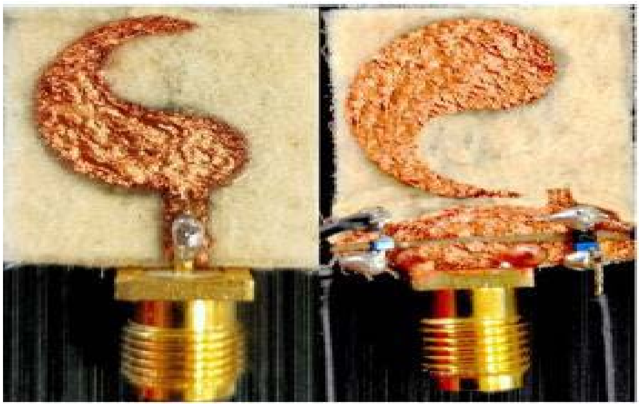
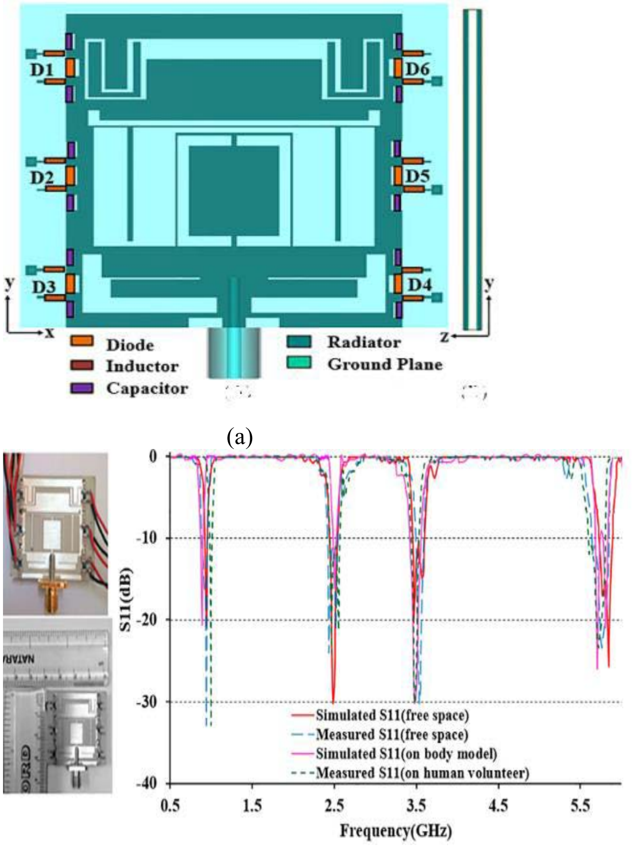


FIGURE 47. **Prototype of circularly polarized Jute textile antenna top view and bottom view [133].**

A dual-band dual-mode reconfigurable antenna for on-body and off-body communication was also presented in [135], The antenna is designed in the ISM band, particularly at 2.45 GHz in on-body mode and 5.8 GHz in off-body mode. The off-body mode is formed by etching a ring slot on the circular patch, which has little effect on the on-body mode. Three PIN diodes were used to switch between on-body and off-body modes. Measurements of the antenna were carried out on pork, the maximum measured gain in on-body mode and off-body modes are 0.36 dBi and 5.06 dBi respectively. The SAR value is below 0.36 W/kg when the input power is less than 19.5 dBm, which is adequate for WBAN applications.

A study in [136] used radiofrequency (RF) varactor diodes to design and develop a metamaterial (MTM)-based directional coplanar waveguide (CPW)-fed reconfigurable textile antenna for microwave breast imaging. The simulated and measured results of the proposed antenna confirmed a continuous frequency reconfiguration to a different frequency band between 2.42 GHz and 3.2 GHz achieving a frequency ratio



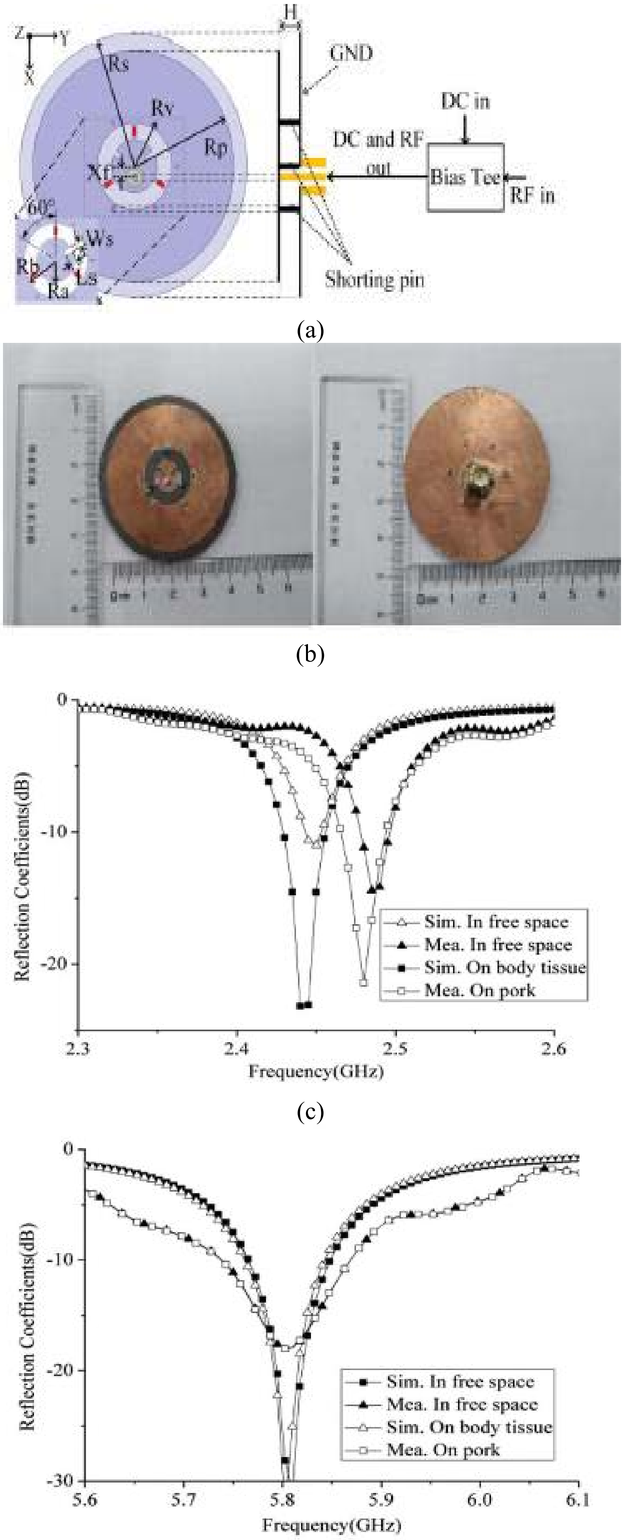
(a)

(b)

FIGURE 48. Photographs of the (a) fabricated prototype (b) measured S_{11} of the antenna [134].

of 2.33:1 and a fixed bandwidth of 4-15 GHz. a directional radiation pattern was formed in the frequency reconfigurable region, and the antenna had a peak gain of 7.56 dBi with an average efficiency of more than 67%. The reconfigurable antenna based on MTM was also tested and analyzed near the breast phantom. This microwave imaging system was used to simulate and measure experiments on a realistic breast phantom custom-fabricated with heterogeneous tissue composition, with image reconstruction using delay-and-sum (DAS) and delay-multiply-and-sum (DMAS) algorithms. Provided that the MWI system detected cancer as small as 10 mm in the breast phantom, the proposed antenna technique could be used in clinical settings to detect breast cancer.

In [137], proposed a frequency reconfigurable microstrip patch antenna for use in WBAN. On a conventional patch antenna, layers of mercury and liquid crystal polymer (LCP) are used to reconfigure the frequency. The antenna was first simulated in free space to ensure that the antenna parameters such as return loss, gain, radiation pattern, and efficiency were accurate. The antenna was then simulated for on-body performance analysis using a numerical model of the human body after the results were obtained. The simulated return loss for both configurations at the radiating frequencies is less than −10 dB. The results of the free space simulation are very close to the results of the on-body results.



(a)

(b)

(c)

(d)

FIGURE 49. (a) The geometry of the proposed antenna (b) Photograph of the fabricated antenna (c) reflection coefficient at on-body mode (d) reflection coefficient at off-body mode [135].

A wearable antenna with a switchable pattern and polarization was designed and fabricated [13]. The antenna was fabricated on glass and four PIN diodes were used to achieve

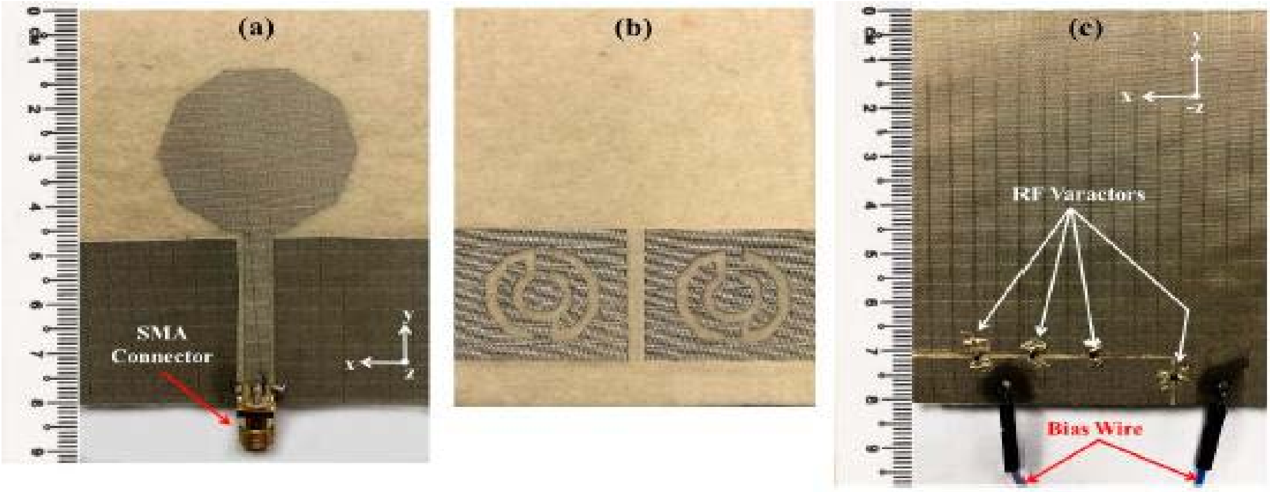


FIGURE 50. Fabricated prototype of the MTM-driven reconfigurable antenna. (a) Top layer (b) MTM layer (c) bottom layer [136].

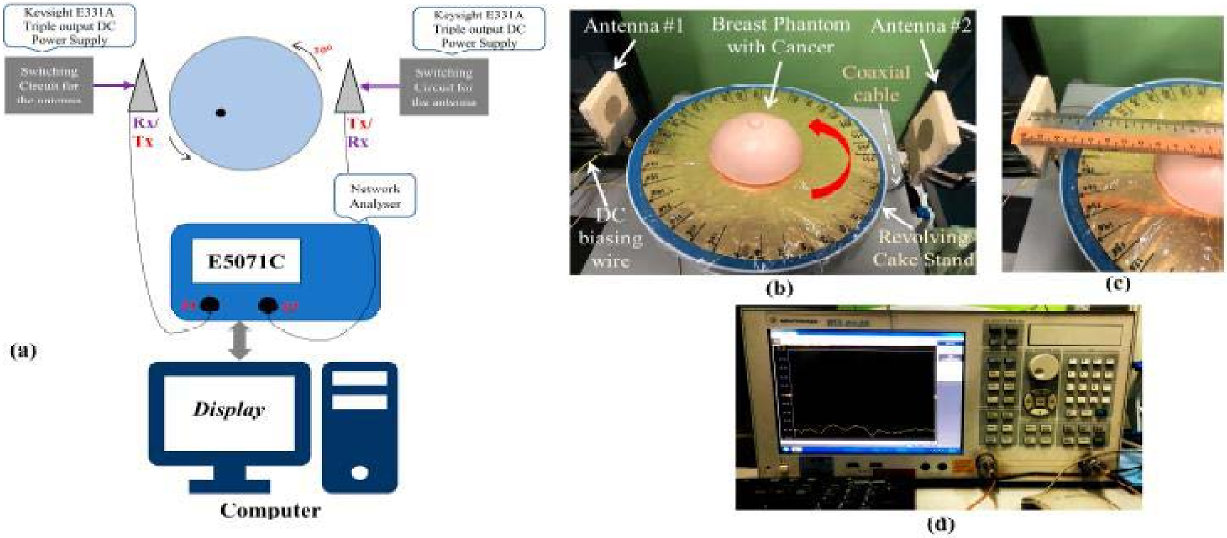


FIGURE 51. (a) Depiction of the data acquisition setup in the study where the antennas are represented by the triangle shape surrounding the breast. Microwave imaging experimental setup: (b) photograph of MBRU-based setup (c) maintaining the distance from antennas to breast phantom (d) sample of backscattering data measurements [136].

the reconfiguration. For medical applications, the proposed antenna resonates in the 2.4 GHz frequency. A single coplanar waveguide feeds an equilateral L-shaped slot in the antenna. Two modes of operation were created by manipulating the slot with switches. Each one's mode of operation corresponds to one of the switches' two states. The correlation between the two modes was less than 0.04 with 41% and 56% efficiency on the body for each mode.

A study in [14], proposed a low-profile reconfigurable antenna for WBAN-related applications. The proposed antenna achieves frequency reconfigurability by using the switching properties of the PIN diode. The proposed antenna has a dimension of 0.136 $\lambda_0\times$ 0.131 λ_0 $\times$ 0.001 λ_0. Three different frequency bands with independence resonance are achieved.1.575 GHz, 2.45 GHz and 5.2 GHz are the frequency bands achieved. At the above working frequencies, the percentage bandwidth reached is 3.17/1.83/2.69 %. Ensuring that the SAR was suitable for wearable applications, it was simulated. Measurements confirm the performance data of the fabricated antenna prototype.

In [15], presented a reconfigurable antenna for on/off body communication. The antenna has a dimension of $\pi\times 242\times 1.6$ mm^3. Fabrication and comparison with simulated results were used to validate the antenna. On-body mode and off-body mode have maximum recorded gains of 0.36 dBi and 5.06 dBi, respectively. The SAR is 1.47 W/kg when the input power is 19.5 dBm.

TABLE 10. Performance comparison of different wearable reconfigurable antenna designs.

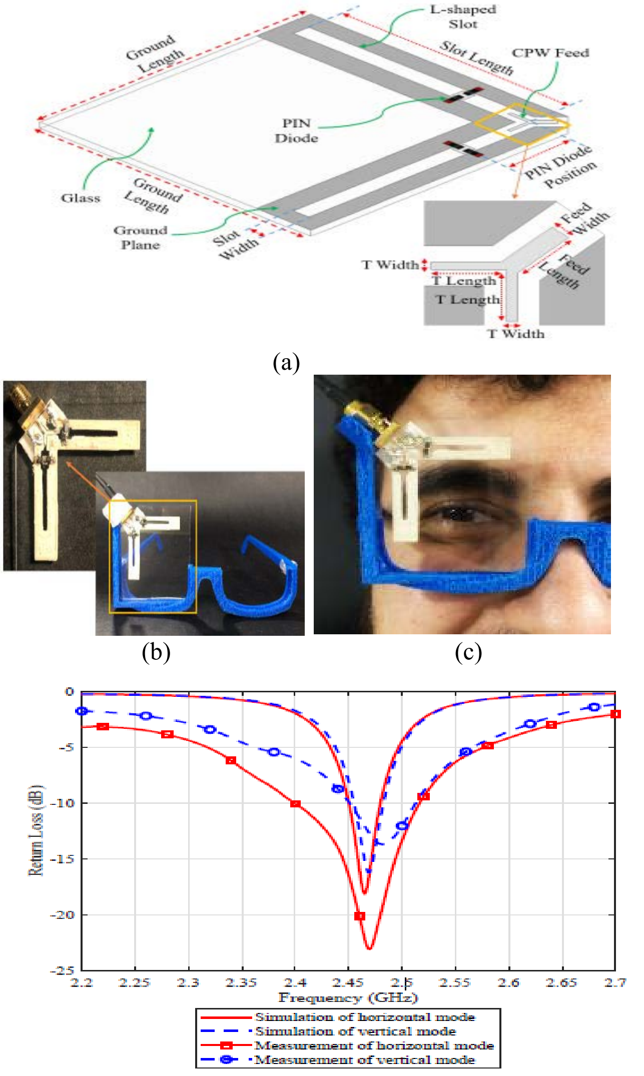
Ref	Size $(\lambda_0)^3$	Material/ ε_r	Reconfiguration/ Number of freq. bands achieved	Number of switches	Freq. (GHz)	SAR (W/kg)	Gain (dBi)	Efficiency (%)	Polarization/ Flexibility
[12]	0.68 × 0.68 × 0.0014 @ 2.45 GHz	Felt / 1.22	Frequency & Polarization / 6	3	1.57, 1.67, 1.68, 2.43, 2.5, 2.55	-	0.2-4.8	26.3-47.2	Circular /Yes
[13]	0.28 × 0.28 × 0.008	Glass / 8.5	Radiation Pattern & Polarization / 1	4	2.4	0.8	1.5	40	Linear / No
[14]	0.13 × 0.13 × 0.0001 @ 2.45 GHz	Rogers / 3.55	Frequency / 3	5	1.575, 2.45, 5.2	0.16 0.52 1.13	3.26, 3.47, 4.04	82, 85, 88	Linear / Yes
[15]	π × 0.2242 × 0.032	F4B /2.55	Radiation Pattern / 1	6	2.45	1.47	3.83	-	Linear / Yes
[121]	0.11 × 0.15 × 0.07	FR-4 /4.3	Radiation Pattern / 1	2	2.45	0.53	0.55	75	Linear / No
[122]	0.19 × 0.04 × 0.008 @ 2.45 GHz	Denim /1.68	Frequency / 2	1	2.45, 5.25	-	3.55, 3.17	-	Linear / Yes
[123]	0.38 × 0.31 × 0.024	Thick Felt / 1.3	Radiation Pattern / 1	1	2.4	0.01	4.9	40.6	Linear / Yes
[125]	0.23 × 0.198 × 0.018 @ 3.5 GHz	Polyester / 3.4	Frequency / 4	5	2-6	-	-	-	Linear / Yes
[126]	0.74 × 0.41 × 0.029	PES / 1.35	Radiation Pattern / 1	2	5.8	0.979	6.6	-	Linear / Yes
[127]	0.56 × 0.47 × 0.03	PF4 Form / 1.06	Frequency / 5	1	1.82-3.79	-	1.07-7.37	29.8-93.7	Linear / Yes
[128]	0.41 × 0.29 × 0.003 @ 3.5 GHz	Rogers / 2.2	Frequency / 3	2	2.05-10.7	-	2.02-5.31	83.5-87.3	Linear / Yes
[129]	0.25 × 0.29 × 0.0012 @ 2.45 GHz	Rogers / 2.94	Frequency / 4	3	2.47, 3.65, 2.48, 4.87	-	5.45, 5.33, 6.06, 6.08	-	Linear / Yes
[130]	0.22 × 0.27 × 0.0001 @ 1.65 GHz	Rogers / 2.1	Frequency & Radiation Pattern / 4	2	1.65-2.5	-	2.2	80	Linear / Yes
[131]	0.82 × 0.82 × 0.0016 @ 2.45 GHz	Thick Felt / 1.3	Frequency & Polarization / 2	4	2.45, 5.8	0.042, 0.09	5.93, 6.02	55.6, 72.5	Circular, Linear / Yes
[132]	0.71 × 0.66 × 0.0012 @ 2.4 GHz	Rogers / 3	Frequency / 1	1	2.45,3.3	0.29	3,6.4	-	Linear / Yes
[104]	0.82 × 0.82 × 0.11	Rogers / 3.66	Radiation Pattern / 1	8	2.45	2.13	6	-	Linear / Yes
[133]	π × 0.2282 × 0.026	FR4 / 4.4 F4B / 2.55	Radiation Pattern / 1	4	2.45	6.73	5.4	-	Linear / No
[134]	0.16 × 0.13 × 0.012 @ 2.4 GHz	Jute / 1.87	Frequency / 4	2	2.4, 3.5, 5.8, 5.9	-	4.93, 5.67, 8.86, 10.07	-	Circular/ Yes
[135]	0.68 × 0.68 × 0.004 @ 5.8 GHz	Rogers / 3.55	Radiation Pattern / 4	6	0.915, 2.38, 3.5, 5.8	0.417, 0.491, 0.698, 0.853	3.22, 4.27, 4.65, 4.82	82, 85, 87, 89	Linear / Yes
[136]	π × 0.2242 × 0.016	F4B / 2.55	Frequency / 2	3	2.45, 5.8	17.8,4	0.36, 5.06	-	Linear / Yes
[137]	0.8 × 0.61 × 0.06 @ 3 GHz	Felt / 1.44	Frequency / 1	4	4-15	0.121	7.56	67	Linear / Yes
[138]	0.78 × 0.6 × 0.0009 @ 3.6 GHz	Rogers / 2.33	Frequency / 2	2	3.6,5	0.615, 0.543	8.93, 7.57	68.3, 26.23	Linear / Yes

VI. SUMMARY

The employment of wearable electronics, specifically wearable antennas, is critical in the present advancement of wireless communication. Several requirements must be fulfilled to design and fabricate wearable reconfigurable antennas which include:

- Material selection
- Linear characteristics
- SAR limit
- Bending investigation
- Fabrication techniques
- Reconfiguration mechanism

Material selection in wearable reconfigurable antenna design is crucial. Wearable reconfigurable antennas reported in the previous literature are mostly focused on lightweight materials. An antenna's characteristics are influenced by the properties of the materials used. The dielectric constant and thickness of the substrate, for example, determine the linear characteristics of the antenna. Recently, conductive materials are introduced for effective electromagnetic radiation, such



(a)

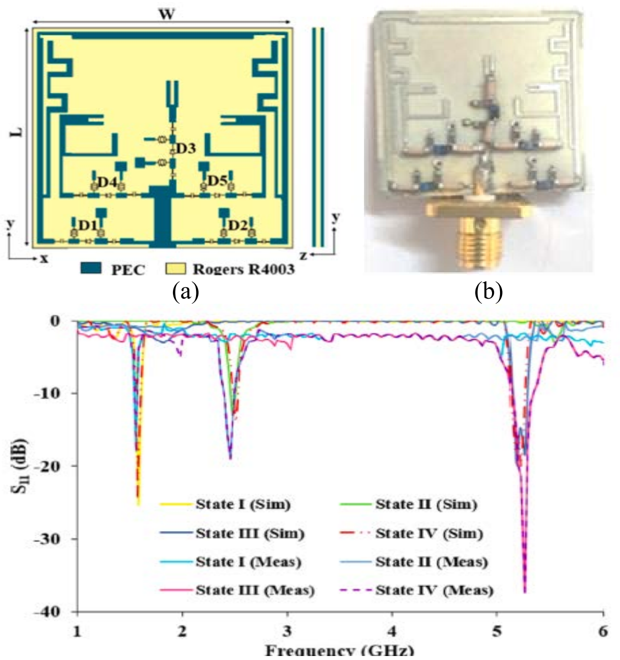
(b)

(c)

(d)

FIGURE 52. Photographs of the (a) model of the antenna (b) prototype of the proposed antenna (c) antenna worn by a human (d) return loss comparison [13].

as metallic inks, conductive polymers and Zelt. In addition, radiation absorption is a critical concern for human body due to its proximity. For that reason, FCC and ICNIRP have introduced a SAR limit. Other issues with wearable reconfigurable antennas include their durability, moisture and temperature, only to name a few. Wearable reconfigurable antennas are intended to be bent or conformed to a certain degree on human body, hence investigation under various bending conditions is essential. In a certain environment, reconfiguration is required to switch between multiple frequencies, radiation patterns, polarization or hybrid between them, to maintain the antenna's performance. PIN diodes, varactors, RF-MEMS and FETs are among the popular switching devices to reconfigure an antenna.

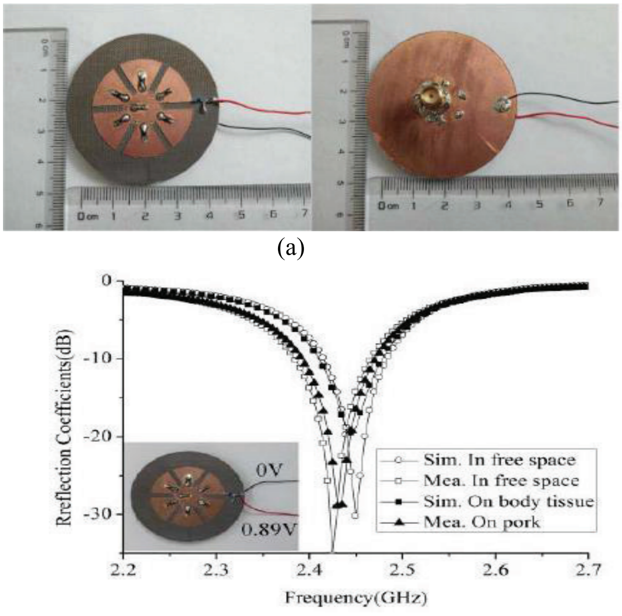


(a)

(b)

(c)

FIGURE 53. (a) Configuration of the antenna (b) fabricated prototype (c) measured return loss [14].



(a)

(b)

FIGURE 54. Photographs of the (a) fabricated antenna (b) measured return loss [15].

VII. CONCLUSION

This paper presents a comprehensive review of the requirements and analysis needed for wearable reconfigurable antenna design and fabrication. The analysis required to be carried out to evaluate the performance of a wearable antenna includes SAR simulation to determine the limit to obey the standard governed by the FCC and ICNIRP and bending investigation. Some of the reported work on wearable antennas have not carried out SAR analysis to evaluate whether the antenna is safe to be worn on human body. On the other hand, the performance metrics of reconfigurable antennas were comprehensively discussed as reported previously. The performance of a wearable reconfigurable antenna can be enhanced by carefully selecting the type of materials to design and fabricate the antenna. In most cases, EBG or AMC structure is highly recommended for lowering SAR values. Above all, the method employed to achieve the reconfiguration in terms of frequency, radiation pattern, polarization or hybrid between them, must be considered in the initial stage of the antenna design to determine its application.

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