Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 38(2), ss. 411-420, Haziran 2023
Cukurova University Journal of the Faculty of Engineering, 38(2), pp. 411-420, June 2023

A Novel Frequency-Configurable Patch Antenna Design Using Flexible Substrates for Biomedical Applications

Emine AVŞAR AYDIN*[1] ORCID *0000-0002-5068-2957*
Mustafa Berkan BİÇER[2] ORCID *0000-0003-3278-6071*

[1]Adana Alparslan Türkeş Science and Technology University, Department of Aerospace Engineering, Adana, Turkey

[2]Tarsus University, Department of Electrical and Electronics Engineering, Mersin, Turkey

Geliş tarihi: 12.04.2023 Kabul tarihi: 23.06.2023

Atıf şekli/ How to cite: AVŞAR AYDIN, E., BİÇER, M.B., (2023). A Novel Frequency-Configurable Patch Antenna Design Using Flexible Substrates for Biomedical Applications. Cukurova University, Journal of the Faculty of Engineering, 38(2), 411-420.

Abstract

The purpose of this research was to design and implement a flexible horizontal H-shaped microstrip antenna (flexible-HHMA) using various materials for cancer tumor detection. Microstrip antennas, which can also be utilized as tumor detection sensors and can function as both a receiver and a transmitter, are composed of two major components: the patch and the ground plane. The copper tape was used to analyze various materials' impacts on antenna performance to form the patch and ground planes, and felt, jean, and photo paper was employed as the substrate. To accomplish this, antennas operating at frequencies ranging from 2 to 10 GHz, frequently used in biomedical applications, were constructed and computations performed using a full wave electromagnetic solver based on finite integration technique (FIT). The proposed microstrip antennas may be used as sensors in biomedical measurement systems that make use of the dielectric contrast between the healthy and malignant tissues at microwave frequencies.

Keywords: Flexible, Horizontal H-shaped microstrip antenna (HHMA), Microwave imaging, ultra-wideband, Gain, Radiation characteristic

Biyomedikal Uygulamalar için Esnek Alt Tabakalar Kullanarak Frekans-Yapılandırılabilir Yeni Bir Yama Anten Tasarımı

Öz

Bu araştırmanın amacı, kanser tümörü tespiti için çeşitli malzemeler kullanarak esnek bir yatay H-şekilli mikroşerit anten (esnek-HHMA) tasarlamak ve uygulamaktır. Tümör tespit sensörleri olarak da kullanılabilen ve hem alıcı hem de verici olarak görev yapabilen mikroşerit antenler yama ve toprak düzlemi olmak üzere iki ana bileşenden oluşmaktadır. Yama ve toprak düzlemlerini oluşturmak için çeşitli malzemelerin anten performansı üzerindeki etkilerini analiz etmek için bakır bant kullanılırken diğer tarafdan alt tabaka olarak keçe, kot pantolon parçası ve fotoğraf kağıdı kullanıldı. Bunu başarmak için, biyomedikal uygulamalarda sıklıkla kullanılan 2 ila 10 GHz frekans aralığında çalışan antenler dizayn

*Sorumlu yazar (Corresponding Author): Emine AVŞAR AYDIN, *eaydin@atu.edu.tr*

edildi ve sonlu entegrasyon tekniğine (FIT) dayalı bir tam dalga elektromanyetik çözücü kullanılarak hesaplamalar yapıldı. Önerilen mikroşerit antenler, mikrodalga frekanslarında sağlıklı ve kötü huylu dokular arasındaki dielektrik kontrasttan yararlanan biyomedikal ölçüm sistemlerinde sensörler olarak kullanılabilecektir.

Anahtar Kelimeler: Esnek, Yatay H-şekilli mikroşerit anten (HHMA), Mikrodalga görüntüleme, Ultra geniş bant, Kazanç, Radyasyon özelliği

1. INTRODUCTION

Cancer is one of the most prevalent and serious illnesses worldwide [1]. Cells divide abnormally in cancer patients, forming malignant tumors, which also cause damage to healthy tissues, particularly in the region where they are located. In other words, cancer cells continue to cause damage to other vital organs and tissues in the body once they reach them, impairing their function and survival. The common types of cancer vary between men and women. Men are most likely to develop prostate and lung cancer, whereas women are more likely to develop breast and uterine cancer [2]. Due to the severity of cancer, emerging medical technologies are critical for early detection and treatment. Apart from these advancements, the most crucial problem is the early detection of cancer. The stage of the disease is determined by the size of the tumor and its metastasis to other areas of the body. Breast cancer, which is reasonably straightforward to identify, has four stages and responds quite well to early-stage treatments. Additionally, it has been scientifically established that diagnosing cancer in its early stages and commencing therapy has a very high success rate across all cancer types. As a result, numerous researchers have studied the difficulty of detecting microscopic tumors in their early stages. Medical imaging technologies are critical for tumor identification, and the need for these devices continues to grow. The most fundamental criteria are the ability to precisely and successfully detect very small and cancerous cells and obtain high-resolution images at a reasonable cost and in the absence of a distracting environment. Currently, numerous modalities of breast imaging are available [3]. X-ray mammography is the most frequently employed imaging technique, which uses X-rays to image the breast. However, X-ray mammography does not provide the significant points preferred in imaging techniques due to its disadvantages, which include using an ionized beam and compressing the breast during measurement. Magnetic resonance imaging (MRI) is a non-invasive superior alternative to X-ray mammography since it allows for breast imaging without hazardous X-rays. However, this technique is not suggested because it may result in misleading detection for dense breasts, requires an extensive imaging time for the patient, and is quite expensive. Another alternative is ultrasonography, a non-invasive imaging technique that utilizes sound waves. The absence of fixation in extremely fatty breast tissues, on the other hand, represents a significant disadvantage. Along with these three frequently used imaging techniques, there are a variety of others, including digital tomosynthesis, magnetic resonance spectroscopy, thermography, optical imaging, electrical impedance tomography, diffuse optical tomography, and microwave imaging (MWI). Each technique offers several advantages and disadvantages. As a result, researchers have concentrated their efforts on imaging technologies that will achieve widespread success. Many researchers carry out research on microwave detection of breast cancer in order to meet the needs of breast cancer imaging technologies [3,4]. Antennas that operate as both receivers and transmitters are essential in MWI and must exhibit specific characteristics. The characteristics of the antennas used in MWI systems should be carefully studied, as should the operating frequency selection for the frequency range to be imaged. The aim of utilizing a wider bandwidth is to collect data for each frequency, which will result in a high-quality image. Another significant point to consider is the antenna's 'back beam-to-front beam' power level ratio, as well as the beam's half-power beamwidth. It is well known that antennas designed with all of these stated factors have a higher gain. Effective antennas also provide high levels of directivity. Antennas that operate efficiently also provide high levels of directivity. Additionally, they must be stable outside of their directionality, which means that the primary lobes of the radiation beams must be focused in near directions throughout the operating frequency range. All of these desired characteristics make it simple to utilize antennas in imaging systems, and good scattering data is another desired characteristic. Thus, antennas employed in the diagnosis of breast cancer using microwave imaging systems must have a wider frequency range, a high and steady directionality, a high gain and efficiency, and a compact structure [3-5].

Along with the high hardware requirements for design and optimization procedures, which is one of the primary constraints to realizing highly efficient and sophisticated system designs today, production costs are crucial. Manufacturing prototypes of high-speed, high-precision and low-cost microwave circuits is a challenging task in microwave engineering. Three-dimensional (3D) printing technology is one of the recent advancements for rapid, high-precision, and low-cost initial production. 3D printing technology provides the manufacturing of three-dimensional models by layering plastic or metallic materials and producing layers according to the requirements. Fused Deposition Modeling (FDM) is one of the most extensively utilized processes in 3D printer technology. The initial model produced with this technique is constructed from melted thermoplastic materials such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Models developed using this technology typically have strong mechanical structures in addition to excellent heat and chemical resistance. In recent years, 3D printing technology has gained widespread adoption in a variety of scientific fields, including architecture, mechanical engineering, biomedical engineering, and aerospace engineering [6-8]. Microwave engineering is one of the fields that utilize 3D printing technology. 3D printing technology can be used to manufacture a variety of designs, including waveguides, integrated dielectric waveguides (DBD), slotted array antennas, frequency selective surfaces, dielectric lenses, and KU band horn antennas, where conventional manufacturing methods are difficult or impractical for laboratory production under certain conditions [9,10]. Implantable, ingestible, and flexible antennas are the three types of antennas utilized in biomedical applications [11]. Implant antennas are permanently implanted into the body and transmit data for the diagnosis of microwave imaging, cardiac rhythm abnormalities, and cancer diagnosis and therapy. Ingestible antennas can be used to identify colon cancer by transmitting specified parameters (e.g., heat) throughout the body. Additionally, recently discovered flexible antennas can be placed on the human skin to transmit blood oxygen and glucose levels, and heart rhythm [12].

This study it is aimed to make the manufacturing of the proposed antenna both easy and cost-effective by utilizing substrate materials with flexible characteristics. Numerous substrate materials, such as paper, fabric, graphene, or jean, have been employed in studies involving flexible structures. While the copper tape was used to design the antennas suited for operating in the ultra-wideband frequency range in this study, substrate materials such as felt with a dielectric constant of 1.3, photographic paper with a dielectric constant of 2.85, and jean with a dielectric constant of 1.76 were used. The antennas that were found to be successful based on the simulation results were manufactured, and it was observed that the fabricated antennas were compatible with the simulation results.

The utilization of flexible materials such as denim, felt, and photographic paper as substrates in antennas can have notable effects on their performance. Here's an explanation of how these materials can impact antenna performance:

1. Dielectric Properties: The dielectric properties of the substrate material influence the propagation of electromagnetic waves within the antenna structure. Each fabric material has its own dielectric constant, which affects the impedance matching and radiation characteristics of the antenna. Therefore, the choice of fabric substrate can significantly alter the antenna's performance.
2. Loss Tangent: The loss tangent of a material determines its ability to dissipate energy in the

form of heat. Higher loss tangent values in fabric substrates can result in increased signal losses and reduced antenna efficiency. Lower loss tangent values are preferable for achieving optimal antenna performance.

3. Flexibility and Deformation: Fabric materials possess inherent flexibility, enabling antennas to conform to irregular or curved surfaces. This flexibility is advantageous for designing conformal antennas that can be integrated into various structures or devices. However, excessive deformation or stretching of the fabric substrate can introduce mechanical stress, altering the electrical properties of the antenna and potentially affecting its performance.
4. Mechanical Strength: The mechanical strength of fabric substrates is crucial in maintaining the structural integrity of the antenna. Durable and robust fabric materials ensure that the antenna can withstand environmental factors such as vibrations, impacts, or bending without compromising its functionality.
5. Fabric Thickness: The thickness of the fabric substrate can impact the overall dimensions and electrical characteristics of the antenna. Thicker fabrics may result in larger antennas, which can affect resonance frequencies and impedance matching. Balancing the desired antenna performance with the thickness and weight constraints of the fabric substrate is essential.
6. Conductivity: Fabric materials are generally not conductive like traditional metal substrates. However, certain fabrics may have conductive properties due to metallic coatings or embedded conductive elements. The conductivity of the fabric substrate directly influences the antenna's radiation efficiency and impedance.

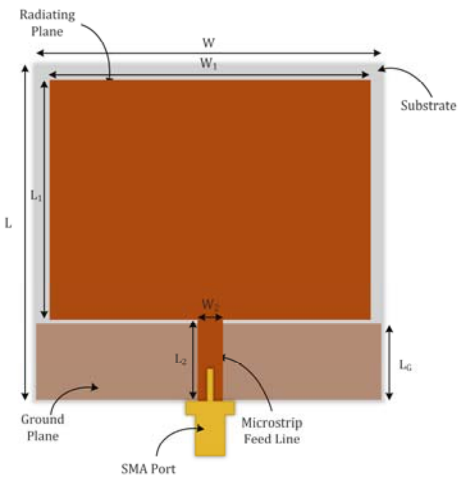
Considering these factors is vital when using fabric materials as substrates, as they can significantly influence antenna performance. Conducting thorough experimental characterization and analysis of the fabric substrate's electrical properties and their impact on antenna performance would provide valuable insights for optimizing the design and implementation of fabric-based antennas.

In summary, both denims, felt, and photo paper, which are frequently preferred substrates in the literature in terms of both textiles and flexible materials, were selected and focused on for the study. Then, a new antenna design in an H-shape was implemented for the radiating part. While different substrates generally had a positive impact on antenna performance, it was observed that they also had differences in terms of dielectric values, which led to variations in antenna return losses and resonance frequencies. Compared to previous studies, our proposed different antenna design allows for operation in wider frequency ranges and offers advantages in terms of providing options based on the desired frequency band or the significance of the material in the intended application, considering the exhibited different resonances.

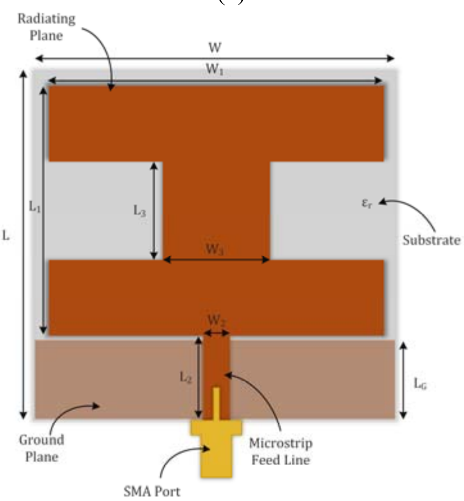
2. ANTENNA DESIGN AND MANUFACTURING

It is crucial to choose the appropriate substrate and conducting materials for the microstrip antenna design. Along with the features of the materials that compose the antenna, the physical and electrical properties of the antenna control its performance. Surface wave formation within the antenna is an undesirable circumstance in antenna design. As a result, flexible materials with a low dielectric constant are interesting alternatives for minimizing surface wave losses. Additionally, antennas used in biological applications, such as implant antennas, must be biocompatible. Another critical factor to consider is the shape and biological structure of the surface on which the antennas will interface with the human body, as this could affect the performance of the antenna. Low dielectric materials are essential to increasing bandwidth and antenna flexibility.

Microstrip patch antennas are formed by aligning the radiating plane with the desired geometry on the dielectric substrate. On the opposite surface of the dielectric substrate, a ground plane is located in the dimensions required for the antenna to perform efficiently. In this study, the antenna design procedure began with the use of a microstrip line-fed monopole microstrip antenna with a rectangular radiating plane, as seen in Figure 1. Due to their flexibility and low dielectric characteristics, felt with a thickness of 1.1 mm, photo paper with a thickness of 0.254 mm, and jeans with a thickness of 0.254 mm are chosen as substrates. Following that, rectangular slots are opened from the right and left edges of the radiating plane of the rectangular microstrip antenna to form a horizontal H-shaped radiation plane. Figure 1 (a) and (b) illustrate conventional rectangular microstrip antenna and proposed horizontal H-shaped microstrip antenna (HHMA) designs.



(a)



(b)

Figure 1. The (a) RMA and (b) proposed HHMA

Table 1. Dimensions of the antennas

Parameters	Dimensions
L	70 mm
L_1	30 mm
L_2	20 mm
L_3	10 mm
W	45 mm
W_1	35 mm
W_2	2.98 mm
W_3	6 mm

The rectangular microstrip antennas illustrated in Figure 1 (a) have their resonant frequencies computed using Equation (1).

$$f_r = \frac{c}{2(L+2\Delta L)\sqrt{\varepsilon_{eff}}} \quad (1)$$

In Equation (1), the parameters f_r, c, L, ΔL, and ε_{eff} denote the resonant frequency, the speed of the electromagnetic wave in free space, the length of the patch, the electrical extension of the patch, and the effective dielectric constant of the substrate, respectively. From this point of view, Equations (2) and (3) are used to compute the W_1 width and L_1 length to obtain effective radiation at the resonant frequency f_r.

$$W_1 = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (2)$$

$$L_1 = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta L \quad (3)$$

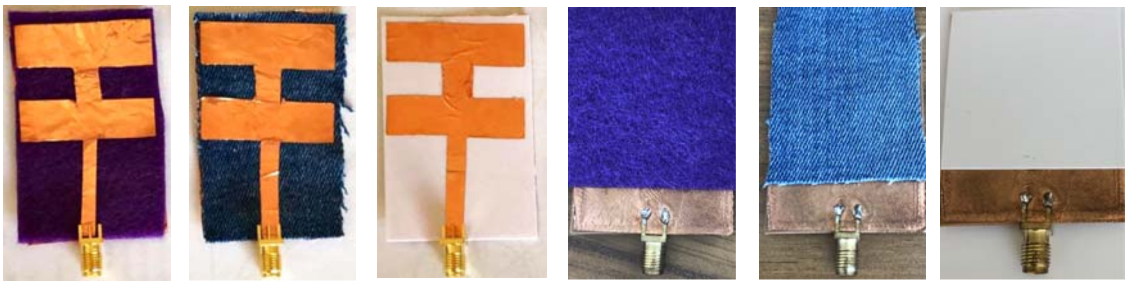
Additionally, Equations (4) and (5) define the electrical extension ΔL, and the effective dielectric constant ε_{eff} stated in Equation (1).

$$\Delta L = (0.412)\cdot h \cdot \frac{(\varepsilon_{eff}+0.3)\left(0.264+\frac{W_1}{h}\right)}{(\varepsilon_{eff}-0.258)\left(0.8+\frac{W_1}{h}\right)} \quad (4)$$

$$\varepsilon_{eff} = \frac{\varepsilon_1+1}{2} + \left(\frac{\varepsilon_1-1}{2}\right)\left(1+12\frac{h}{W_1}\right)^{-\frac{1}{2}} \quad (5)$$

Equation (1)-(5) is used to determine the initial dimensions of the antenna design in Figure 1 (a). Following that, as illustrated in Figure 1 (b), two distinct slots were opened. Due to the fact that the loaded slots modify the resonant length of the antenna, the resonant frequency of the proposed antenna cannot be computed using Equation (1)-(5). To optimize the performance of the proposed antenna design, simulations with various antenna dimensions were carried out by using CST Microwave Studio. The proposed antenna was built using a rectangular patch with dimensions $L_1 \times W_1$ on a substrate with dimensions L×W. The ground plane of the antennas is sized $L_G \times W$. The dimensions of the microstrip feed line were determined to be $L_2 \times W_2$, and the antennas were fed via an SMA connector. The proposed antenna was formed by opening two rectangular patches with dimensions of $L_3 \times \left(\frac{W\text{-}W_3}{2} \right)$ on the radiating patch. Table 1 contains the parameters and values utilized in the design of the antennas.

To analyze the performance of the simulated antennas, three different substrates were used to manufacture the proposed antennas. Figure 2 illustrates antennas manufactured using felt, jean, and photo paper substrates.



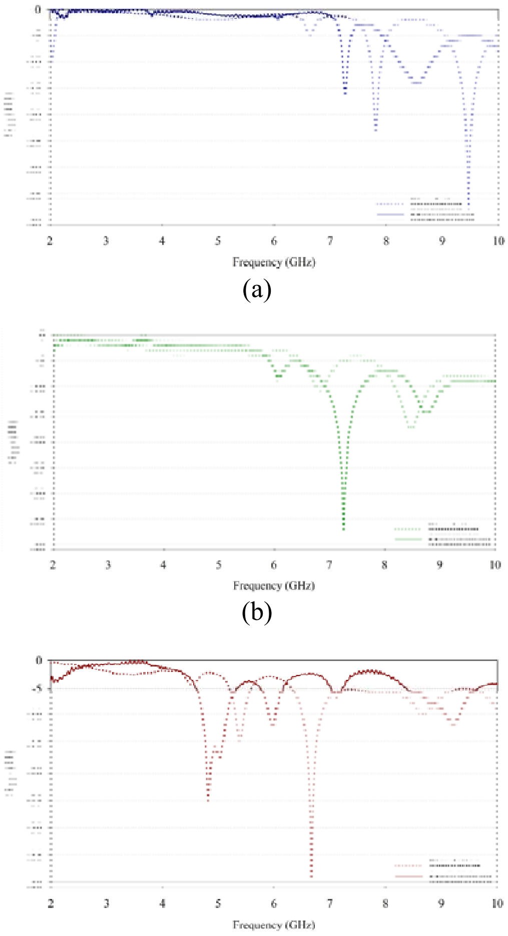
(a) (b) (c) (d) (e) (f)

Figure 2. The proposed antennas are based on (a) felt, (b) jean, and (c) photo paper substrates and in (d), (e), and (f), the ground and soldered photos of the respective substrates, felt, denim, and photo paper are as follows.

The antennas were designed, simulated, and manufactured using felt jeans and photo paper substrates. The substrates used had dielectric values ranging from 1.3 to 2.85. The copper tape was used to form the microstrip feeding line, ground plane, and radiating plane of the antennas due to its flexibility and suitability. Due to the fact that microstrip line feeding is preferred in antenna manufacturing, SMA connectors are utilized. The S_{11} values of the manufactured antennas were measured using a PNA-L vector network analyzer over the frequency range of 2 GHz to 10 GHz.

3. NUMERICAL RESULTS AND DISCUSSIONS

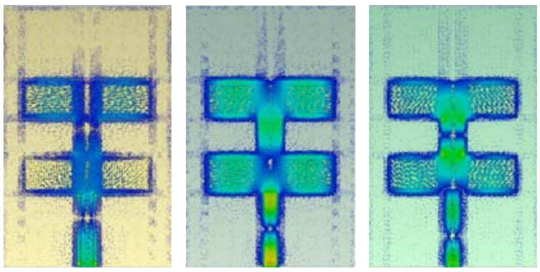
The primary objective of this study is to develop a microstrip antenna capable of operating in the ultra-wideband (UWB). There are numerous approaches for obtaining UWB antennas, including using high dielectric materials, increasing the antenna substrate height, and adding circuit components. This study aims to present a new antenna design suitable for biomedical applications by forming slots in a conventional microstrip antenna patch. The substrate material selection greatly aids impedance matching, and the proposed antenna design should achieve impedance matching. To ensure compatibility with biomedical applications, the proposed antennas were manufactured utilizing materials that are safe for humans, flexible, and have been shown to be the most preferred in literature studies. As seen in Figure 2, the proposed antenna was fabricated utilizing felt, jean, and photo paper materials. The S_{11} performance of the fabricated antennas was measured using a PNA-L microwave network analyzer and is shown in Figure 3. As can be seen from Equation (1), as the dielectric constant increases, the antenna's frequency characteristic shifts to the lower frequency region. The dielectric constant differences cause significant changes in S_{11} over the 2 GHz and 10 GHz frequency bands and -10 dB bandwidth, respectively. Additionally, due to its low dielectric constant, the felt substrate has the highest resonant frequencies of the three substrates.



(a) (b) (c)

Figure 3. The simulated and measured S11 curves of the (a) felt-based, (b) jean-based, and (c) photopaper-based HHMAs

Reducing dielectric constants minimize surface wave loss, hence increasing the impedance bandwidth of the material. Additionally, Figure 3 illustrates the effect of various dielectric constants on antenna performance. Numerous factors such as modifications to the conductive patch of the antenna, inaccuracies in the dimensions of the substrate and conducting planes, inhomogeneity of the dielectric constant across the material due to fabrication and soldering of the feeding all contribute to the discrepancy between simulation and measurements. While the dimensions of the slots in the copper patch are tuned for antenna designs that work well in ultra-wideband, numerous situations involving various substrate applications are considered in this study. The microstrip feeding line with a width of 2.98 mm appears to provide the best impedance matching and radiation characteristics stability. The antennas performed well in terms of S_{11} and bandwidth with all substrate materials. However, the felt substrate outperforms the other two substrates in terms of radiation performance, as the low dielectric constant material minimizes surface wave loss, increasing impedance bandwidth. Their primary benefits are these three antennas' performance, flexibility, low cost, and ease of fabrication. Figure 4 illustrates the surface currents of the proposed antennas utilizing felt, jean, and photo paper substrates at 7 GHz.



(a) (b) (c)

Figure 4. Simulated surface currents of the (a) felt-based, (b) jean-based, and (c) photopaper-based HHMAs for 7 GHz

While all three antennas have a reasonable gain, the felt-based antenna has the highest gain. Typically, the gain of microstrip antennas is fairly low due to their small size. However, the gain of the proposed antennas is quite remarkable. The polarity variation of gain is critical when analyzing antennas. By observing this change, it is possible to clearly identify how the gain changes with the 3dB-aperture of the antennas. The two-dimensional variation of the pattern provides information on the angles at which the transmitting signal is concentrated, the directionality of the antenna, and the optimal location of the receiving antenna. The three-dimensional radiation patterns of the proposed antennas are illustrated in Figure 5.

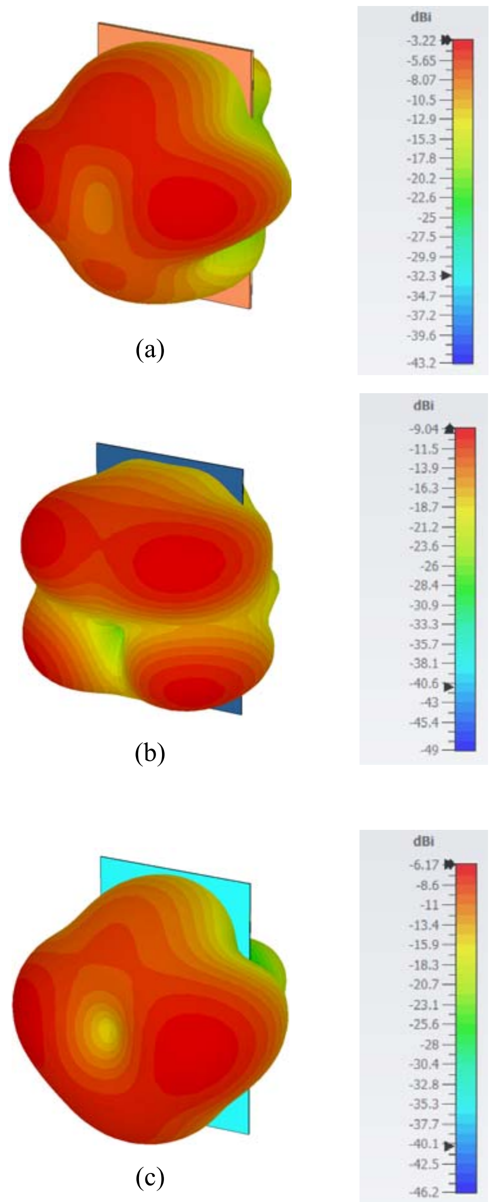


Figure 5. Simulated 3D radiation patterns of the (a) felt-based, (b) jean-based, and (c) photopaper-based HHMAs for 7 GHz

As illustrated in Figure 5, the antennas have remarkable directivity, and the power is distributed almost uniformly. As a result, a new flexible antenna design for biomedical applications is proposed, which increases the bandwidth by opening slots in the radiating plane. Comparative analyses of reflection coefficients, gain, and directivity was performed, and the measured reflection coefficients were found to be consistent with the simulated results. In Table 2, the proposed antennas in this study are compared to those in previous studies, and it is clear that the manufactured antennas perform remarkably well.

4. CONCLUSION

This study proposes a flexible HHMA that may be utilized as both a transmitter and a receiver in microwave imaging systems for the detection of malignancies in organs such as the lung, brain, liver, kidney, and most especially the breast. It was designed and simulated in a full-wave electromagnetic solver prior to getting manufactured as a flexible antenna. To make the antenna flexible, its substrate was made of felt, jean, and photographic paper. A PNA-L microwave network analyzer was used to perform experimental measurements on the fabricated antennas. As a result, the proposed antenna can effectively be used to monitor patients that are at a high risk of developing cancer.

Flexible substrates are important for antennas due to several reasons. Firstly, flexible substrates allow for the design and implementation of conformal antennas. Conformal antennas can be easily molded or shaped to fit irregular or curved surfaces, such as the exteriors of vehicles or aircraft. This flexibility in form factor enables better integration of antennas into various devices and structures. Secondly, flexible substrates offer mechanical robustness and durability. They can withstand vibrations, impacts, and deformations without compromising the performance of the antenna. This is particularly crucial for applications where antennas may be subjected to harsh environmental conditions or physical stresses. Moreover, flexible substrates enable miniaturization and lightweight antenna designs. By utilizing thin and flexible materials, the overall size and weight of antennas can be significantly reduced. This is especially beneficial in portable or wearable devices where space and weight constraints are critical.

From a future research perspective, there are several areas that can be explored. One direction is the development of novel materials with enhanced flexibility and electrical properties. Researchers can investigate new polymers, composites, or hybrid materials that offer improved flexibility while maintaining high conductivity and low signal losses. Another research area could focus on the optimization of flexible antenna designs for specific applications. Different antenna types, such as patch antennas, helical antennas, or flexible dipole antennas, can be further studied and tailored to meet the unique requirements of diverse wireless communication systems or IoT devices. Additionally, exploring advanced fabrication techniques, such as additive manufacturing or flexible electronics printing, can contribute to the development of cost-effective and scalable manufacturing processes for flexible antennas. Furthermore, investigations into the impact of mechanical deformation on antenna performance, as well as the development of techniques to mitigate any adverse effects, would be valuable for ensuring reliable and consistent antenna operation in real-world scenarios. Overall, the use of flexible substrates in antennas offers numerous advantages, and future research can focus on material improvements, optimized designs, advanced fabrication methods, and performance analysis to further enhance the capabilities and applications of flexible antennas.

Table 2. A comparison of previous designs with the proposed antennas [13]

Antenna type	Size (in mm) and application	Bandwidth	Conductive material (S/m)	Substrate material
Microstrip patch antenna	65×46×0.127 ISM band application	N/A	Flexible Copper tape	Kapton Polymide
Microstrip-based koch fractal	39×39×0.508, WBAN applications	2.36-2.55	Cu	Vinyl Polymer based substrate
Microstrip patch	60×60×0.110, C-band and future organic electronics applications	4.43-4.76	PANI/MWCNTs	Rogers RT/Duroid 5870
Multilayer microstrip fractal patch antenna	22×31×0.125, On-package, and on-chip printed antennas	4.79-5.04	Ag NP	Kapton Polymide
Microstrip patch antenna	40×35×0.6, Intrabody telemedicine systems in the 2.4 GHz ISM bands	2.33-2.53	Cu strips	Photopaper
Z-shaped microstrip patch antenna	45×36×0.135, dual-band Wi-Fi and Flexible devices	N/A	Ag NP	PET
This work (Antenna 1)	35×35×1, UWB tumor detection systems	2.0-10.0	Flexible Copper Tape	Felt
This work (Antenna 2)	35×35×1 UWB tumor detection systems	2.0-10.0	Flexible Copper Tape	Jean
This work (Antenna 3)	35×35×1, UWB tumor detection systems	2.0-10.0	Flexible Copper Tape	Photographic

5. REFERENCES

1. Sung, H., Ferlay, J., Siegel, R.L., Laversanne, M., Soerjomataram, I., Jemal, A., Bray, F., 2021. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. CA: A Cancer Journal for Clinicians, 71(209-49).

2. WCRF International, Cancer Trends - Statistics per Cancer Type, https://www.wcrf.org/diet-and-cancer/cancer-trends/, Access date: June, 2021.

3. Aldhaeebi, M.A., Alzoubi, K., Almoneef, T.S., Bamatra, S.M., Attia, H., Ramahi, O.M., 2020. Review of Microwaves Techniques for Breast Cancer Detection. Sensors, 20(8), 1-38.

4. Kwon, S., Lee, S., 2016. Recent Advances in Microwave Imaging for Breast Cancer Detection. International Journal of Biomedical Imaging, 2016, Article 5054912.

5. Sergieiev, O., 2010. Requirements Analysis and Modelling of an Antenna Element for Breast Cancer Microwave Imaging. Master of Engineering Thesis, Auckland University of Technology.

6. He, Y., Liu, Y., Dyer, B.A., Boone, J.M., Liu, S., Chen, T., Zheng, F., Zhu, Y., Sun, Y., Rong, Y., Qiu, J., 2019. 3D-printed Breast Phantom for Multi-purpose and Multi-modality Imaging. Quantitative Imaging in Medicine and Surgery, 9, 63-74.

7. Butscher, A., Bohner, M., Doebelin, N., Hofmann, S., Müller, R., 2013. New Depowdering-friendly Designs for Three-dimensional Printing of Calcium Phosphate Bone Substitutes. Acta Biomaterialia, 9(11), 9149-9158.

8. Farooqui, M.F., Shamim, A., 2016. Low Cost Inkjet Printed Smart Bandage for Wireless Monitoring of Chronic Wounds. Scientific Reports, 6, 2-3.

9. Ghazali, M.I.M., Karuppuswami, S., Kaur, A., Chahal, P., 2017. 3-D Printed Air Substrates for the Design and Fabrication of RF Components. IEEE Transactions on Components, Packaging and Manufacturing Technology, 7(6), 982-989.

10. Zhang, S., Arya, R.K., Pandey, S., Vardaxoglou, Y., Whittow, W., Mittra, R., 2016. 3D-printed Planar Graded Index Lenses. IET Microwaves, Antennas and Propagation, 10(13), 1411-1419.

11. Topsakal, E., 2009. Antennas for Medical Applications: Ongoing Research and Future Challenges. Proceedings of the 2009 International Conference on Electromagnetics in Advanced Applications, 890-893.

12. Sondas, A., Ucar, M.H.B., 2013. An Implantable Microstrip Antenna Design for Biomedical Telemetry. International Conference on Electronics, Computer and Computation, 32-35.

13. Kirtania, S.G., Elger, A.W., Hasan, M.R., Wisniewska, A., Sekhar, K., Karacolak, T., Sekhar, P.K., 2020. Flexible Antennas: A Review. Micromachines, 11(9), 847.