Journal of Artificial Intelligence, Machine Learning and Neural Network
ISSN: 2799-1172
Vol: 03, No. 05, Aug-Sept 2023
http://journal.hmjournals.com/index.php/JAIMLNN
DOI: https://doi.org/10.55529/jaimlnn.35.14.27

Recent Advancements in Modern Antenna Design for Wearable Devices

Md. Shafikul Islam Shawan[1*], Md. Abdullah Kawser[2], Fatema Tuz Zohra[3], Sorup Kumer Das[4], Md. Hazrat Ali[5]

[1,2,3,4,5]Department of EEE, European University of Bangladesh, 2/4 Gabtoli, Mirpur, Dhaka-1216*

Email: [2]abdullah.kawser1994@gmail.com,[3]fatema@eub.edu.bd, [4]sorupantu@gmail.com, [5]ahazrat31@gmail.com
Corresponding Email: [1]shawanju147@gmail.com*

Received: 04 April 2023 **Accepted:** 20 June 2023 **Published:** 08 August 2023

***Abstract:** The rapid growth of wearable technologies within wireless body area networks (WBANs) has increased the demand for advanced wearable antennas. The human body's presence creates significant challenges for these antennas since it behaves differently as a wave propagation medium. It is necessary to prioritize specific requirements for antenna design, such as size, frequency, efficiency, wideband and multiband operation, because of body interaction and signal attenuation. The development of novel methodologies, the use of state-of-the-art fabrication methods, and the advancement of antenna designs have been the main areas of attention for researchers in this field in recent years. This research investigates contemporary advancements in wearable antennas, particularly emphasizing utilizing recent materials, fabrication processes, and new techniques. It also highlights the unique applicability of these antennas in advanced WBAN systems.*

***Keywords:** WBAN, Internet of Things, SIW, Defected Ground Structures, Electromagnetic Bandgap Structure.*

1. INTRODUCTION

In recent years, wearable technologies have seen substantial growth and adoption, influencing numerous sectors and revolutionizing the way we interact with technology. This growth creates its way for various integrated systems of many wireless devices in the near future, especially in the field of the Internet of Things (IoT) [1]. The IoT is one of the most rapidly developing technologies aiming to bring revolution and connect the world through its distributed smart infrastructure. In recent studies by Ericsson, by 2021, we will encounter an approximation of 28 billion smart devices, focusing on automation and various secured electronic systems [6].

The IoT has a widespread influence in many parts of wireless technologies where healthcare applications are particularly prominent. From smart watches and fitness trackers to augmented reality glasses and smart clothes, these products provide multiple benefits in terms of health monitoring [3]. Wearable devices are essential in successful wireless connectivity as they support continuous, uninterrupted communication with other devices in a system.

Effective antenna design for wearable devices has unique requirements to conventional design as these devices are compact, and there are not enough spaces for integrating antennas. Furthermore, the existence of the human body, which is primarily made of water, causes extra complexity and affects antenna performance. Designing antennas for such delicate applications requires special attention to other electric components' size, efficiency, power consumption, and integrability.

Wireless Body Area Networks (WBANs) have received much attention among the numerous applications of wearable technology. Because of improvements in wireless communication technologies such as Industrial Scientific Medical (ISM) and Wireless Local Area Networks (WLAN), the requirement for miniaturized planar antennas has increased due to their comprehensive bandwidth behaviour [4]. In a successful WBAN and WLAN, miniaturization is necessary, as compact antenna systems are essential to maintain high performance in such systems [5].

In recent years researchers have focused on using different materials, characterization, geometry, and various fabrication methods: inkjet, additive 3D manufacturing, electroplating, etc. Despite producing acceptable results, these approaches have yet to completely overcome all the existing difficulties [6]. In contrast to traditional antennas, wearable antennas should be tested in realistic, complex, real-world environments. The presence of the human body, the bending of body parts, the texture of clothes, humidity, and temperature should be considered while designing and testing antennas for wearable applications.

This review paper discusses the most recent advancements in wearable antenna materials, fabrication processes, designs, and advanced applications in WBAN. This article starts with an introduction, followed by Section II, where requirements for wearable antennas are discussed. Section III discusses a few of the most widely used fabrication methodologies. Section IV discusses the recent advancement in designing technologies to meet the requirements, such as miniature and single and multi-band antennas. Finally, Section V concludes and proposes future guidance.

Advancement in Materials for Wearable Antennas:

The selection of materials is one of the key parameters to look for while designing wearable antenna, as the materials need to be used in case of deformations and for different weatherconditions. In general, the antenna is built using conductive and dielectric materials. In recent years, various types of other materials, such as fabric, have also been used [7].

Conductive Materials:
In a typical scenario, the characteristic of a material consisting of high conductivity is preferred as a radiating element for flexible antennas. Nowadays, various E-textile are used to provide high flexibility, and the radiating patch can also be sewn into a clothing piece [8]. Also, Polymers are low-lossy materials with great wet stability due to their low moisture absorption rate, making them an excellent choice for wearable applications [9]. In [10], the authors have used conductive fibers to design frequency-independent antennas by embedding them in the polymer substrate. However, that is not good for stretching while deforming into other shapes. Also, the antennas that can be stretchable have not shown great performance in their radiation pattern and shows low gain as well. To make the material stretchable various doped materials like CNT [11], MXene INK [12], and fluorine rubber [13] are being used. In [14,15] the authors have used doped oxide with tin, transparent fabrics, and indium to achieve stretchability for wearable antennas.

Substrate Materials:
Substrates are essential in terms of controlling radiation characteristics. In most cases, substrates with low permittivity, and low loss tangent are preferred to increase the radiation performance. To design flexible antennas, as substrates, polymer substrates are most widely used due to their electrical and mechanical characteristics. In [16], the authors used polymer to build liquid antennas. The other most common polymer materials that are being widely used are PET, PDMS [17,18], and polyimide [19]. These substrates have gained significant attention due to their lossless flexible properties, and the thickness is also mentionable less. A novel type of polymer is presented in [20], which can be used for bonding purposes, focusing on surface uniformity, which can be easily implemented for various other applications. In Table 1 the electric properties of a few widely used conductive and substrate materials are presented:

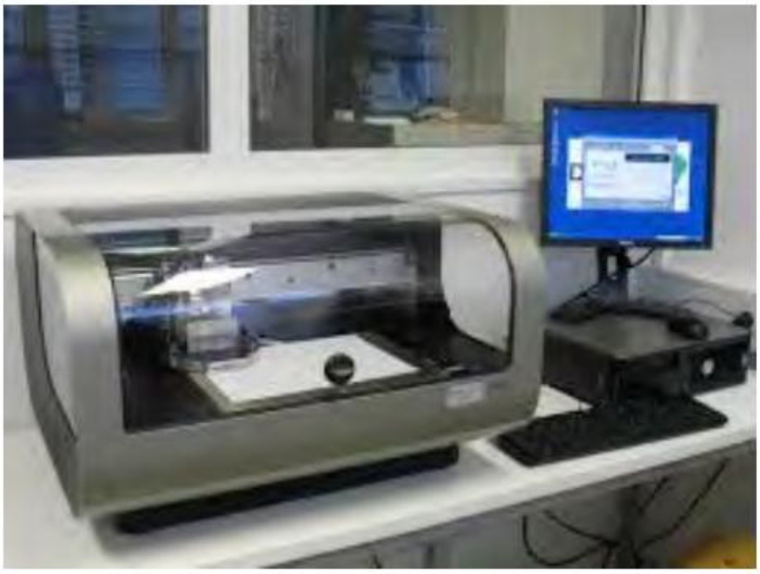
Conductive Materials [21]	Thickness (t in mm)	Conductivity (σ in S/m)	Dielectric Substrate	Dielectric Constant (ε_r)	Dielectric loss (tan δ)
Zoflex + Copper	0.175	1.93 × 10e5	PDMS-ceramic composite [22]	6.25	0.02
Graphene	100 µm	33 × 10e3	PTFE[23]	2.05	0.0017
AgNW/PDMS	0.5	8.1e5	PDMS[23]	3.2	0.01
Meshed Fabric	0.057	2e5	EVA [24]	2.8	0.002

Different Manufacturing Technologies

Inkjet Printing:

Inkjet printing is a technology that deposits small droplets of ink onto a surface using sophisticated printers, which allows accurate and controllable printing for the user. Inkjet printing has received a lot of attention lately for flexible substrates as it delivers accuracy and is less time-consuming nature to fabricate antennas [25]. In this process, conductive nanoparticle ink droplets are deposited in the substrate to form a conductive nature [26]. In [27] a multiband antenna is printed on a flexible Kapton substrate using a specialized printer. Also, the authors presented a unique patch antenna fabricated on a cotton fabric [28]. However, one of the main challenges in this process is the requirement for high post-curing temperatures, which makes the process costly [59]. There are multiple approaches have been researched to make this more cost-effective. A few of the mentionable innovative approaches to eliminate the time and cost of post-processing are instant chemically cured conductive inks [30], and water-soluble silver ink in simultaneous sintering and deposition systems [31].

Figure 1 Screen Printing [29]



Screen Printing:

Another printing method which is recently got very popular due to its cost-effectivity. This method involves pushing ink onto a substrate through a mesh screen using a bade. This technique can be adopted for different applications such as WBAN, WLAN, etc. In [32], the authors have used the screen-printing method to represent an E-shape antenna for the WiMAX application on a multi-layered fabric. It has proven to work adequately while using different clothing as substrate. In [33], the researchers successfully built a highly efficient patch antenna using composite materials. Another efficient, lightweight, breathable antenna is presented in [34] using the evlon nonwoven as a substrate using this technique. However, there are a few limitations presented in this technique, such as low resolution, and the user cannot control the thickness of the conductive layer [35].

Substrate Integrated Waveguides:
Substrate integrated waveguides (SIW) are a potential alternative to the traditional fabrication system for wearable antennas. One of the main concerns for wearable antenna systems is the interaction of the human body as media. To minimize this coupling between the antenna and the user's body, this technique employs shorting vias and a complete back conductive plane [36], restricting electric fields. There are multiple successful attempts at using this technique, such as a multiband antenna designed on a leather substrate [37]. In [38], a compact textile antenna is presented where a woolen felt is used as a substrate.

Recent Advancements in Antenna Design Technologies

Metasurface Antennas:

A metasurface is a multifaceted superstructure comprising meta-atoms usually in periodic patterns. It modifies the electromagnetic wave at the surface level by controlling polarization and phase. Meta surface-based antennas are very popular for reducing the size of the antenna. They are usually electrically and physically small and designed through a complex geometry consisting of multiple unit cells. A perfect example of a metasurface-based antenna utilizing the SIW technique is provided in [39], where the authors introduced shorting pins in a flexible substrate. Still, the radiation pattern didn't reach the expectation. In [40], the authors presented a novel approach to design a compact wearable antenna using a right-left-handed transmission line to tune the resonant nodes more effectively. A printed monopole antenna is proposed to excite the meta surface and finally two antennas are designed for wearable applications.

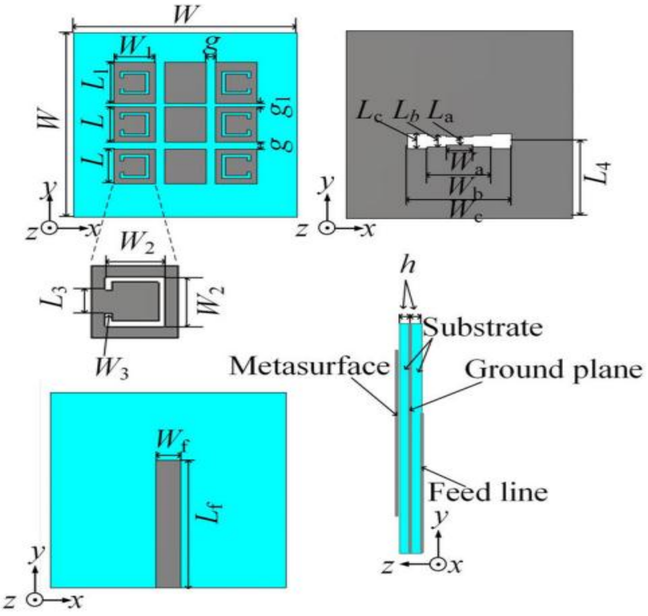


Figure 2 Configuration of metasurface antenna [41]

The first one resonating at 2.65 GHz operates at the negative mode and enables the feature of miniaturization. Also, the second antenna successfully achieves dual-band operation resonating at 2.45 and 3.65 GHz. In another work [41], the authors proposed a compact metasurface antenna resonating at 5GHz with an enhanced gain in the WLAN band.

Metamaterial:
Metamaterial represents artificial materials designed in such a way that they cannot find in nature. In this case, the unit cells are designed in a unique way to create the desired electromagnetic responses. A reconfigurable patch antenna is proposed in [42] to improve the radiation pattern by utilizing this technique. The article [43] proposed a compact dual-band metamaterial-based planar patch antenna resonating at 2.45 GHz, while a semi-flexible Rogers is used as a substrate. The circular polarization is achieved by designing a complementary split-ring resonator, showing an excellent specific absorption rate at different radius and bending conditions. A low-profile metamaterial-based ultra-wideband antenna resonating at 4.55 to 13 GHz is proposed in [44]. The researchers have successfully reduced 93% of the dimension of the proposed antenna by utilizing the metamaterial structure. The two most essential requirements for wearable antennas are miniaturization and multiband response; both can be achieved using this technique.

Electromagnetic Bandgap Structure:
Electromagnetic bandgap structure (EBG) successfully reduces the geometry of the RF structure. A circular textile antenna is presented in [45] using this EBG in a self-monitoring device. Not only for miniaturization, but this EBG structure can also manipulate surface waves and be implemented using conductive fabric and threads. In another work [46], a complemented split ring resonator is designed to miniaturize the patch antenna, though a gain reduction is visible in this case. [47] proposes a rectangular eight-shaped Electromagnetic Band Gap (EBG) structure at 5.8 GHz. The proposed antenna improves the impedance bandwidth of the antenna, reduces surface waves, and enhances the front-to-back ratio. The antenna's performance under bending and on-body conditions demonstrates the effectiveness of the EBG structure in reducing the Specific Absorption Rate (SAR) on a three-layer body model.

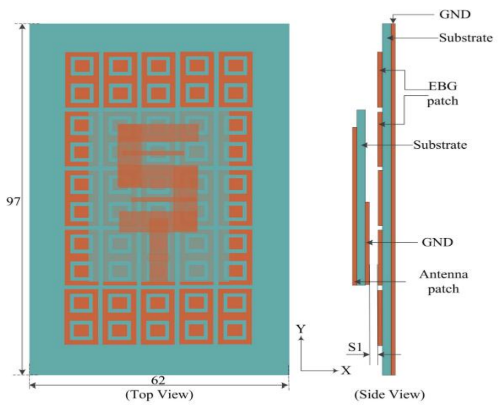


Figure 3 Monopole antenna with electromagnetic bandgap structure

Defected Ground Structure:

Defected ground structures (DGS) are the intentional slots in the ground plane to achieve the miniaturization and multiband response by controlling the surface current distribution through the slots. To develop a modern wearable mobile device, the authors in [48] adopted the DGS technique to care for the antenna's size, bandwidth, and gain. And finally, they proposed a DGS-based microstrip patch antenna resonating at 2.45 GHz on different flexible substrates like felt and Teflon. Another narrowband microstrip patch antenna with DGS is proposed in [49], with a 17.63% higher efficiency with a 7.04 dBi gain. Three U-shaped DGS unit cell is proposed in [50], to build a compact patch antenna to resonate at four different frequencies covering a good bandwidth. Due to the slot in the backplane, visible backside radiation is presented in this case, which is unsuitable for optimum gain. Another multi-band wearable monopole patch antenna is proposed in [51], which resonates at 2.12, 4.78, 5.57, and 6.11 GHz, where the maximum gain is achieved at 6.15 GHz around 10.7 dBi. Due to the slot in the ground plane, most of the DGS-based antenna has backside radiation and more side lobes, increasing the specific absorption rate out of the limit. This is not a good property for wearable devices as the target is to place the antenna close to the human body. Several improvements have been made to overcome this disadvantage in the design of the DGS-based antenna [52-54], which shows a satisfactory result to be used these antennas as wearable devices.

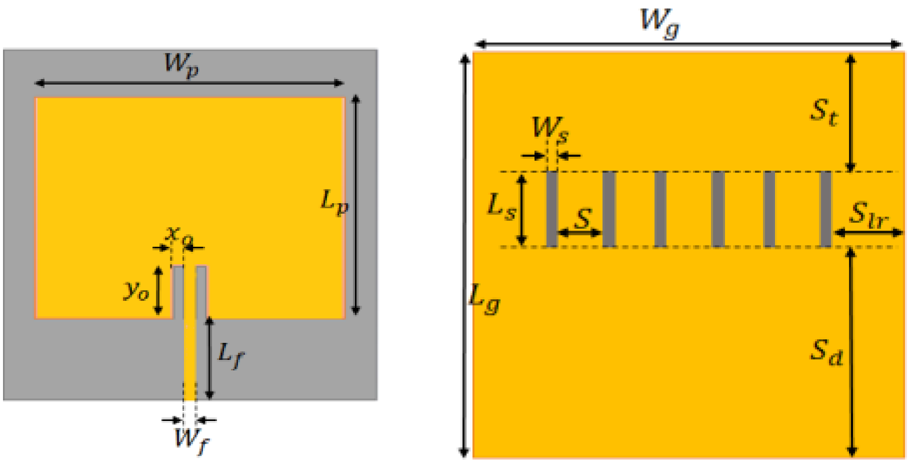


Figure 4 Patch antenna top plane and bottom plane with defected ground structure

Advanced techniques such as Artificial Intelligence, metamaterials, radio frequency energy harvesting, and reconfigurable antennas have greatly influenced future advancements in modern antenna design for wearable devices. The researchers implement these techniques to make automated antenna designs and improve antenna performance for the application of biomedical devices and health monitoring. Artificial Intelligence can design automated different antenna configurations for wearable devices. There are different algorithms, such as neural networks, and genetic algorithms, to analyze complex data sets to make the antenna design more effective for health monitoring systems such as microwave imaging, and ablation [55]. These algorithms can improve the adaptability of wearable antennas in the case of reconfigurable antennas and also for designing biomedical sensors. Table 2 presents different antenna designs with the help of AI for biomedical applications. Another technique that has recently become more popular is the meta-materials. These materials have unique electromagnetic properties to control the electromagnetic waves for next-generation antennas [43]. Another milestone for wearable devices is the reconfigurable antennas [42] that can control and optimize the characteristic of the antenna, such as polarization, and radiation. It helps to dynamically change the properties in a wearable device for different frequency bands.

Antenna design	**Technique**	**Frequency**	**Gain**	**Size in mm^3**	**Application**	**Ref**
Corrugated Vivaldi antenna (CVA)	To achieve the final design the lengths of the corrugations are independently optimized	3 GHz	5.6 to 10.4 dBi	50 × 62 × 1.52	Microwave imaging	[56]
Microstrip antenna	This wideband coplanar waveguide microstrip antenna is developed by oval shape patch and string in ground plane. The antenna is also incorporated with The antenna is also incorporated with metamaterial-based artificial magnetic conductor structure to achieve higher gain	3.1 GHz, 4.05 GHz, 6.1 GHz	20,25,32 dB respective to the resonant frequency		Breast tumor detection	[57]
Antipodal Vivaldi Antenna	Nine antipodal Vivaldi antennas are proposed and designed	2.06 GHz to 2.61 GHz	2.45 dBi	50 × 60 × 1.52	Brain stroke detection	[58]
MIMO antenna with EBG	A tutorial is intended here to offer a simple, analytical, and comprehensive step-by step manual on the development, in vitro/in vivo testing, and design of embedded antennas.	2.14-2.58 GHz	-15.18 dBi	18.5 × 18.5 × 1.27	Implementable devices	[59]
Microstrip antenna	An octagonal shaped ultra-monopole microstrip antenna is proposed here for wideband application	3 to 15 GHz		27 × 29 × 1.6	Breast cancer detection	[60]

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Bowtie Antenna	an ultra wideband (UWB) bowtie antenna and balanced-to-unbalanced (balun) is proposed	1 to 6 GHz		60 × 60 × 50	Imaging system	[61]
Bowtie Antenna	The design is developed by a bowtie element on the bottom layer and in the top layer , the bowtie elements connected to each other by meandered lines. The top and bottom layers are also connected to four vias.	0.75 to 4 GHz		18 × 18 × 0.5	Wearable brain microwave imaging systems	[62]
Monopole Antenna	A 3 X 3 array frequency selective surface (FSS) is proposed for miniaturization and wideband application. Copper square-ring and cross-dipole were combined on the top side as a unit cell of FSS.	3.8 to 10.6 GHz	3.5 dBi	30 × 31.9 × 21.6	Microwave imaging	[63]

2. CONCLUSIONS

The growth of wearable technologies in integrated wireless systems is remarkably increasing. To meet this trend, the antenna design plays a critical role by ensuring uninterrupted communication, focusing on a wide range of frequencies and wireless protocols. In terms of wearable antenna, the size, frequency, gain, and the material on which the antenna will be placed are the most crucial parameters. This paper presents an overview to understand the widely used materials for antenna design, both for conductive and substrate. Also, to fabricate this wearable device, the most common fabrication process is also mentioned. And finally, a different technique used in recent years to achieve miniaturization, muti-band operation, and satisfactory gain is being presented here. Researchers have explored materials, antenna geometry, superstructure, and multiple fabrication methods for the application of a Wireless body area network and Wireless local area network. However, further advancement is required to drive innovation and enhance the performance of antennas in wearable devices for industries and healthcare.

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