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Flexible Substrate based Printed Wearable Antennas for Wireless Body Area Networks Medical Applications

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ABSTRACT. The wireless body area networks (WBANs) enable communication with the on-body wireless devices and systems. For on-body applications, the key requirement for the antennas is the flexibility of the antennas to mount the antennas on the body. Wearable antennas are fabricated on a flexible substrate to make these antennas suitable for mounting on the human body. Due to the wearable feature of these antennas, they are used in many on-body applications. The wearable characteristic also makes these antennas suitable for many on-body medical applications. This paper presents the technical review of the WBAN, WBAN frequency bands, wearable antenna fundamentals, flexible substrate characteristics, design and development of wearable antennas for medical applications. The wearable antennas are fabricated on the fabrics. The review of the material properties of various flexible substrates is given in detail. Due to the presence of the air in the gaps of fabrics, the dielectric constants of these materials are very low. Detailed analysis of antenna performance due to flexible substrate material characteristics is also discussed. The developments of wearable antennas for WBAN medical applications are presented. The paper also focuses on the design considerations, fabrication methods, challenges, and proposed solutions for the wearable printed antennas.

Keywords: *wearable printed antennas; wireless body area networks (WBANs); on-body; flexible substrate; wearable antennas for medical applications*

1. INTRODUCTION

Due to the rapid growth of wireless technology, nowadays, wireless communication systems play an important role in almost every sector. Wireless body area networks (WBANs) are getting researchers' attention due to their potential on-body applications [1]. In medical applications, WBANs can be utilized in real-time health care, operation theatres, ambulances, clinics, homes, etc [2]. WBANs are also used for linking the body with wearable devices. WBANs are used in various medical applications, military applications, wireless communications, etc [3]. The different frequency bands for various WBAN applications such as human body communication (HBC), medical implant communication system (MICS), wireless medical telemetry service (WMTS), industrial, scientific and medical (ISM), ultra-wideband (UWB) are allocated [4]. Frequency ranges 5-50 MHz (wavelength range 60-6 m), 402-405 MHz (wavelength range 0.7462-0.7407 m), 863-870 MHz (wavelength range 0.3476-0.3448 m), 902-928 MHz (wavelength range 0.3325-0.3232 m), 950-956 MHz (wavelength range 0.3157-0.3138 m), 2.36-2.4 GHz (wavelength range 12.71-12.5 cm), 2.4-2.45 GHz (wavelength range 12.5-12.24 cm) and 3.1-10.6 GHz (wavelength range 9.67-2.83 cm) are allotted as HBC band, MICS band, WMTS band (used in Japan), WMTS band (used in Europe), ISM band (used in New Zealand, Australia, North America), ISM band (used in Japan), ISM band, ISM band (used worldwide) and UWB, respectively [4].

The use of wearable technology in printed antennas has been increasing significantly to make printed antennas suitable for wearable applications. Wearable antennas are made on a flexible substrate so that these antennas can be mounted on various human body parts for on-body applications. Wearable technology allows communication with the on-body electronic devices [5]. Due to the compact size and easy fabrication of microstrip patch antennas, these antennas are suitable for various wireless applications. Microstrip antennas suffer from low gain and narrow bandwidth [6]. The performance of these antennas can be improved by using various techniques such as by changing substrate parameters [6], gap-coupling [7], stacked coupling [8], defected ground structure (DGS) [9-14], metamaterials [15-16], frequency selective surface (FSS) [17], DGS and reflected surface [18], etc. The wearable antennas are the printed antennas that utilize a substrate that is flexible and makes these antennas suitable for moun feature of wearable printed antennas, these antennas are suitable for various on-body applications and this topic is a hot topic for research in the present days. Various flexible substrates such as fabrics, substrates with small thickness, etc. can be used in wearable printed antenna design. The dielectric constant of these flexible fabric substrates is low as air is filled in the gaps. Due to the low dielectric constant, the spurious radiation is lower in wearable antennas and make these antennas good radiators. There are many favorable characteristics of wearable antennas such as low profile, light-weight, flexible, low spurious radiation, etc, however, these antennas suffer from some limitations such as different characteristics for on-body and off-body conditions, bigger size, etc. There are many fabrication techniques for the fabrication of wearable printed antennas such as fabric-based embroidery technique, polymer embedding technique, microfluidic with injection alloys, inkjet printing, screen printing, photolithography and 3D printing [19].

A detailed review of wearable printed antennas is presented in this article. The introduction and theoretical concepts of wearable printed antennas are discussed. The substrate material properties and their effects on antenna performance are explained in detail. Manufacturing methods of flexible printed antennas, various designs of wearable printed antennas for medical applications are discussed and analysed. The challenges in wearable antenna design along with possible solutions are also discussed. Rest of the paper is organized as follows. The introduction of wearable antennas along with the theoretical concepts and flexible substrate material properties is presented in section 2. Section 3 discusses the developments of wearable antennas for medical applications. Section 4 and section 5 present the challenges along with possible solutions in wearable printed antenna design and conclusions, respectively.

2. DESIGN FUNDAMENTALS OF FLEXIBLE PRINTED ANTENNAS

In wearable antennas, the flexible substrate is used to make these antennas flexible. The basic configuration of a wearable rectangular printed antenna is depicted in Figure 1. On one side of the flexible substrate, the patch is fabricated and the microstrip line is used to feed the patch on the same side. On the other side of the flexible substrate, a ground plane is fabricated. The flexible substrate is sandwiched by the patch fed by the microstrip line and the ground plane layer as shown in Figure 1.

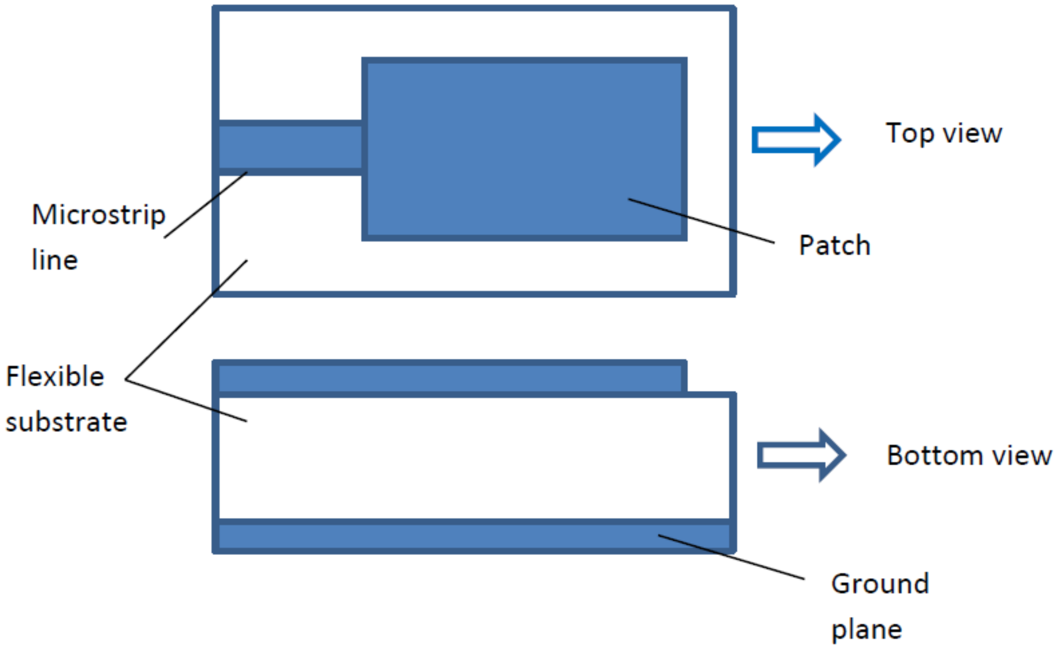

FIGURE 1. The basic configuration of a flexible rectangular printed antenna.

The design procedure of the flexible printed antenna is depicted in Figure 2. According to design specifications and feasibility, the conductive material and dielectric material should be selected in the first step. In the next step, the material properties of conducting material such as conductivity, and the material properties of the substrate such as dielectric constant and loss tangent should be analysed. In the next step, the antenna should be designed theoretically using design fundamentals, design equations, etc. After that, the antenna structure should be simulated and optimized using antenna software such as CST Microwave Studio, HFSS, IE3D, etc. The effects of bending, on-body applications, off-body should be analysed in simulations. In the next step, the antenna prototype should be fabricated and measured. The effects of bending, on-body applications, off-body applications, etc should be analysed.

As shown in Figure 1, the substrate used in wearable printed antennas is made from a flexible material. The dielectric constants of flexible materials used in flexible printed antennas are low, which improves the radiation performance of these antennas. In the wearable printed antenna design, the substrate material properties play an important role. The substrate used in the wearable antennas should not be rigid as the antenna can be mounted in any curved shape for on-body applications. So, the substrate should be flexible to wear on the various body parts. Further, the properties of the dielectric substrates are characterized by their permittivity and the loss tangent. The permittivity (ε) of the substrate material is defined by [20]:

$$\varepsilon = \varepsilon_r \varepsilon_0 \tag{1}$$

where, ε_0 is the permittivity of free space and ε_r is the relative permittivity of the substrate material, which can be represented as [20]:

$$\varepsilon_r = \varepsilon_r^r + j\varepsilon_r^i \tag{2}$$

Where ε_r^r is the real part of relative permittivity and is known as the dielectric constant of the substrate material; and ε_r^i is the imaginary part of the relative permittivity. The dielectric constant of the material varies with frequency, temperature, etc [20].

The loss tangent $(tan\delta)$ is given by [20]:

$$tan\delta = \frac{\varepsilon_r^i}{\varepsilon_r^r} \tag{3}$$

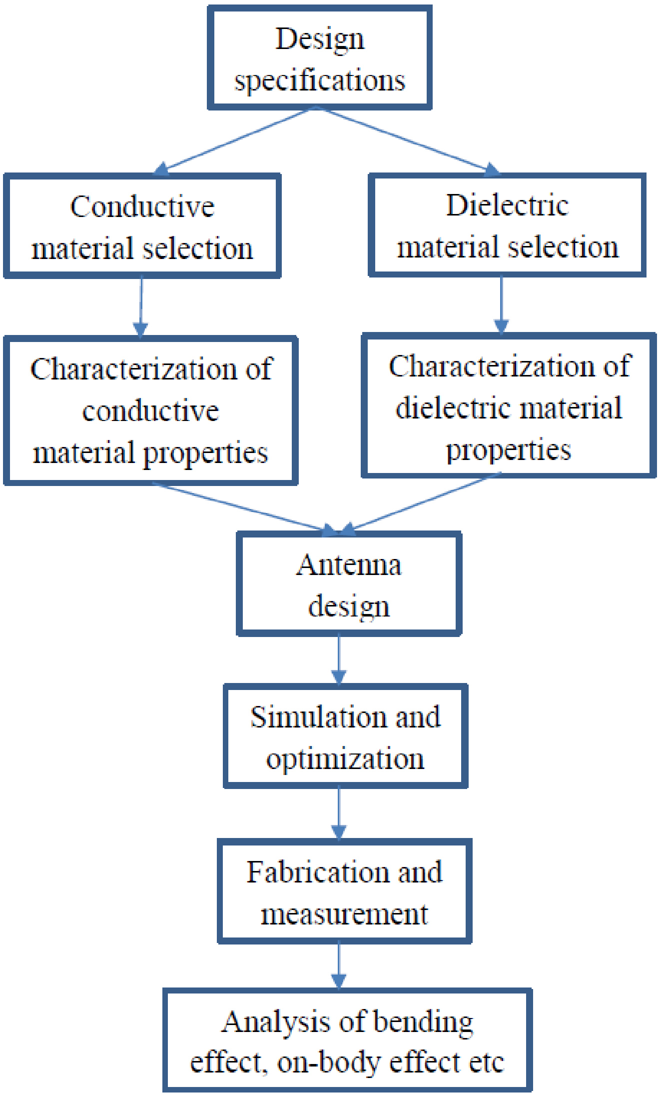

FIGURE 2. Design steps of a flexible printed antenna.

Various flexible substrate materials such as Tween, Polytetrafluoroethylene (PTFE), Silk, Felt, Moleskin, Panama, Fleece, Perspex, Cordura/Lycra®, Cotton, Cordura®, 100% Polyester, Quartzel® fabric, Flannel, Rogers Duroid RO3003™ (semi-flexible), Polyurethane, Jeans, etc are commonly used substrates in wearable antennas [20-25]. The dielectric constants of Cordura/Lycra®, Cotton, Cordura®, 100% Polyester, and Quartzel® fabric at 2.6 GHz are 1.5, 1.6, 1.9, 1.9, and 1.95, respectively [20]. The loss tangent of Quartzel® fabric, 100% Polyester, Cordura/Lycra®, Cordura® and cotton at 2.6 GHz are 0.0004, 0.0045, 0.0093, 0.0098 and 0.0400, respectively [20]. The dielectric constants of felt, moleskin, tween, silk, PTFE, and panama for the frequency range 2.6-3.95 GHz are 1.38, 1.45, 1.69, 1.75, 2.05, and 2.12, respectively [21]. The loss tangent of PTFE, tween, silk, panama, felt and moleskin for the frequency range 2.6-3.95 GHz are 0.0017, 0.0084, 0.012, 0.018, 0.023 and 0.05, respectively [21]. The dielectric constant and loss tangent of Flannel substrate used in [22] for the frequency range 2-20 GHz are 1.7 and 0.025, respectively. The dielectric constant and loss tangent of Rogers Duroid RO3003™ (semi-flexible) substrate used in [23] at 2.45 GHz are 3 and 0.001, respectively. The dielectric constant and loss tangent of the Polyurethane substrate used in [24] for the frequency range 2.38-6 GHz are 1.28 and 0.016, respectively. The dielectric constant and loss tangent of Jeans substrate used in [25] at 2.4 GHz are 1.68 and 0.05, respectively. The material properties of the flexible substrates given in [20-25] are summarized in Table 1.

TABLE 1. Flexible substrate materials properties.

S. No.	**Reference**	**Material**	**Frequency/ frequency range**	**Dielectric constant (ε_r)**	**Loss tangent ($tan\delta$)**
1	[21]	Fleece	2.6-3.95 GHz	1.17	0.0035
2	[24]	Polyurethane	2.38-6 GHz	1.28	0.016
3	[21]	Felt	2.6-3.95 GHz	1.38	0.023
4	[21]	Moleskin	2.6-3.95 GHz	1.45	0.05
5	[20]	Cordura/Lycra®	2.6 GHz	1.5	0.0093
6	[20]	Cotton	2.6 GHz	1.6	0.0400
7	[25]	Jeans	2.4 GHz	1.68	0.05
8	[21]	Tween	2.6-3.95 GHz	1.69	0.0084
9	[22]	Flannel	2-20 GHz	1.7	0.025
10	[21]	Silk	2.6-3.95 GHz	1.75	0.012
11	[20]	Cordura®	2.6 GHz	1.9	0.0098
12	[20]	100% Polyester	2.6 GHz	1.9	0.0045
13	[20]	Quartzel® fabric	2.6 GHz	1.95	0.0004
12	[21]	PTFE	2.6-3.95 GHz	2.05	0.0017
13	[21]	Panama	2.6-3.95 GHz	2.12	0.018
14	[21]	Perspex	2.6-3.95 GHz	2.57	0.008
15	[23]	Rogers Duroid RO3003™ (semi flexible)	2.45 GHz	3	0.001

The effect of the flexible substrate parameters on the performance of the wearable printed antenna can be analysed by using the quality factor of the wearable printed antenna. The quality factor of the printed antenna is given by [6]:

$$Q_t = \left(\frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}}\right)^{-1} \tag{4}$$

where Q_t, Q_{rad}, Q_c, Q_d and Q_{sw} are the total quality factor, quality factor due to radiation losses, quality factor due to conduction losses, quality factor due to dielectric losses, and quality factor due to surface waves, respectively.

The quality factors Q_{rad}, Q_c, Q_d and Q_{sw} depend upon the substrate parameters as per given below [6].

$$Q_{rad} \propto \frac{\varepsilon_r}{h} \tag{5}$$

$$Q_c \propto h\sqrt{\varepsilon_r} \tag{6}$$

$$Q_d = \frac{1}{tan\delta} \tag{7}$$

where h is the thickness of the substrate.

The losses due to surface waves can be minimized by using a thin substrate. For thin substrate, Q_c, Q_d and Q_{sw} are negligible. So, by choosing flexible substrate with a low dielectric constant, Q_{rad} can also be reduced, which results in a large bandwidth. Further, the resonant frequency of the printed antenna can be increased by choosing a flexible substrate with a low dielectric constant, and the resonant frequency of the printed antenna can be decreased by choosing a flexible substrate with a high dielectric constant.

The fabrication process also plays an important role in the development of flexible antennas as these antennas are mounted on a flexible substrate. The antennas fabricated using printed circuit board technology are difficult to be used for on-body applications as these antennas are difficult to integrate within clothing [26]. Various fabrication methods for flexible antennas exist such as line patterning, flexography, thermal evaporation, sewing and embroidering, polymer-based, inject printing, screen printing, photolithography, 3d printing technology, etc [26-27]. In the flexography fabrication technique, a printmaking of an image is performed using the inking of a protuberating surface. The flexography fabrication technique provides high resolution and is cost-effective. The limitation of this flexography technique is that the solid ink coverage may washed out [28]. The thermal evaporation fabrication method is based upon physical vapour deposition. The vacuum method with the pure material coating is used over the film surface by heating the solid material inside the vacuum chamber and the evaporated material is deposited on the substrate. The thermal evaporation method provides the excellent purity of the film but the control of film composition is difficult [29]. The flexible antennas based upon textile can be fabricated using the sewing or embroidering machine. This is an easy and low-cost fabrication technique. However, in this fabrication technique, there is no direct adhesion of the conducting material over the fabric, this may affect the electrical properties. In the fabrication of flexible antennas using inject printing, the high conductive inks are injected on the substrate. The inject printing fabrication method provides fast prototyping and high resolution. The cost of inject printing techniques is low. The disadvantages of injecting printing are nozzle clogging and ink with large particles are not compatible. In the fabrication of flexible antennas using photolithography, the metallic patterns are generated using photoresist. The photolithography fabrication method can generate complex metallic patterns, but this fabrication method is not cost-effective. The flexible antennas with complex 3d configurations can be fabricated using the 3d printing technique. The comparison of the fabrication techniques of flexible printed antennas is given in Table 2.

TABLE 2. Flexible printed antenna fabrication techniques.

S. No.	**Fabrication technique**	**Description**	**Advantages**	**Disadvantages**
1	Flexography	Printmaking of an image is performed using the inking of a protuberating surface.	High resolution, cost-effectiveness.	Solid ink coverage may wash out.
2	Thermal evaporation	This method is based upon physical vapour deposition. The vacuum method with the pure material coating is used over the film surface by heating the solid material inside the vacuum chamber and the evaporated material is deposited on the substrate.	Excellent purity of the film.	Difficult control of film composition.
3	Sewing and embroidering	In this method, the sewing or embroidering machine is used and used in textile-based antennas.	Easy and low-cost fabrication method for wearable antennas on clothing.	As there is no direct adhesion of the conducting material over the fabric, the electrical properties may be affected.
4	Inject printing	In the fabrication using inject printing, the high conductive inks are injected on the substrate.	Fast prototyping, high resolution, low cost.	Nozzle clogging, some inks with large particles are not compatible.
5	Photolithography	In photolithography, the metallic patterns are generated using a photoresist.	Complex metallic patterns can be generated.	Expensive.

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6	3d printing	This fabrication method utilizes the 3d printing technique.	Complex 3d structures can be fabricated.	Expensive.

3. WEARABLE ANTENNAS FOR MEDICAL APPLICATIONS

Wireless technology plays an important role in various applications of health care systems. Wearable printed antennas can be mounted on various body parts due to their flexible, compact size and light-weight characteristics. The wearable characteristics of these antennas make them an attractive candidate in many wireless communication systems. This section focuses on the developments of wearable printed antennas for medical applications.

In [22], Singh et al presented a wearable printed antenna for ultra-wideband medical applications. The antenna configuration of the ultra-wideband wearable antenna is shown in Figure 3. The VSWR 2:1 bandwidth of the ultra-wideband antenna is approximately 2.5 -20 GHz with a gain of 6.365 dB at 19.48 GHz. In [30], Nisha et al proposed a coplanar waveguide-fed wearable textile patch antenna for medical applications. The configuration of the wearable textile patch antenna is shown in Figure 4. The C-shaped patch is used and the antenna is fed by using a coplanar waveguide as shown in Figure 4. The approximate VSWR 2:1 bandwidth of the antenna is from 2.4 GHz to 2.5 GHz with a gain of 1.24 dB at 2.45 GHz.

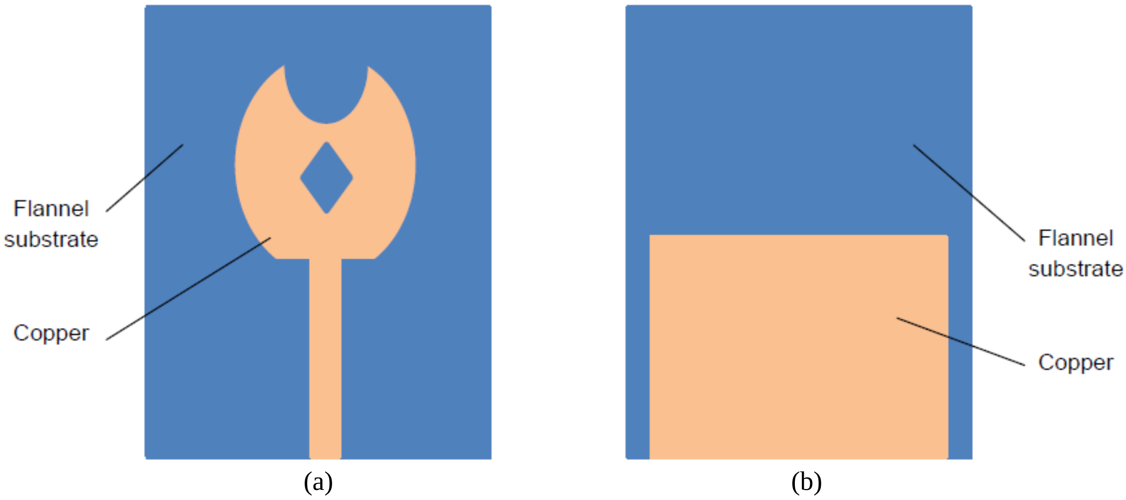

FIGURE 3. Geometry of the UWB wearable antenna (a) front view, (b) back view [22].

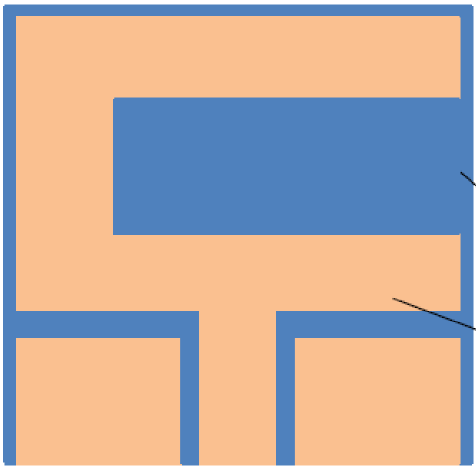

FIGURE 4. C-shaped wearable antenna [30].

In [23], Shah et al presented a semi-flexible wearable antenna for 2.45 GHz industrial, scientific and medical applications. The antenna is designed and fabricated on a semi-flexible Rogers Duriod RO3003^{TM} substrate. The antenna configuration is shown in Figure 5. The approximate VSWR 2:1 bandwidth of the antenna is from 2.1 GHz to 2.9 GHz. The bending effects on the antenna performance are analysed. The reflection coefficient of the antenna is less than -10 dB at 2.45 GHz for the bend of diameter 70 mm. In [24], Sivabalan and Jothilakshmi proposed a reconfigurable wearable antenna for medical applications. The structure of the reconfigurable wearable antenna is shown in Figure 6. The circular patch and a ring are connected through a switch. The bandwidth of the antenna is 2.38-2.52 GHz, when the switch is in ON state, and 5-5.5 GHz, when the switch is in OFF state. The gain of the reconfigurable wearable antenna is 9.18 dB at 5.5 GHz in E-plane in OFF mode and 7.51 dB at 2.5 GHz in E- plane in ON mode. In [25], the authors presented a metamaterials-based wearable antenna for 2.4 GHz medical applications. The geometry of the metamaterial-based wearable antenna is shown in Figure 7. Figure 7(a) and Figure 7(b) present the front view of the patch and back view of the patch, respectively. Figure 7(c) and Figure 7(d) show the front view of metamaterial structure and back view of metamaterial structure, respectively. The designed antenna is compact and robust. The maximum gain of the antenna is 7.5 dBi and the bandwidth of the antenna is 14.5 %. In [31], Kumar et al proposed a hexagonal-shaped flexible printed antenna for 2.4 GHz medical applications. The performance of the antenna is enhanced by utilizing an electronic bandgap structure. The antenna structure is shown in Figure 8. The bandwidth and gain of the antenna are 89.5 MHz with a resonant frequency of 2.45 GHz and 6.55 dBi, respectively. In [32], Dawood et al designed a compact antenna for 24 GHz biomedical applications. The antenna consists of circular and rectangular slots in the radiating element and the cross plus four square slots in the ground plane. The antenna provides a peak gain of 5.44 dB at 24.25 GHz. In [33], Du and Jin presented a multiple-input multiple-output (MIMO) flexible antenna on a liquid crystal polymer substrate for UWB applications. The F-shaped branch is included between the two orthogonal antennas to improve isolation between the ports. The bandwidth of the antenna is from 2.4 GHz to 11.3 GHz with a notch band from 3.1 GHz to 4.3 GHz. The isolation between the ports of more than 23 dB is achieved. In [34], Ashyap et al. proposed a compact antenna on the fabric for wearable applications. The EBG structure is used to provide the shielding for the antenna from the body and to reduce the size of the antenna. The comparison of the performance of the wearable printed antennas for medical applications is shown in Table 3. From Table 3, it can be observed that the compact reconfigurable wearable printed antenna provides the reconfigurable feature for two different frequencies. The gain of the reconfigurable antenna is highest among all wearable printed antennas. The maximum bandwidth is provided by the ultra-wideband wearable printed antenna.

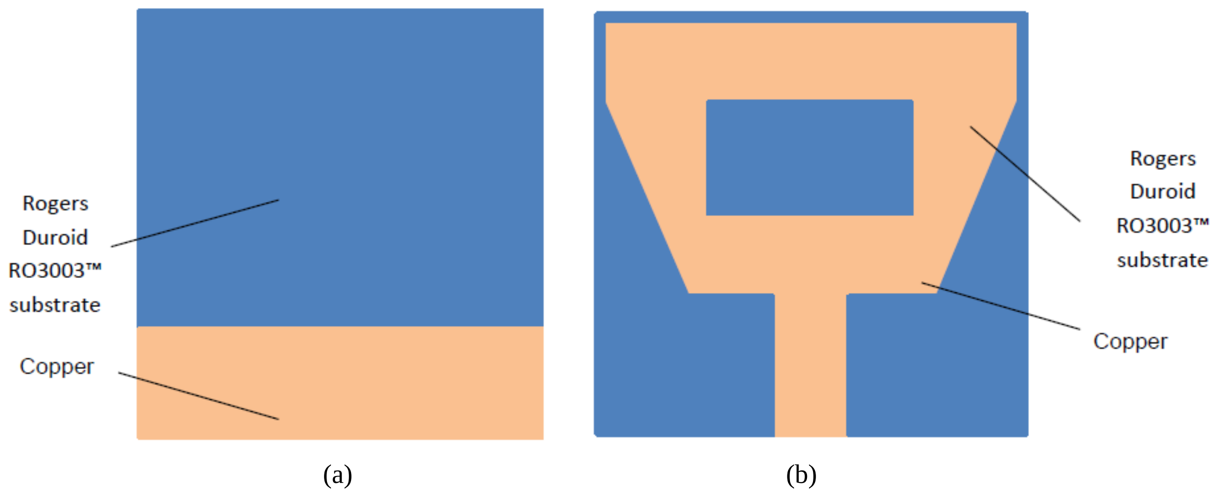

FIGURE 5. Semi-flexible wearable antenna (a) bottom view, (a) top view [23].

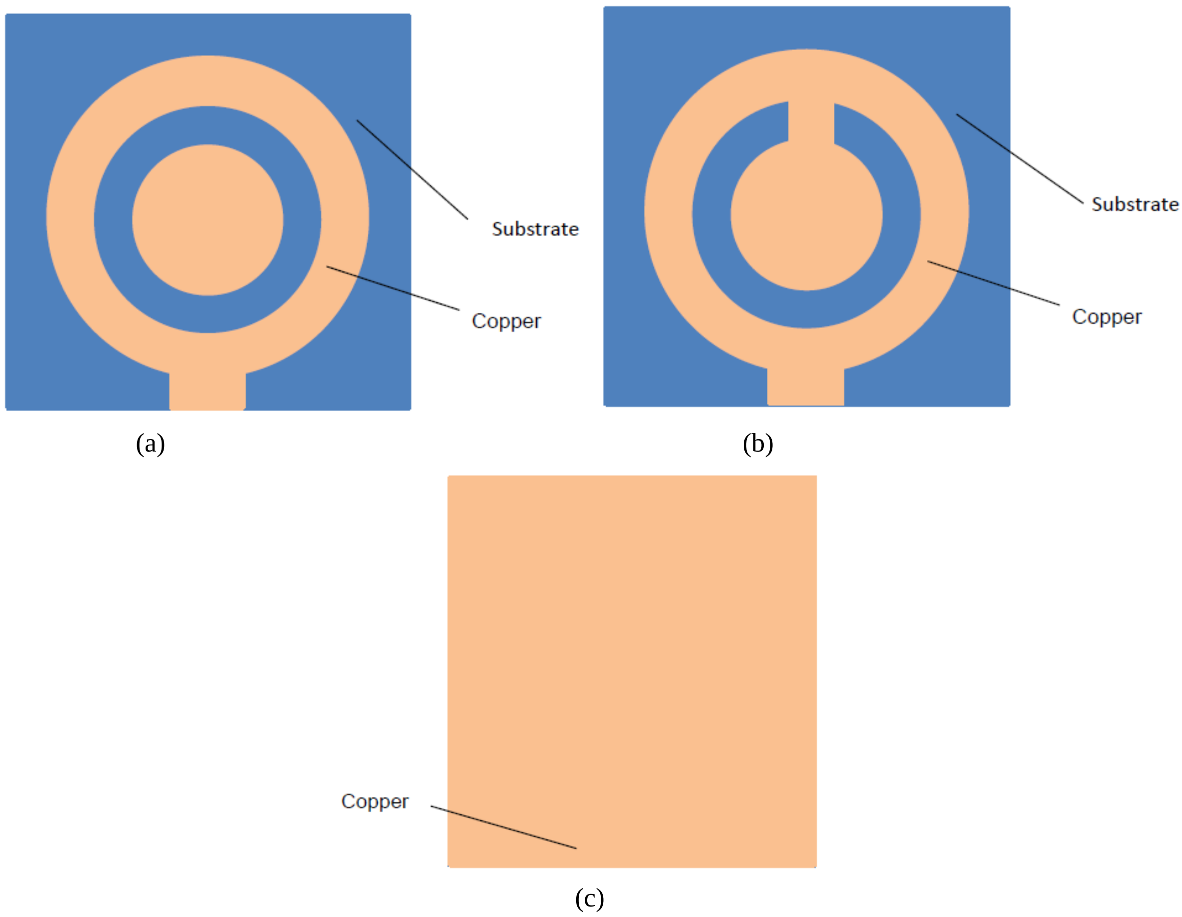

FIGURE 6. Reconfigurable wearable printed antenna (a) front view (OFF state), (b) front view (ON state), (c) back view [24].

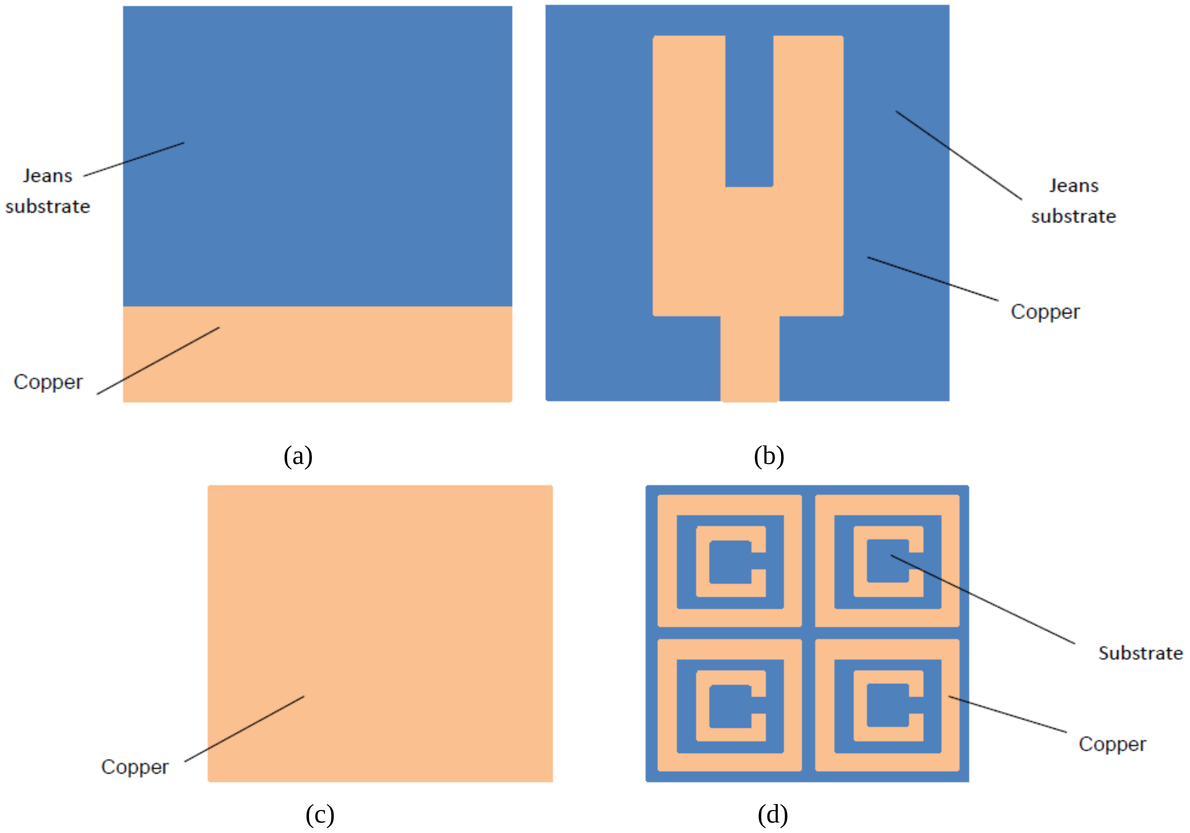

FIGURE 7. Metamaterial based wearable printed antenna (a) back view of patch antenna, (b) front view of patch antenna, (c) back view of metamaterial structure, (d) front view of metamaterial structure [25].

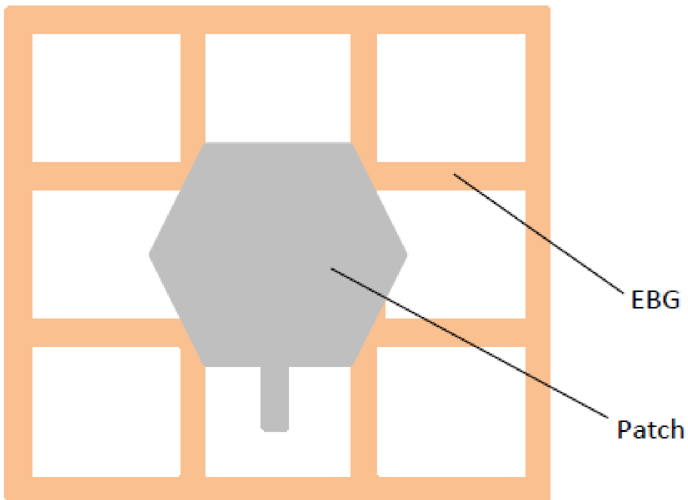

FIGURE 8. EBG based hexagonal wearable printed antenna [31].

TABLE 3. Comparison of various wearable printed antennas for medical applications.

Reference	Dielectric constant of substrate	Size	Bandwidth	Gain, directivity	Applications
[22]	1.7	60×60 mm^2	Approx. 2.5-20 GHz	Gain= 6.365 dB (at 19.48 GHz)	UWB medical applications

[30]	1.6	38 × 36 mm^2	Approx. 2.4-2.5 GHz	Gain=1.24 dB (at 2.45 GHz), Directivity=2.22 dBi (at 2.45 GHz	2.45 GHz ISM band applications
[23]	3	28 × 24 mm^2	Approx.. 2.1-2.9 GHz	--	2.45 GHz industrial, scientific and medical applications.
[24]	1.28	11 × 11 mm^2	2.38-2.52 GHz (switch ON state), 5-5.5 GHz (switch OFF state)	9.18 dB (5.5 GHz, E-plane, OFF mode), 7.51 dB (2.5 GHz, E-plane, ON mode)	Reconfigurable medical applications
[25]	1.68	60 × 60 mm^2	14.5%	7.5 dBi	2.4 GHz medical applications
[31]	1.38	116 × 116 mm^2	89.5 MHz (resonant frequency= 2.45 GHz)	6.55 dBi	2.4 GHz medical applications
[32]	3	6.8 × 6.8 mm^2	488 MHz (center frequency=24.25 GHz)	5.44 dBi	24 GHz biomedical applications
[33]	2.9	30 × 56.5 mm^2	2.4-11.3 GHz (notch band from 3.1 GHz to 4.3 GHz)	5.35 dB	WBAN MIMO applications
[34]	1.7	46 × 46 mm^2	approx. 2.35-2.45 GHz (center frequency=2.4 GHz)	7.2 dBi	Wearable medical devices

4. DESIGN CHALLENGES AND POSSIBLE SOLUTIONS

In wearable printed antennas, the metallic patch is printed on a flexible substrate to make it suitable for on-body applications. The behavior of the input and radiation characteristics of the printed antennas is different in different mounting positions on the human body. The parameters of the wearable antennas should be analysed in all possible mounting positions of the antenna. A detailed analysis of some antennas on different on-body positions is given by Alomainy et al in [35]. The effect of the distance of the antenna from the human body is also analysed. When the antenna is placed on the left side of the chest at different distances from the human body, it is observed the free-space resonance detunes when the antenna is placed closer to the human body. The detuning of free space resonance is due to a change in the effective length of the antenna and this change in antenna effective length is due to the presence of the human lossy tissues of different dielectric constant [35]. The gain and efficiency of some antennas for various on-body positions and different distances (1 mm/4 mm/8 mm) from the body are given in Table 4 [35].

TABLE 4. Gain and efficiency of antennas for various on-body positions and different distances (1 mm/4 mm/8 mm) from the body [35].

Antenna type	**Gain/ efficiency**	**Antenna position**				
		Right chest	Left chest (distance from	Left ear (distance	Left waist (distance	Right thigh (distance from

		(distance from the body=1 mm/4 mm/8 mm)	the body=1 mm/4 mm/8 mm)	from the body=1 mm/4 mm/8 mm)	from the body=1 mm/4 mm/8 mm)	the body=1 mm/4 mm/8 mm)
Printed dipole antenna	Gain (dBi)	2.6/3.1/3.6	0.9/1.6/2.4	1.0/2.1/3.2	-/2.2/-	-/2.9/-
	Efficiency (%)	39/47/48	28/33/38	27/33/43	-/26/-	-/44/-
Printed monopole antenna	Gain (dBi)	4.0/4.5/5.0	3.5/4.0/4.5	2.5/3.5/4.4	-/5.2/-	-/4.5/-
	Efficiency (%)	49/53/59	45/51/58	32/39/49	-/56/-	-/48/-
Circular loop antenna	Gain (dBi)	2.0/2.6/3.0	1.4/-/3.0	1.7/2.3/3.3	-/5.3/-	-/3.7/-
	Efficiency (%)	30/34/38	25/-/35	26/30/36	-/49/-	-/39/-
Inverted L antenna	Gain (dBi)	3.2/3.4/3.8	3.4/3.5/3.9	0.8/2.4/3.4	-/4.0/-	-/4.3/-
	Efficiency (%)	44/46/50	35/39/45	23/32/41	-/43/-	-/50/-
Parasitic L antenna	Gain (dBi)	1.9/2.1/2.5	0.5/0.8/1.4	1/1.5/-	-/3.5/-	-/2.2/-
	Efficiency (%)	29/31/35	26/29/32	20/23/-	-/39/-	-/32/-

The materials of flexible substrate used in the wearable antennas are normally different types of fabrics. The fabrics are filled with the air in the gaps, which makes these fabrics very low dielectric constant materials. Further, the fabric material also absorbs the moisture very quickly that increases the dielectric constant of the material significantly as the dielectric constant of the water is much higher as compared to the fabric dielectric substrate. The change in the dielectric constant changes the characteristics of wearable printed antennas. Hence, the performance of the wearable antenna is different in different weather conditions. So, these effects should be considered and the antenna characteristics should be analysed in various conditions. The human body also has its effects on antenna characteristics. The dielectric constant of the muscle tissue decreases with an increase in frequency and the conductivity of the muscle tissue increases with increase in frequency. The different body parts affect antenna performance differently as the material characteristics of different body parts are different. The dielectric constant of skin, fat, muscle and bone at 2.45 GHz are 44, 12, 49.6, and 4.8, respectively [23].The conductivity of skin, fat, muscle, and bone at 2.45 GHz are 1.85 $(\Omega\mathrm{m})^{-1}$, 0.85 $(\Omega\mathrm{m})^{-1}$, 2.26 $(\Omega\mathrm{m})^{-1}$, and 0.21 $(\Omega\mathrm{m})^{-1}$, respectively [23]. The dielectric constant (ε_r), conductivity (σ) of different body parts and the thickness of different tissues are given in Table 5 [36]. The dielectric constant (at 44 MHz) of skin, fat, muscle, bone, and heart tissues are 116.54, 7.1176, 80.069, 18.4, and 124.85, respectively. The conductivity (at 44 MHz) of skin, fat, muscle, bone and heart tissues are 0.38954 S/m, 0.034347 S/m, 0.67297 S/m, 0.055928 S/m and 0.63689 S/m, respectively [36]. So, different body parts have different effects on antenna characteristics. Also, the different size of the body part has a different effect on the wearable antenna. Hence, human body effects on wearable antennas should be analysed and considered in the wearable printed antenna design. For long-distance applications and better system quality, the antenna should be designed with high gain. For accommodating more users and applications, the antenna should be designed with a wideband and multi-band operation.

TABLE 5. The dielectric constant, conductivity, and thickness of different body parts [36].

Body part	**Thickness of skin (mm) [$\varepsilon_r(44MHz) =$ 116.54, $\sigma(44MHz) =$**	**Thickness of fat (mm) [$\varepsilon_r(44MHz) =$ 7.1176, $\sigma(44MHz) =$**	**Thickness of muscle (mm) [$\varepsilon_r(44MHz) =$ 80.069, $\sigma(44MHz) =$**	**Thickness of bone (mm) [$\varepsilon_r(44MHz) =$ 18.4, $\sigma(44MHz) =$**	**Thicknes s of grey matter (mm)**	**Thickness of heart (mm) [$\varepsilon_r(44MHz) =$ 124.85, $\sigma(44MHz) =$**

	$\mathbf{0.38954}\ \boldsymbol{S/m}$]	$\mathbf{0.034347}\ \boldsymbol{S/m}$]	$\mathbf{0.67297}\ \boldsymbol{S/m}$]	$\mathbf{0.055928}\ \boldsymbol{S/m}$]		$\mathbf{0.63689}\ \boldsymbol{S/m}$]
Head	4	-	9.5	20.5	51	-
Chest	2	4	38	46	-	-
Abdomen	2	7	25	-	-	56
Upper arm	2	6.1	20.3	9.1	-	-
Forearm	2	4.3	14.9	6.3	-	-
Thigh	2	8.8	28.7	13	-	-
Lower lag	2	6.3	20.8	9.4	-	-

Due to the low dielectric constant of the fabrics the size of the antenna is large. The size reduction techniques such as using shorting posts between patch and ground plane, slots in patch, etc can be utilized to minutuarize the size of the antenna. The size of the antenna can be miniaturized using the high impedance surface (HIS) [37]. The thin substrate sheet of higher dielectric constant material can be used for the miniaturization of wearable printed antennas with the semi-flexible property. The behavior of the wearable antennas in on-body and off-body state is different as explained before. The antenna characteristics should be analysed in both states. The antenna with the least human-body effect should be designed. In [38], Khan and Hossain desigend a compact planar F inverted antenna for wireless wearable body sensor networks. The planar F inverted dual-band antenna is suitable for on-body and off-body applications in both bands. If the variation in the antenna parameter is out of the antenna parameter requirements, it should be designed for on-body state only. The wearable antenna shows different behavior in different on-body positions due to the different properties of different body parts. The antenna characteristics should be analysed in various possible mounting positions as discussed earlier. Variation in dielectric constant due to air in gaps of fabric and water absorption in the humid weather. Instead of fabric, substrate sheets of the substrate such as Rogers Duriod RO3003^{TM} with thin substrate sheet may be used with a semi-flexible feature. Waterproof material can also be utilized on the non-metal surface of the antenna substrate to minimize the effect of the moisture. The effect on antenna parameters due to different sizes of body parts should be analysed with the different body structures as the dielectric constant and other properties will be different for antenna for different sizes of body parts. Some flexible printed antennas provide low gain. The antenna should be designed with a high gain by utilizing various suitable techniques. In [39], Alhawari et al presented a flexible wearable UWB elliptical antenna for breast imaging and WBAN applications. The modified grain rice-shaped metamaterial unit cell is utilized and the six-unit cells are integrated with the antenna to enhance the gain of the antenna. The maximum gain of 8.85 dBi is achieved. In [40], Das et al proposed a compact high gain wearable antenna for 2.4 GHz industrial, scientific and medical applications. An omega-shaped metamaterial unit cell is utilized to increase the gain of the antenna. The gain enhancement of 3 dB is achieved. A very low specific absorption rate is achieved using metamaterial, which makes the proposed antennas suitable for biomedical application. Other gain enhancement techniques such as stacked coupling, EBG, FSS, DGS with reflector surface, etc. The use of DGS technology should be avoided as it will cause more variation in antenna parameters in on-body and off-body applications. However, DGS with a reflector surface can be used for improving the gain of the wearable antennas. The bandwidth of the conventional microstrip antennas is narrow and these antennas are not suitable for wireless systems with high capacity. The antenna should be designed with wideband and/or multi-band operation by utilizing various suitable techniques such as gap-coupling, stacked coupling, metamaterials, EBG, FSS, etc. The bandwidth of the printed antenna can be increased by manipulating the characteristic modes [41]. It is confirmed that the resonant behaviour of the characteristic modes can be modified by incorporating the inductive loading at some specific positions of the loop antenna [41]. To enhance the capacity of the wireless systems wearable MIMO antennas can be designed. In [42], Wen et al proposed a MIMO antenna for smartwatch applications. The theory of characteristic modes is utilized to achieve high isolation between the ports. The challenges and suggested possible solutions are summarized in Table 6.

TABLE 6. Challenges in wearable printed antenna design and possible solutions.

S No	Design challenges	Possible solutions
1	The larger size of the wearable antennas due to the low dielectric constant of fabrics.	The size reduction techniques such as shorting post, slots, HIS, etc can be used. The thin substrate sheet of higher dielectric constant material can be used for the miniaturization of wearable printed antennas with the semi-flexible property.
2	Different behaviour of wearable antenna in on-body and off-body state.	The antenna characteristics should be analysed in both states. If the variation in the antenna parameter is out of the antenna parameter requirements, it should be designed for on-body state only. EBG may be used to provide shielding for antenna from the body. The antenna should be mounted at a distance from the body as the effect of body on the antenna reduces upon increasing the distance between the body and the antenna.
3	Different behaviour of wearable antenna in different mounting positions.	The antenna characteristics should be analysed in various possible mounting positions.
4	Variation in dielectric constant due to air in gaps of fabric and water absorption in the humid weather.	Instead of fabric, substrate sheet of the substrate such as Rogers Duriod RO3003^{TM} with thin substrate sheet may be used with the semi-flexible feature. A waterproof material may be used on the uncovered surface of the substrate to minimize the weather effects on the dielectric constant of the substrate.
5	Different size of body parts.	The effect on antenna parameters due to different sizes of body parts should be analysed with the different body parts and structures.
6	Antenna design with high gain.	The antenna should be designed with a high gain by utilizing various suitable techniques such as stacked coupling, metamaterials, EBG, FSS, DGS with reflector surface, etc. The use of DGS technology should be avoided as it will cause more variation in antenna parameters in on-body and off-body applications. However, DGS with reflector surface can be used for improving the gain of the wearable antennas.
7	Wearable printed antenna design for wireless systems with high capacity.	The antenna should be designed with wideband and/or multi-band operation by utilizing various suitable technique(s) such as gap-coupling, stacked coupling, metamaterials, theory of characteristic modes, EBG, FSS, MIMO antennas etc. MIMO antennas using the theory of characteristic modes may be used for achieving high isolation.

5. CONCLUSION

WBAN enables the communication between the on-body devices; and the communication between on-body devices and off-body wireless devices/systems. Various frequency bands are allotted for different on-body applications. Wearable antennas are the key devices in the WBAN systems. The concept of the printed antennas along with the flexible substrate material is utilized in designing the wearable antennas. Most of the flexible substrates are fabric materials. However, thin substrate sheets can also be used as the substrate in semi-flexible wearable printed antenna design. A detailed list of substrates with dielectric constant ranging from 1.17 to 3 is given. As the thin substrate is used in the wearable antenna design, conduction losses, dielectric losses, and surface waves are negligible, which makes wearable printed antennas as good radiators. The low dielectric constant substrates give larger size of the patch. For size reduction of the wearable printed antennas, various techniques such as shorting post-loading, slot-loading, etc can be used for reducng the size of the flexible printed antennas. Various flexible printed antennas are designed for WBAN medical applications. The design of flexible antennas utililizes the printed antennas' technology with the flexible substrate. UWB wearable printed antenna on Flannel substrate gives the large bandwidth. The circular patch loaded ring reconfigurable wearable antenna provides high gain. In general, the techniques used in the microstrip patch antennas can be utilized to improve the performance of the wearable antennas. Due to the low dielectric constant of the fabric material, the design of the compact wearable antenna is a challenge. The thin substrate sheet of a higher dielctric constant can be utilized for designing the compact semi-flexible wearable printed antennas. Further, the changes in the antenna characteristics in on-body applications due to body effects need detailed analysis and design of antennas with large bandwidth as the resonant frequency of the antenna also changes due to body effects. The gain enhancement techniques and bandwidth enhancement techniques of printed antennas can be utilized to design wearable antennas with high gain and large bandwidth, respectively. The gap-coupling, stacked-coupling, FSS, EBG, metamaterials, DGS with reflector surface, etc may be used to improve the performance of the wearable printed antenna. The use of DGS technology in wearable printed antennas may cause more body effects on antenna characteristics in on-body applications.

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