International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(4):969-990

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i04.01536

Design and Fabrication of L and U Slot Wearable Antennas for Wireless Body Area Network Applications

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Abstract

Wearable microstrip patch antennas are compact, low-profile antennas designed for integration into wearable devices, offering wireless communication capabilities. Wireless body area networks (WBANs) are a promising technology with potential applications in a variety of biomedical fields. Patient surveillance, healthcare monitoring, and medical diagnostics are a few examples. The Specific Absorption Rate (SAR) in close proximity to the body, as well as the device's size, vulnerability to the environment, and limited bandwidth, all have an impact on its efficacy and dependability. This paper gives a thorough look at the planning, testing, and production of a wearable antenna that works at 2.4 GHz and has unique U-cut and double L-cut slots inside a patch antenna structure. The primary focus is on reducing specific absorption rate (SAR) exposure while maintaining optimal performance metrics. We rigorously analyze parameters such as SAR reduction, VSWR, return loss, radiation pattern, gain, and efficiency using the High Frequency Structural Simulator (HFSS). This SAR-aware wearable antenna design, which includes parameter analysis, addresses concerns about people being too close to electromagnetic radiation from wireless devices. We tested the fabricated antennas using a VNA testing instrument. Following the testing process, we conducted a comparison between the simulation and fabrication results. Upon comparison, we found that the antenna's software simulation and hardware testing results were identical. They both operated at 2.4 GHz and achieved a gain of 20 dB. This indicates a successful design and validation process for the fabricated antenna.

Keywords: Body Area Networks, HFSS, Specific Absorption Rate, Wearable Antennas.

Introduction

At present, there is a significant global trend towards the use of flexible and wearable devices. Activity trackers, smart watches, eyewear, helmets, and smart apparel are among the wearable devices that are acquiring popularity as they enter the market. Wearable and flexible devices' primary goal is to improve quality of life by incorporating technology into their current activities. The increasing prominence of wireless networks and other electronic devices has resulted in the widespread use of wireless body area networks. Utilization of the most recent wireless sensor networks has been advantageous for modern infrastructure, healthcare, traffic monitoring, and agriculture. This is now feasible due to the accelerated development of physiological sensors, wireless networking, and low-power integrated circuits. The potential to facilitate continuous, affordable, Internet-based health surveillance with immediate updates to medical data is a multidisciplinary subject known as body area networks. In the future, a wearable wireless body area network with sophisticated physiological sensors could prove beneficial in medical scenarios or computer-assisted patient rehabilitation. The fundamental concept that underpins this field of research is the feasibility of incorporating biosensors that are both diminutive and pleasurable, while also ensuring that they do not disrupt the body's natural processes. A promising technology with potential applications in a variety of biomedical disciplines is Wireless Body Area Networks (WBANs). These activities include medical diagnosis, healthcare monitoring,

(Received 06th July 2024; Accepted 25th October 2024; Published 30th October 2024)

and patient surveillance. These networks consist of wearable and implantable devices equipped with sensors and communication modules to collect and transmit vital physiological data wirelessly. However, the efficient operation of WBANs heavily relies on the design of compact and high-performance antennas capable of reliable communication while ensuring minimal interference with the human body. In the context of WBANs, the design of wearable antennas poses several challenges. One key issue is the assumption that electromagnetic radiation can be harmful to human health. The Specific Absorption Rate (SAR) is an important indication of biological tissues' ability to absorb electromagnetic energy. High SAR levels can lead to tissue heating and other health hazards, necessitating the development of antennas with reduced SAR while maintaining satisfactory performance. Wearable antennas must be compact, lightweight and conformable to the human body's contours to ensure comfort and unobtrusiveness. Additionally, they should exhibit robust performance characteristics, including impedance matching, radiation efficiency, and gain, to facilitate reliable communication in diverse operating environments.

To address these challenges, this paper focuses on the design and analysis of two wearable antennas operating at 2.4GHz frequency for WBAN applications. The first antenna is an inverted U-shaped design, while the second is a double L-shaped patch antenna. These designs are chosen for their potential to reduce SAR levels while simultaneously enhancing critical antenna parameters relevant to biomedical applications. The literature review's meticulous organization led to its placement in Section 2 of the report. The proposed wearable antennas are described in Section 3. In Section 4, the proposed antenna performance is presented as simulation results. In Section 5, discussion on testing the fabricated antenna using VNA is presented and concluding the paper is done in Section 6.

Associated Work

A literature survey on wearable patch antennas typically begins with an overview of the current state of wearable technology and its applications. It then delves into the specific area of wearable patch antennas, covering topics such as design considerations, materials used, fabrication techniques, and performance metrics. The survey would also include a review of existing research and advancements in wearable patch antenna technology, highlighting key findings, challenges, and future directions. In the past study researchers (1) developed a small circular fractal antenna suitable for use on the body. Specifically designed for WBAN applications, this antenna made its debut in early 2019. This paper describes a discreetly hidden tiny receiver for use in wireless body area networks (WBANs). The triangle patch antenna under consideration is based on a generally available and fairly flexible vinyl polymer substrate. The wandering apertures, Koch fractal geometry, and inadequate ground structure combine to form a novel hybrid building. The final result is an antenna setup that operates at a frequency of 2.45 GHz in the industrial, scientific, and medical frequency spectrums. This antenna design is compact, versatile, and has a wider impedance bandwidth. The numerical findings, testing results, and antenna prototype all demonstrate a high degree of agreement. We achieved a 75% total radiated efficiency, a peak gain of 2.06 dB, a decreased form factor of 0.318o × 0.318o × 0.004o, and a BW impedance of 7.75% when compared to popular samples on the market at the time. We use an actual heterogeneous voxel model to assess the particular absorption rate (SAR) efficacy of our architecture. Because of its high resistance to body weight and structural deformation, this material is an excellent choice for wearable and flexible technologies, according to numerical and experimental investigations.

In a study researchers (2) published the transparent neural implantable devices: A comprehensive review of challenges and progress. This article describes a wearable patch antenna designed for military wireless applications. The rectangular and flat antenna has two L-shaped apertures and operates at two different frequencies. The traditional embroidery technique creates stunning motifs by meticulously weaving metallic threads over a linen foundation. The antenna, measuring around 40_ed̦3, is significantly smaller than the wavelength of the resonant frequency. Use the CST programming simulator to calculate gain, directivity, and antenna efficiency. Confirm that it matches the resistance value (S11). The position of the RF connector at the antenna's reception point is critical for achieving an absolute perfect impedance match. The location and direction of a wearable antenna will influence its sensitivity point. The proposed design employing Jeans fabric (with a dielectric constant of 1.7) is being compared against the standard FR4 patch structure (with a dielectric constant of 4.4) to establish their relative importance. The antenna's primary goal is to be circularly polarised at around 3.17 GHz and linearly polarised at approximately 5.04 GHz, frequencies that have historically been relevant in military applications. With a 10-dB impedance bandwidth and an average gain of about 5 dB, the proposed technique increases amplification.

In a study researchers (3) published the Key factors in the implementation of wearable sensors for wearable antennas for wireless body area networks (WBNs) and industrial, scientific, and medical applications.Modern antennas, with their powerful electronics, could be employed in novel ways, such as interfacing with the human body. The growing prevalence of wireless technologies prompted the creation of these sophisticated antennas. Telemedicine and recognition systems that use this current antenna design rely on proximity to the body to provide higher performance than previous antenna designs. Interactions and absorption inside human body tissues have an impact on the device's efficacy, radiation emission, and specific absorption rate, and frequency range, ability to focus signals, amplification, and flexibility. In addition to utilizing cutting-edge technology such as band-gap construction, DGS, and artificial magnetic conductors, the wearable antenna exhibits a high degree of body separation and a remarkably low Specific Absorption Rate (SAR). The purpose of this study was to look into the history of on-body antennas and how the human body affects their functionality. We have also conducted more research into key factors influencing the operation of this unique antenna, such as the main technologies and materials. As a result, researchers will be better able to identify the factors contributing to the shortage of highly efficient antennas, as well as the factors that improve the performance of portable antennas.

In the past study, researchers (4) presented the Flexible and Wearable Electronics for Smart Clothing. This endeavour produces portable, tiny broadband receivers. Feed antennas for coplanar waveguide (CPW) are rectangular structures with tapered bottom angles and cut-off top angles. The operating frequency ranges from 3.2 to 14 GHz. The antenna in question is relatively small, measuring 37.91 by 28.39 by 0.88 mm3. Liquid crystal polymer (LCP) composes a bendable substrate. When the reflection coefficient is -10 dB, the antenna has a fractional bandwidth of approximately 125.58 percent. The antenna's performance is also being evaluated in a variety of scenarios, such as its orientation on the human body, moisture exposure, and shape changes. The suggested antenna is well-suited for wireless body area networks (WBANs) due to its small size, low signal absorption, immunity to on-body configuration frequency de-tuning, and ability to operate across a wide frequency spectrum.

In a study researchers (5) proposed a wearable antenna for the 2.45 GHz ISM band in 2010, drawing inspiration from metamaterial design and analysis. The current study presents a silver nanoparticle-based wearable inkjet printer antenna suitable for wireless biological sensors. Experiments in the 868/915 MHz and 2400 MHz industrial, scientific, and medical frequency bands are carried out using a synthetic, multi-layered test platform that resembles human flesh. The radiating efficacy of the prototype copper antenna and ghost antennas was evaluated using a comparative analysis. Copper and silver nanoparticles, with performance variations of less than 0.5 dB and reported total radiation efficiencies of up to -6.5 dB, can serve as disposable, low-cost wireless sensors. Antennas designed for wearable electronics, such as VSMs worn on the breast, should be tiny and curved to closely mimic the body. The antenna's radiation efficiency and return loss can be measured using imitation tissue. To conduct all of the tests, Bluetest.se installed a 2.5 m x 2.5 m vibrating box. To maintain a constant separation distance between the antennae and the tissue, the antennas were positioned atop 5 mm Roha cell HF51 foam (with a relative permittivity of 1.07).

In a study (6) developed the concept of a Dual-mode patch antenna with capacitive coupling structure for on- and off-body applications. This initiative serves as a model for future developments. A dual-band, dual-mode antenna is recommended for the 2.4 GHz industrial, scientific, and medical frequencies. Whether worn or not, this antenna facilitates communication. The antenna's polydimethylsiloxane design makes it simple to wear and lightweight. On the lower substrate, four evenly spaced metal vias appear as a circular zone. This produces an on-body mode, also known as the TM_{01} mode. A smaller circular component attached to the upper substrate activates the TM_{11} mode, producing a directional radiation pattern. This activates the off-body mode. The suggested antenna can operate in the 2.40–2.49 GHz and 5.6–5.96 GHz bands, covering a frequency range of 90 MHz to 330 MHz in each band. When the gadget is not in close contact with the body, the gain is 6.67 decibels. However, when the gadget comes into contact with the body, the gain drops to -2.38 decibels. With low specific absorption rates, the antenna is effective near human tissue. Table 1 shows the existing antenna techniques for wearable antenna.

Table 1: Existing Antenna Techniques for Wearable Antenna

Ref	Techniques	Structure	Applications
(7)	Manual cutting felt substrate	Truncated patch	On-body mechanism (from 2 GHz to 10.6 GHz)
(8)	HIS	Inverted L antenna	Wristwatch (2.4GHz)
(9)	Electromagnetic band gap used for SAR decrease (0.024)	Fractal-based monopole patch	Wearable
(10)	The parasitic components used	Meander line antenna	Sensor wearable nodes
(11)	Tinny wire mesh sheet	Monopole antenna	802.11 ac application
(12)	Frame uses the ground plane	Wire antenna	Eyeglass for 4G application
(13)	Metal shape Metasurface	Broadband monopole	Wearable application
(14)	Ferrite radiating for antenna	Patch	Mobile phone
Current study	Textile fabrication	Circular Antenna	Wearable application
(15)	Coating Method measurable is in use	Monopole Antenna	Energy harvesting application: GSM and DCS bands

Wearable microstrip patch antennas necessitate material selection, electromagnetic field design, and simulation through electromagnetic modeling software, photolithography, etching, assembly, integration, design testing, and validation. Rogers, FR-4, and various other bending materials serve as substrates. Wearable devices engineer their antennas using U-cut and double L-cut apertures to optimize performance. Wearable electronics such as smartwatches, fitness trackers, and smart glasses can all cause antenna issues. Maintaining them close to the body is the main concern. The skin's inherent fragility impacts the antenna's frequency response as well as its radiation emission capabilities. To avoid detuning, wearable antennas must be able to withstand near-field impacts induced by the human body. Maintaining a distance between the antenna and the body may aid in this process. It is possible to add a ground plane. One should examine the body's impact on the antenna and vice versa. The FCC defines 1.6 watts per kilogramme of human tissue as the maximum quantity of radiation that can pass through a certain physiological component (16, 17). An antenna is what determines the best performance of wearable electronics. For optimal antenna performance, Taconic fibre glass and Roger hydrocarbon ceramic are ideal materials. Film substrates, wires, and flexible materials can enhance the adaptability of wearable antennas. Nonetheless, many people who use wearable antennas report feeling at peace in certain body positions and actions (17, 18). It is impossible to fix the antennas in a way that makes them convenient to wear on clothing. This creates a market for flexible antennas. For a wearable app to communicate with the base station and other devices, the fabric antenna must send out a strong, omnidirectional signal (19, 20). The Planar Created - F several bidirectional antennas suitable for use in wearable technology include antenna types, patch antennas, and dipole antennas. The design should take into account the antenna's proximity to the body, the effect of bending, and the effects of humidity. The antenna must function regardless of the body's location, mobility, or spatial changes (21, 22). Wearable patch antennas play a crucial role in achieving several objectives within biomedical applications. Firstly, they enable seamless wireless communication between various medical devices, sensors, and monitoring systems. This communication capability allows for the real-time transmission of critical health data, facilitating prompt analysis and decision-making by healthcare professionals. These antennas are critical for ongoing patient surveillance. We record and forward the patient's vital signs to doctors, enabling a comprehensive assessment of their overall state. Several of these include temperature, heart rate, blood pressure, oxygen levels, and oxygen concentration. Those with chronic illnesses or those who require immediate medical attention would benefit the most from this continuous monitoring (22, 23). Wearable patch antennas contribute significantly to the advancement of telemedicine. This allows doctors to conduct video conferences and remotely monitor their patients as needed. This allows them to react rapidly when needed (24, 25). This feature is particularly useful when it is difficult or impossible to physically visit a healthcare facility. In addition to telemedicine, these antennas facilitate the integration of wearable medical devices into the healthcare ecosystem (26, 27). By seamlessly connecting with devices like smart watches, fitness trackers, and implantable sensors, they enhance the overall functionality and connectivity of these devices. This integration fosters a more comprehensive and interconnected approach to healthcare delivery (28, 29).

Methodology

This paper focuses on the design and analysis of two wearable antennas operating at 2.4GHz frequency for WBAN applications. The first antenna is an inverted U-shaped design, while the second is a double L-shaped patch antenna. These designs are chosen for their potential to reduce SAR levels while simultaneously enhancing critical antenna parameters relevant to biomedical applications. Choosing materials that are safe for prolonged contact with the human body is essential. Biocompatible materials such as medical-grade silicone or flexible polymers help minimize the risk of allergic reactions or adverse tissue responses. Moreover, the selected materials should be non-toxic, non-irritating and compatible with sterilization methods for medical-grade applications. Maintaining reliable signal transmission and reception in WBANs, despite the challenges posed by body movements, tissue effects, and environmental factors, requires careful consideration. This includes optimizing antenna design to mitigate signal attenuation, multipath propagation and electromagnetic interference caused by surrounding tissues, clothing, or external sources (30, 31). Antenna production involves a range of assembly processes, precise photolithography, high-quality etching, and substrate cleansing. The use of high-resolution photolithography and reduced substrates to expose U-cut and double L-cut slots optimizes system performance. However, it's the controlled etching that truly shines, as it effectively eliminates unwanted elements and significantly extends the durability of the antennas.

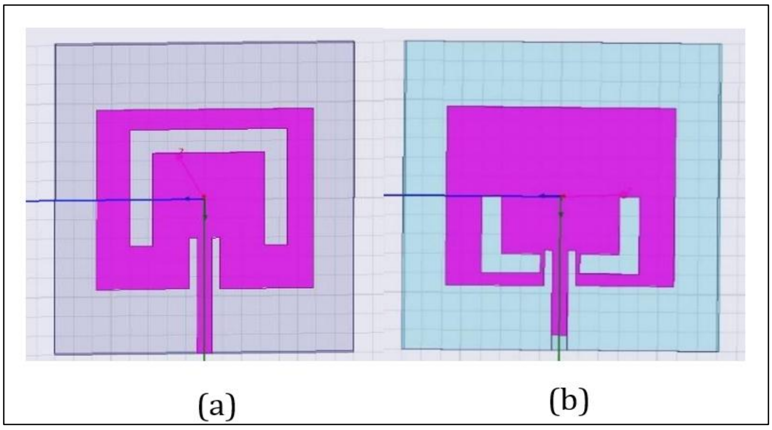


Figure 1: (a) U-Slot Patch Antenna and (b) Double L Slot Patch Antenna

The above Figure 1 shows the proposed antennas, namely the U-slot patch antenna and the double L-slot patch antenna. Despite their restricted range and bandwidth, wearable microstrip patch antennas exhibit commendable performance in the 2.4 GHz band. This is attributed to their minimal loss through human tissue, compatibility with other wireless technologies, and control functionalities. Medical, scientific, and industrial contexts utilize this technology to improve the interoperability of wearable health applications. The frequency can transmit data with sufficient bandwidth and range for wearable devices.

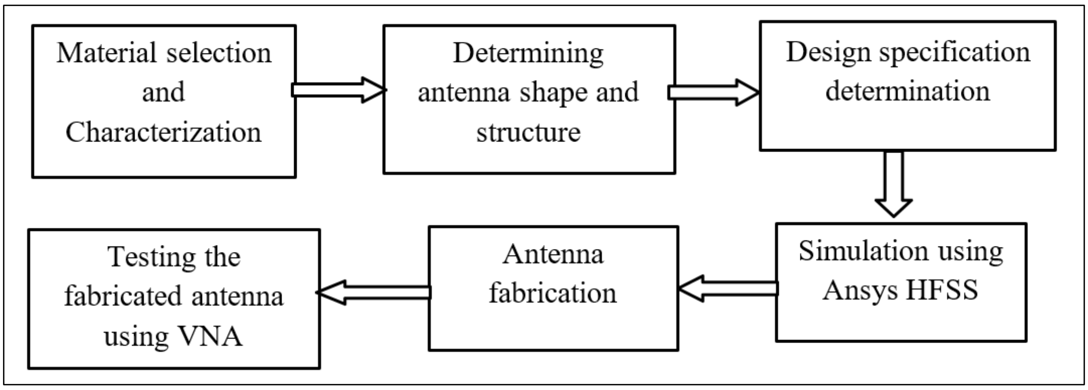


Figure 2: Antenna Design Methodology

The above Figure 2 provides a structured overview of the steps involved in designing a wearable patch antenna, ensuring that the final product meets the intended requirements and performance standards.

Antenna Design by Equation

Compared to other microwave antennas, a micro strip patch antenna's cost-effectiveness, mobility, compatibility with the 2.4 GHz frequency, and small dimensions make it an appealing alternative for this paper. Micro strip antennas typically consist of a ground plane, an insulating substrate, and a conducting material. The conductive material allows for the transmission and reception of electromagnetic waves. Thin copper, with its high electrical conductivity, primarily makes up the ground plane and conducting material. We applied conductive material to the exposed intermediate layer. The feeding technique, structure, and dimensions (such as width, w, and length, l) all have a direct impact on the efficiency with which conductive materials convert electromagnetic waves into electrical energy, and vice versa. This experiment utilized a micro strip patch antenna constructed in accordance with the principles indicated in Figure 1. Figure 2 illustrates the intended front-facing antenna. The proposed inverted U-slot microstrip patch has an antenna that is 80 mm wide, 80 mm long, and 3 mm high. The denim layer is 3 mm thick and has a relative permittivity (i) of 1.70. It behaves as an insulator.The proposed antenna's microstrip structure features an integrated input line. The feed is 4 mm in width and 32 mm in length. The spreading zone measures 58 mm wide (Wp) and 46.4 mm long (Lp). The antenna's radiating patch specific Absorption Rate (SAR) includes an inverted U-shaped gap in its upper extremities. U-shaped chamber measures 42x6mm^2 horizontally and 24x6mm^2 vertically.Table 2 below lists the specifications of the suggested antenna. Use the following formulas to determine the optimal settings for your microstrip patch antenna: We can use mathematical methodologies to determine the optimal width of a sing-e band microstrip patch antenna. Ion 1 uses the substrate dielectric constant (ρr), speed of light (c), and resonance frequency (f_0) to determine width.

Equation 2 provides the exact length of the patch, as specified.

$$W = \frac{c}{f_0\sqrt{2\varepsilon_r+1}} \quad [1]$$

$$L = L_{eff} - 2\Delta L \quad [2]$$

Where L_{eff} is the effective length and can be determined as [3] and ΔL is the extension of length can be determined from expression [4].

$$L_{eff} = \frac{c}{2f_0\sqrt{\varepsilon_{reff}}} \quad [3]$$

$$\Delta L = \frac{(0.412h)(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)\,(\frac{W}{h}+0.8)} \quad [4]$$

Where ε_{reff} is effective permittivity calculated from [5] $\varepsilon_{reff} = \frac{\varepsilon_r + 1 + \frac{\varepsilon r - 12}{\sqrt{1}} + 12\frac{h}{w}}{2}$ [5]

ε_r is the dielectric constant of the substrate, 'h' is the height of substrate and 'W' is the width of ground plane.

Table 2: Measurements of Inverted U-slot Patch Antenna

Parameters	Values
Substrate width	80mm
Substrate Length	80mm
Substrate Thickness	3mm
Patch Width	46.5mm
Patch Length	58mm

The above Table 2 represents the measurements of inverted U-slot antenna. The antenna which was designed with a shape of double L-slot patch antenna, with dimensions measuring $80 \times 80 \times 3 mm^3$, is meticulously crafted on this substrate to ensure optimal performance and operating at 2.4GHz. The ground plane, connected via a 50-Ω micro strip line, plays a crucial role in the antenna's functionality. Its dimensions length and width ($L \times W\ mm^2$) are carefully chosen to enhance signal propagation and radiation efficiency. Notably, the dielectric constant of the substrate remains below 10GHz, ensuring consistent performance across the desired frequency range. A key feature of the antenna design is the inclusion of strategically placed slots, which serve to further enhance its performance. An L-shaped slot is etched onto the radiating patch length of the patch and width of the patch ($PL \times PW\ mm^2$), while two additional slots are positioned adjacent to the feed line ($D \times E\ mm^2$). These slot configurations are instrumental in achieving dual-band resonance, allowing the antenna to operate across multiple frequency bands.

In terms of resonance, the antenna exhibits two distinct peaks. This dual-band capability enables the antenna to cater to a wide range of applications, making it a versatile solution for various communication systems. Overall, the proposed antenna design offers a compelling combination of performance and versatility. By harnessing the substrate's unique properties and incorporating strategic design elements, the antenna achieves exceptional performance across multiple frequency bands, making it well-suited for a diverse range of applications in the biomedical industry. Table 3 represents the measurements of double L-slot antenna.

Table 3: Measurements for Double L-slot Patch Antenna

Parameters	Values
Substrate width	80mm
Substrate Length	80mm
Substrate Thickness	3mm
Patch Width	46.5mm
Patch Length	58mm

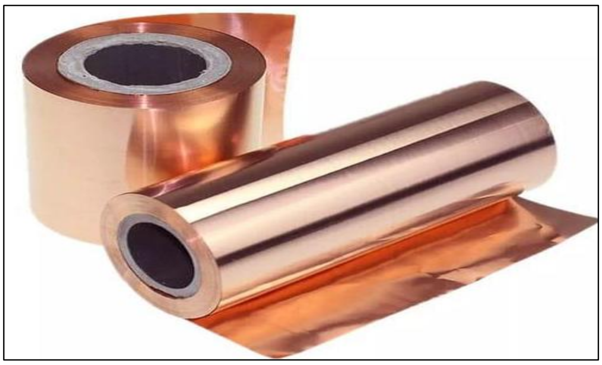


Figure 3: Copper Sheet (Foil) 0.1mm

Many different wireless communication systems use patch antennas. Figure 3 shows the Copper foil. Copper foil has a significant impact on both the production process and the final product quality. Table 4 represents the properties of Copper. Copper is chosen for its excellent electrical conductivity, which allows for efficient energy transfer within the antenna structure. In patch antenna construction, copper foil is typically laminated onto a dielectric substrate such as FR4, creating a sandwich-like structure (32, 33).

Table 4: Properties of Copper

Parameters	Values
Electrical Conductivity	59.52
Permitivity	3.18
Permeability	1
Resistivity	0.0168

Figure 4: Jeans Material

Table 5 represents the properties of Copper. Using jeans material as a substrate for a wearable patch antenna presents both advantages and challenges. Figure 4 represents the Jeans material. One of the key advantages is its flexibility, allowing the antenna to conform to curved or irregular surfaces. This flexibility is particularly beneficial for wearable antennas that need to be integrated into clothing or accessories. Another advantage is cost-effectiveness; jeans material is generally more affordable than specialized antenna substrates, making it suitable for projects with budget constraints. Jeans material is widely available, making it easy to procure for experimentation and prototyping purposes (34, 35).

Table 5: Properties of Jeans Material

Properties	Values
Relative Permittivity	1.7
Relative Permeability	1
Dielectric Loss Tangent	0.0025
Bulk Conductivity	10^-7 siemens/m

In reality, environmental factors such as bodily movements, temperature, weather, and perspiration may influence the effectiveness of microstrip patch antennas. Specific Absorption Rate and signal strength fluctuate as the receiver moves closer to or further from your skin. Environmental variables and perspiration result in conductive skin. This exacerbates loss and alters impedance, thereby diminishing antenna efficiency.

Results and Discussion

This section provides a subjective evaluation of the simulation results for the proposed wearable patch antenna, as well as a detailed analysis.

Antenna Design

The Figure 5 shows the perspective front view and back view of the Inverted U-slot antenna which was designed in HFSS software. The Figure 6 shows the front, back and side view of the double L slot antenna.

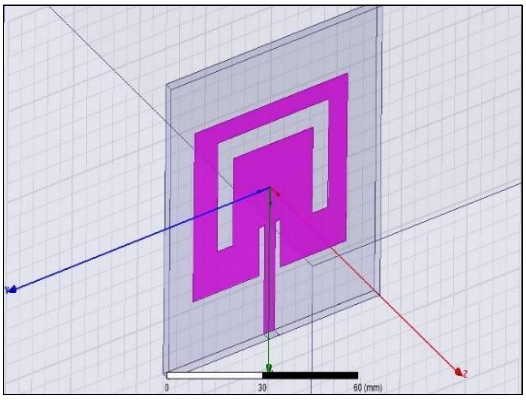


Figure 5: Front View and Side View of Inverted U-Slot Patch Antenna

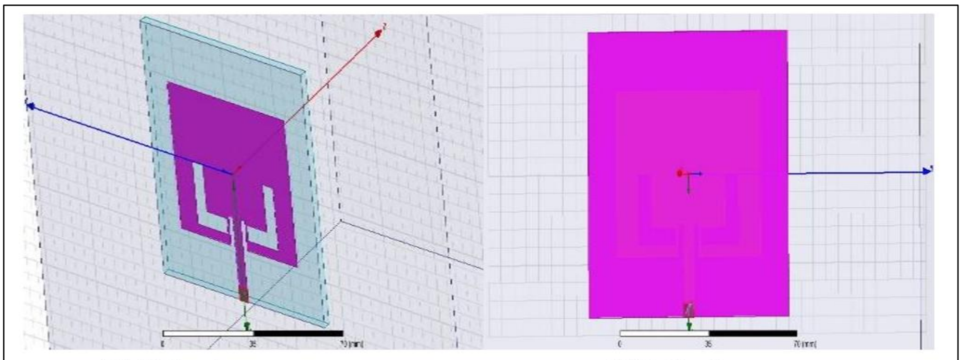


Figure 6: (A) Side View and (B) Back View of Double L Slot Patch Antenna

Return Loss

The return loss of an antenna, commonly known as the S11 statistic, is a straightforward and easy-to-understand way to analyze its performance. Using an antenna's return loss allows you to estimate the energy it reflects. Graphs depicting the relationship between frequency and return loss assist in determining the operational frequency and antenna bandwidth. The antenna's resonance increases as the S11 parameter value decreases. Figure 7's graph depicts the frequency-based link between S11. With a resonance frequency of more than 2.4 GHz and a return loss value of about -20 dB, the graph clearly demonstrates that it has not yet reached peak performance.

Figure 7: Return Loss of Inverted U Slot Patch Antenna

The 0dB S11 means that all the power of the signal is reflected, and -10dB means that 3dB of power is transmitted to the antenna and -7dB of power is reflected, so the S11 should be less than -10dB for an antenna. The below Figure 8 shows that double L-slot antenna design provides return loss of -30dB and resonating at 2.4 GHz respectively.

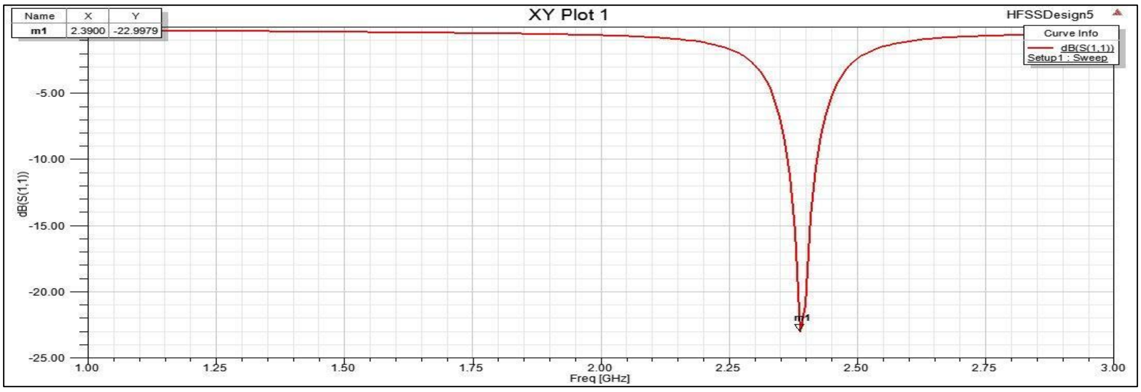


Figure 8: Return Loss of Double L-Slot Patch Antenna

Voltage Standing Wave Ratio (VSWR)

The voltage-to-current ratio (VSWR) is another way of determining the degree of impedance matching between the antenna and resistance. It is essentially a test to see how well the loads match the line's usual resistance. Standing waves occur when two transmission lines have an impedance mismatch. We calculate the standing wave ratio (SWR) by dividing the amplitude of a partial standing wave at one end of a line by its amplitude at the other end. The VSWR typically ranges from 1 to 2. The below Figure 9 shows the VSWR result of inverted U-slot antenna. Figure 10 shows the simulation result of VSWR for double L-slot antenna. The graph of a single-element antenna clearly shows that the VSWR value is within the allowable spectrum for the given frequency range.

Figure 9: VSWR of Inverted U Slot Patch Antenna

Figure 10: VSWR of Double L Slot Patch Antenna

2D Radiation Pattern

In antenna design, the radiation pattern represents the variation in radio wave intensity with regard to each direction. Figure11 shows the results of 2D radiation pattern for inverted U-slot antenna. A single-element antenna in two dimensions has a narrow beam width and a well-planned radiation pattern. We discovered a radiation pattern that remarkably resembles a semi-circle. This pattern demonstrates the distinct characteristics of a microstrip patch antenna.

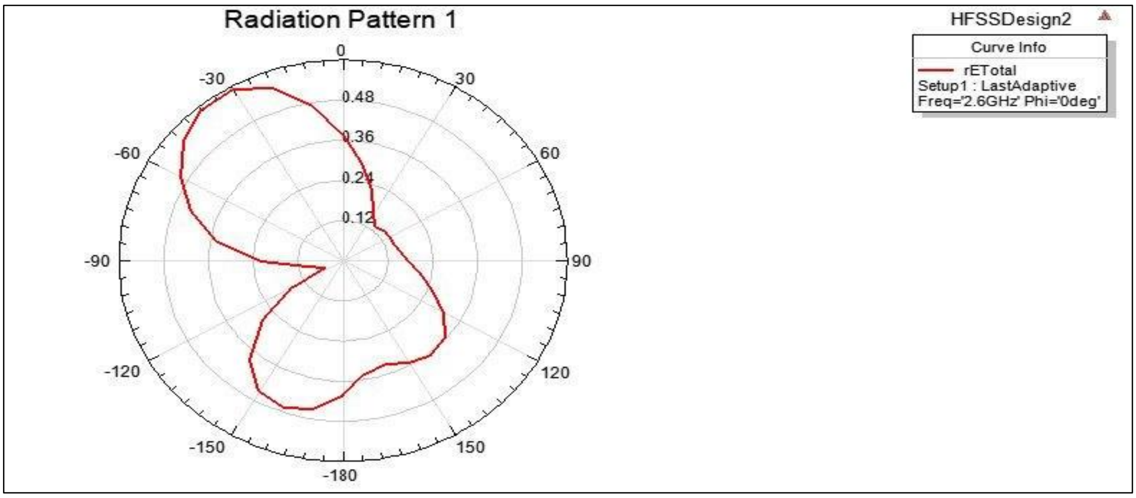


Figure 11: 2D Radiation Pattern of Inverted U Slot Patch Antenna

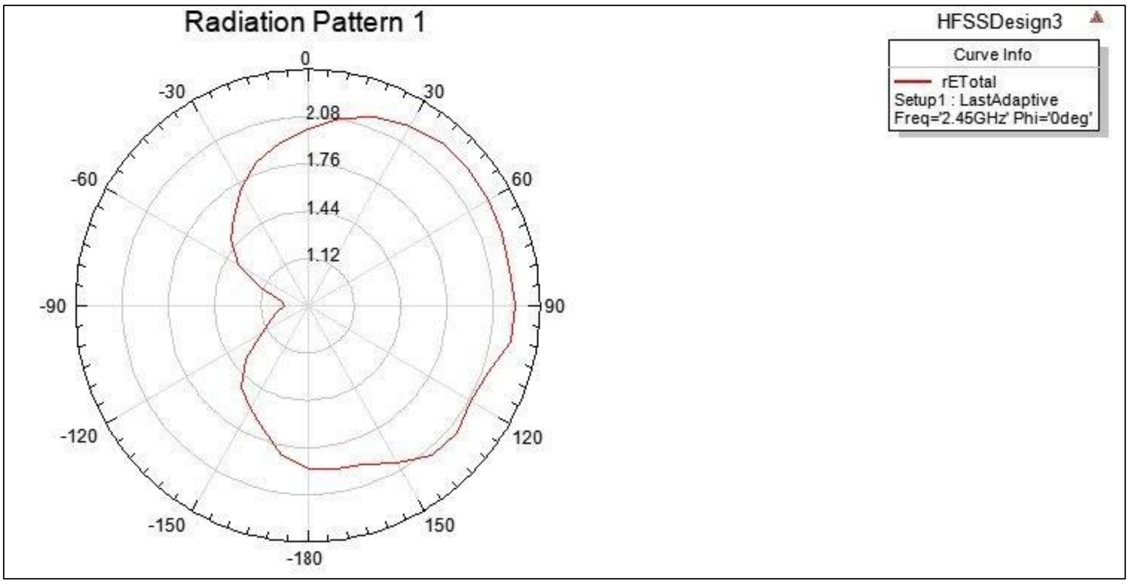


Figure 12: 2D Radiation Pattern of Double L-slot patch antenna

Figure 12 shows the results of 2D radiation pattern for double L-slot antenna.

3D Radiation Pattern

Graphically, a 3D radiation pattern represents the power emitted by an antenna in its surroundings. Typically, the far field also known as the optimal distance from the receiver helps to establish this pattern. Figure13 shows the results of 3D radiation pattern for inverted U-slot antenna.

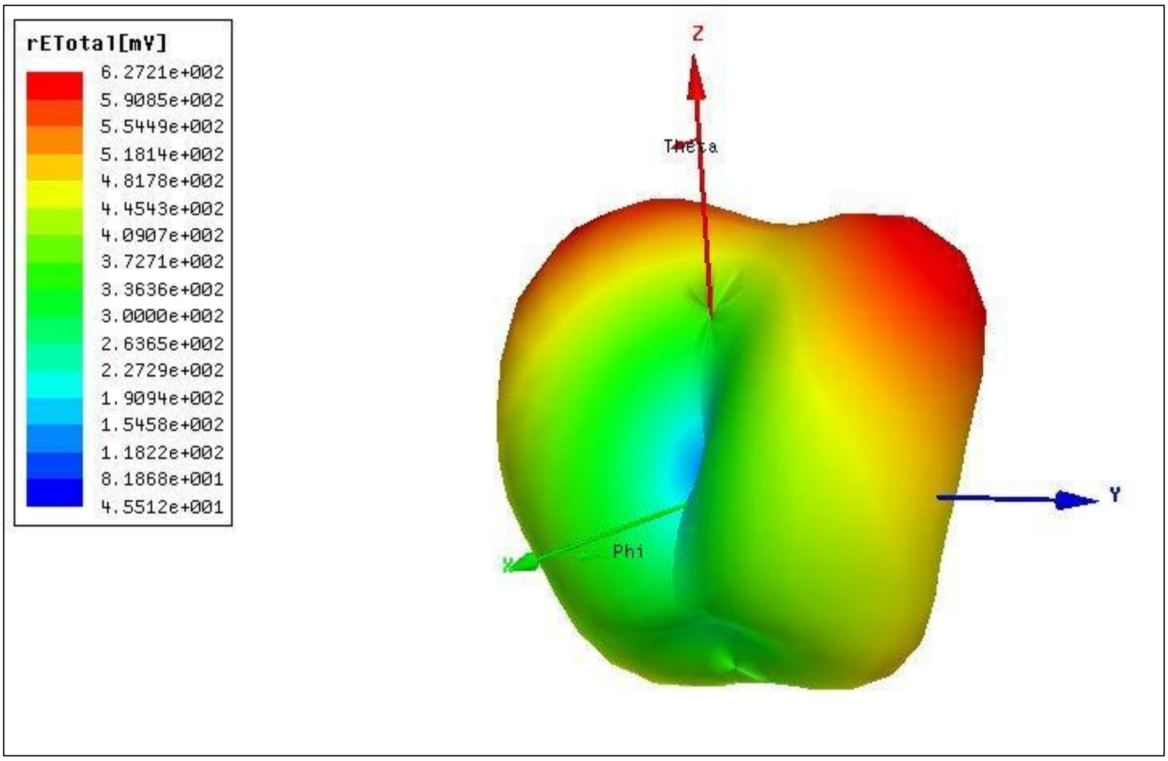


Figure13: 3D Radiation Pattern of Inverted U Slot Patch Antenna

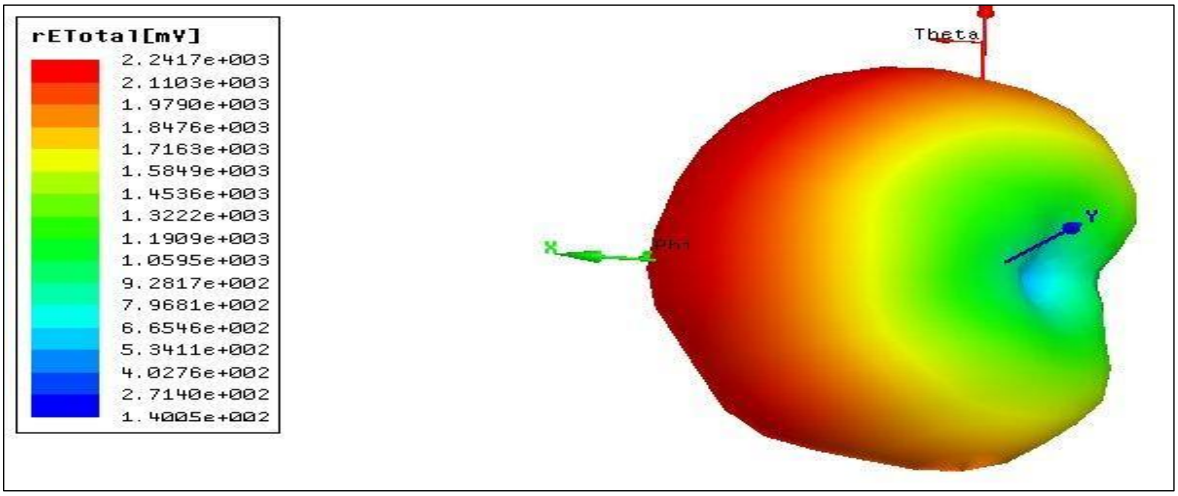


Figure 14: 3D Radiation Pattern of Double L-Slot Patch Antenna

The above Figure 14 shows the results of 3D radiation pattern for double L-slot antenna. Essentially, it indicates an antenna's focused power as opposed to an isotropic antenna, which distributes output evenly in all directions. An optimal antenna has a three-dimensional radiation pattern that is consistent across all operating frequencies, similar to its two-dimensional radiation pattern. One can easily reveal the amount of power focused in a specific direction using a 3D radiation pattern.

Peak Gain

Peak gain is a fundamental metric in electronics, representing the maximum amplification capability of a device or system for a given input signal frequency. The peak gain plot illustrates its amplification characteristics across different frequencies. Notably, the antenna exhibits a peak gain exceeding 5dBi within its designated operating bands, particularly at frequencies of 2.6GHz. Figure 15 shows the results of peak gain for inverted U-slot antenna.

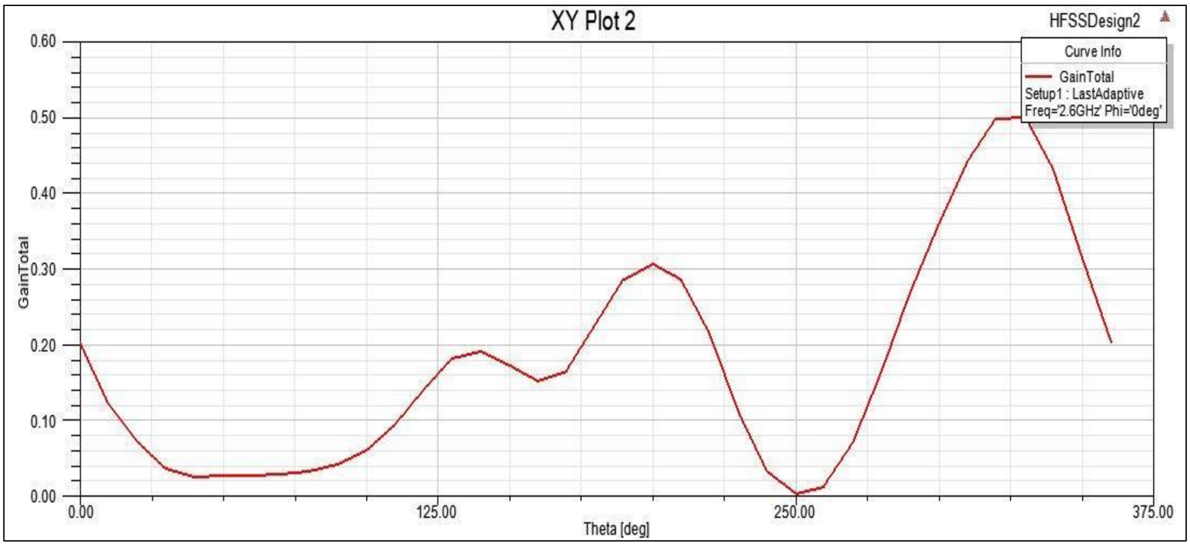


Figure 15: Peak Gain of Inverted U Slot Patch Antenna

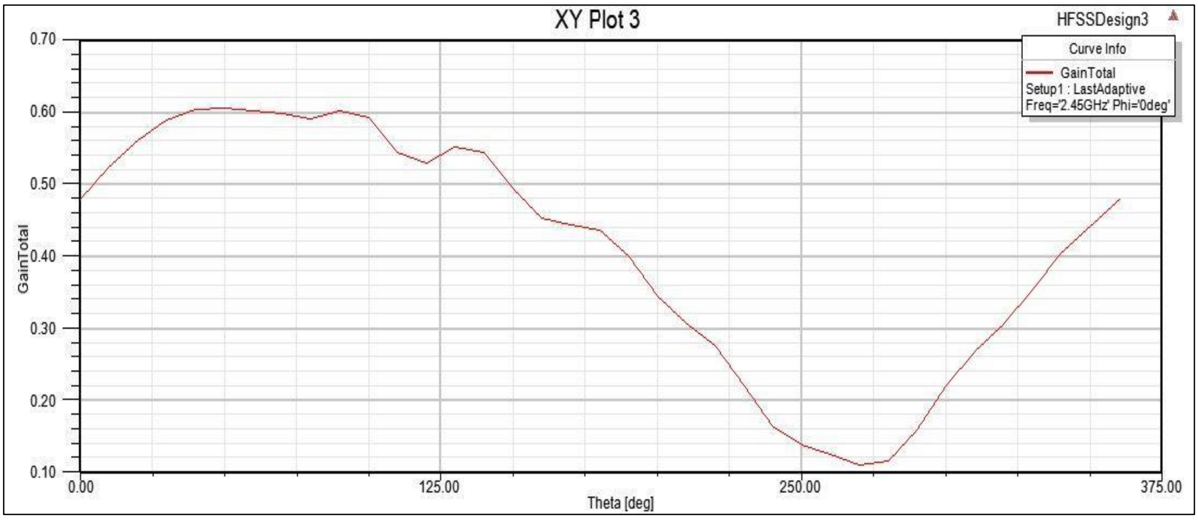


Figure 16: Peak Gain of Double L-Slot Patch Antenna

Figure 16 shows the results of peak gain for inverted U-slot antenna. Thus, the gain is maximum at 60db.

Electric Field Variation

In patch antenna design using HFSS, the electric field primarily moves perpendicular to the surface of the patch antenna. This means the electric field lines are oriented in the z-direction, which is perpendicular to the xy-plane of the antenna's substrate. This vertical orientation of the electric field is crucial for efficient radiation of electromagnetic waves in the desired direction, ensuring optimal antenna performance. HFSS allows for detailed analysis of the electric field distribution, which is critical for achieving desired radiation characteristics, impedance matching, and overall antenna efficiency. By studying the electric field variation, engineers can fine-tune parameters such as patch dimensions, substrate properties, and feed configuration to meet specific design requirements and performance goals. Figure 17 shows the movement of electric field in inverted U-slot antenna.

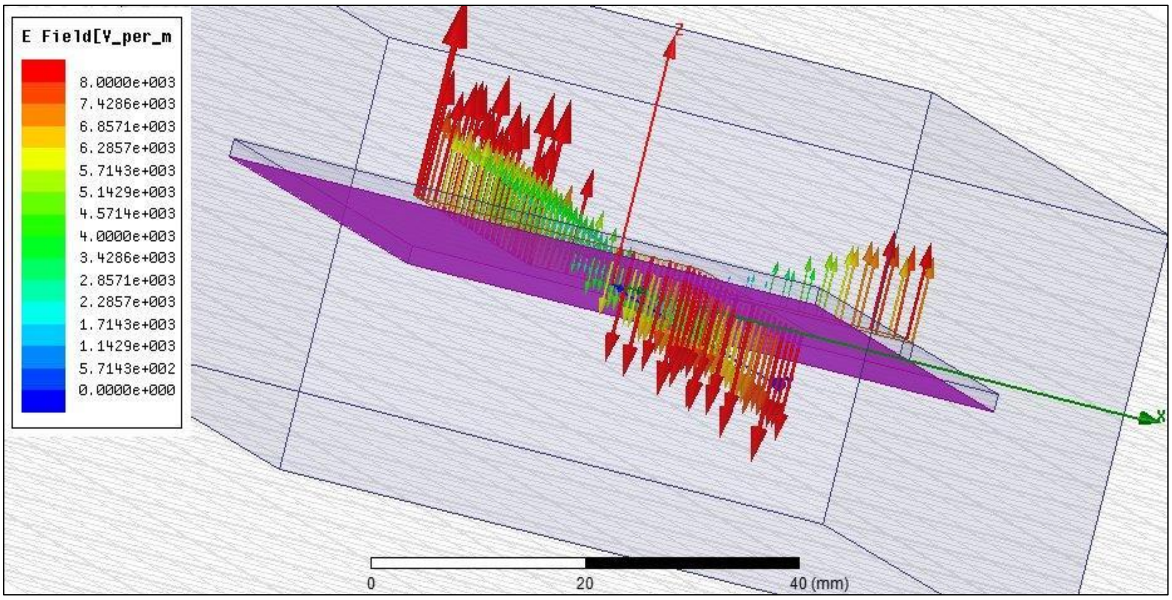


Figure 17: Electric Field Variation

Electric Field Distribution

In designing a wearable patch antenna and analyzing its electric field distribution, assigning a perfect electric (P.E.) boundary condition is a common approach. This boundary condition assumes that the tangential electric field at the boundary is zero, effectively making the boundary an electrical insulator.

When assigning a perfect electric boundary condition to a wearable patch antenna, you are essentially simulating a scenario where the electric field does not penetrate beyond the boundary of the antenna structure. This is particularly useful in simulations to understand how the electric field behaves within and around the antenna. The process typically involves setting up your simulation environment, which can be done using software like HFSS (High-Frequency Structure Simulator) or CST Microwave Studio. In the software, you would define the geometry of your patch antenna, specify the material properties (such as the dielectric constant of the substrate), and then assign the perfect electric boundary condition to the outer edges of the antenna structure. The Figures 18 and 19 show the perfect electric field boundary for inverted U-slot antenna and double L-slot antenna.

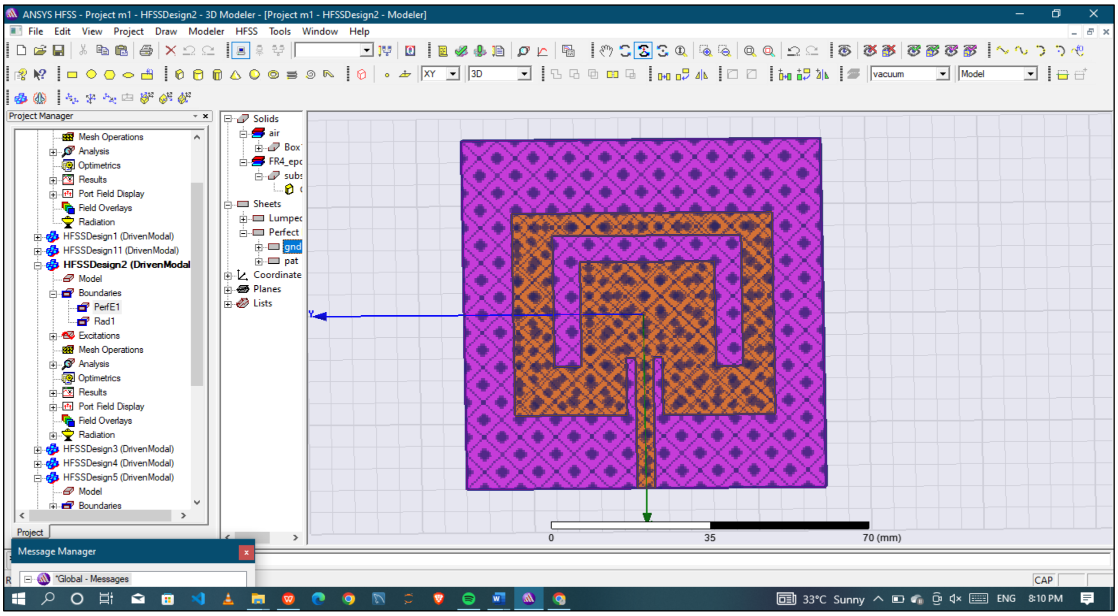


Figure 18: Perfect E for Inverted U-Slot Patch Antenna

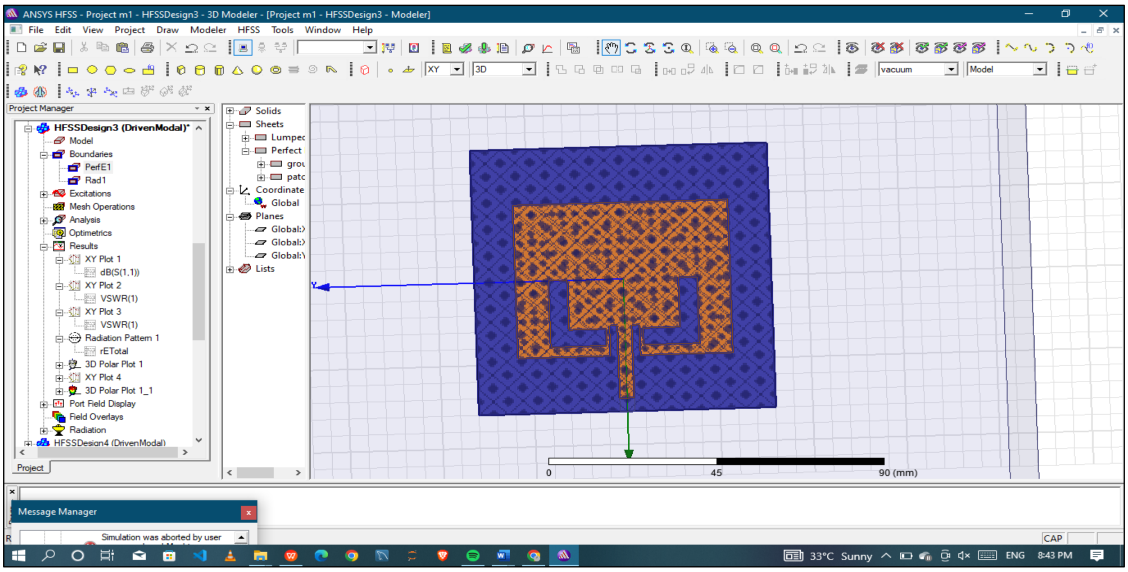


Figure 19: Perfect E for Double L-Slot Patch Antenna

Fabrication and Testing of Antennas

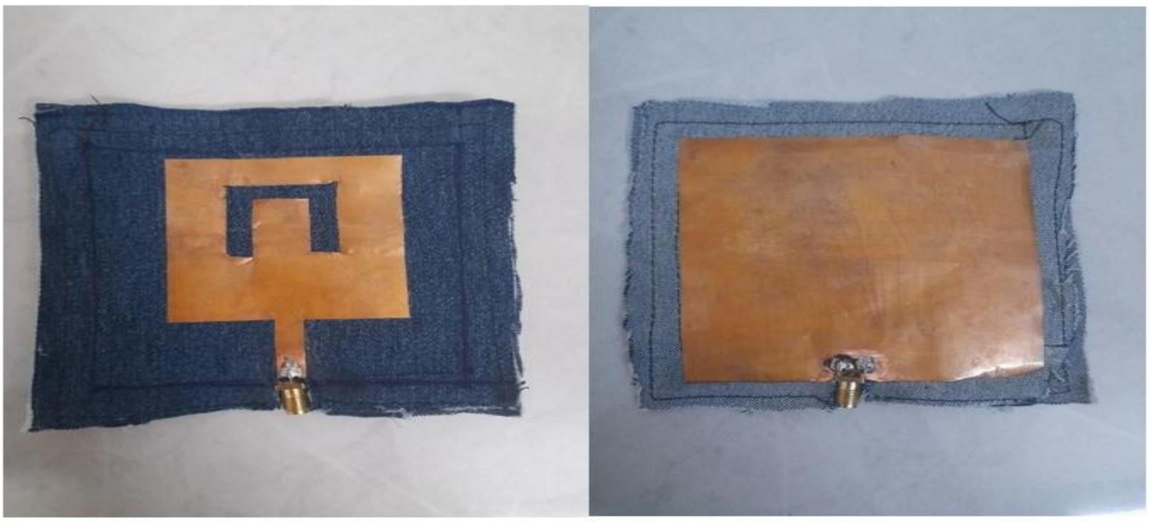
We have completed the following steps in developing a prototype textile antenna:

Determine each stratum's elevation

Knowing the thickness of each layer of substrate material is critical for achieving the desired breadth. A thickness scale allows you to measure a single-layer pair of trousers. It gives each layer 3 mm of thickness.

Fasten the jeans tightly to the exact required length

Aligning the jeans' measurements with the substrate's dimensions (80 x 80 mm) and stitching their sides together would allow for a thickness of 3 millimeters. We then used scissors to cut the surplus denim into pieces. We used a blade to cut the self-adhering copper tape, which lacks electrical conductivity, based on the provided reference measurements. Consequently, we constructed a ground plane from the same material and secured it to a denim foundation. The preliminary research indicates that efficiency metrics are favorable. The dimensions, configuration, and composition of antennas influence their effectiveness. Tissue influences antenna radiation efficiency, gain, and electromagnetic field distribution. The effects of water and body fat on antenna efficacy must be investigated to validate their effectiveness. We have completed the following steps in developing a prototype textile antenna.



(A) Front View (B) Back View

Figure 20: Hardware Design of Inverted U-slot Patch Antenna

The product is examined after manufacture with a scalar network analyzer in the test setup depicted in Figure 20. At 2.4 GHz, the test produces a return loss of -30 dB. The simulated and produced results have a significant degree of similarity. Many factors contribute to a modest variation between the expected and actual outcomes. Figure 21 to Figure 24 shows the output of an inverted U-slot antenna under ideal condition.

Figure 21: Ideal Position of the inverted U-Slot Antenna

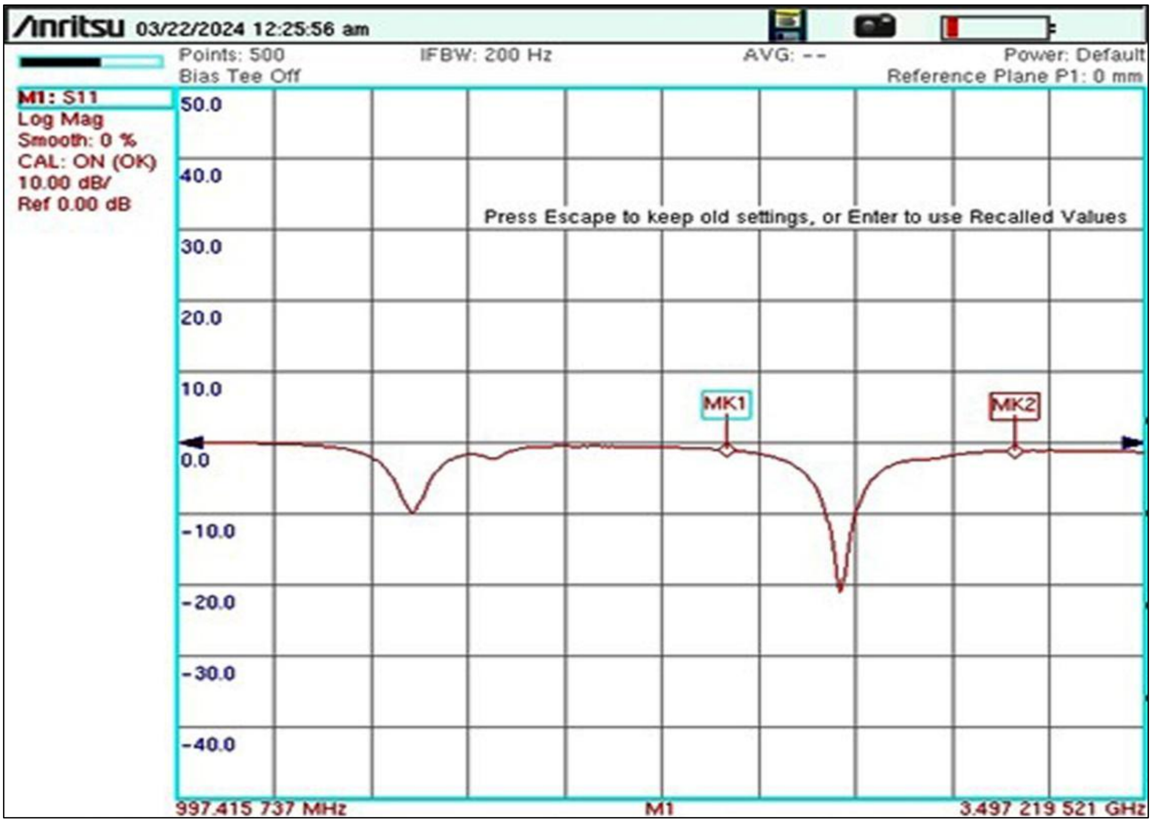


Figure 22: Graphical Output of the Inverted U-Slot Antenna under Ideal Condition

Figure 23: Bending Position of the Inverted U-Slot Antenna

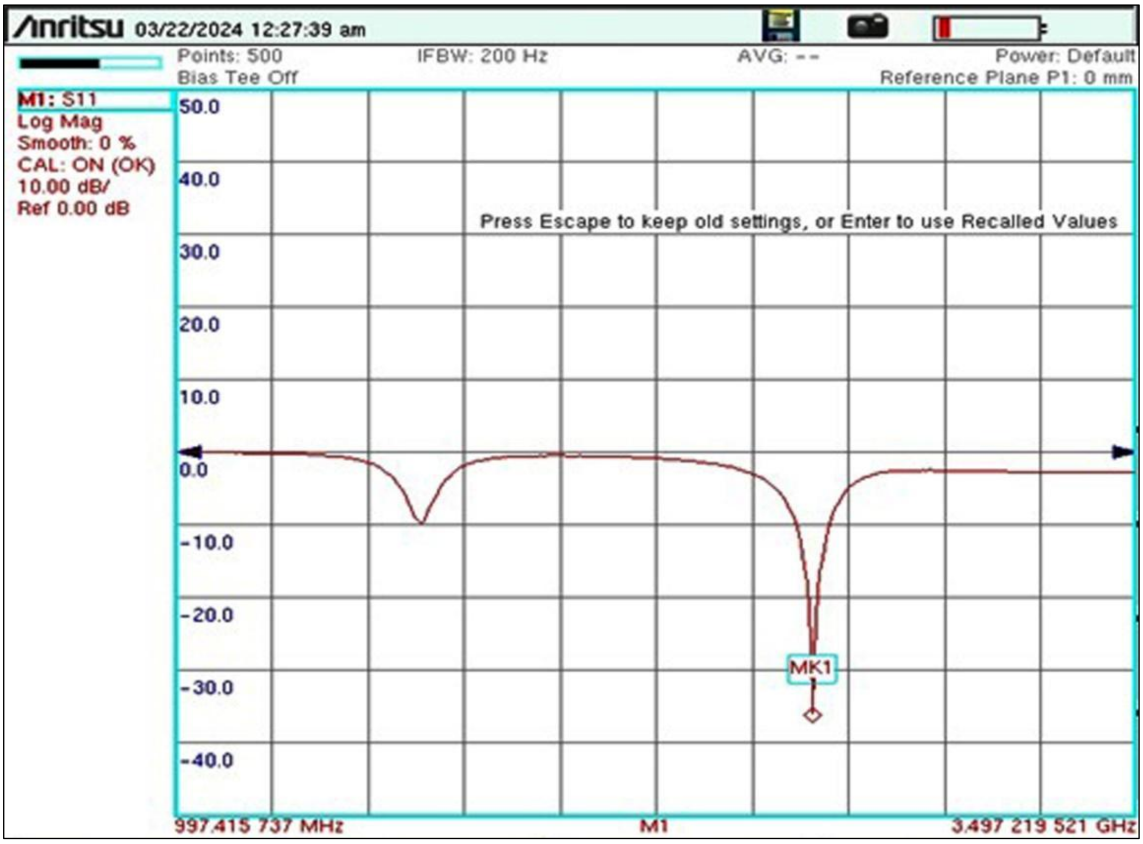


Figure 24: Graphical Output of the Inverted U- Slot Antenna under

Bending Condition

In VNA (Vector Network Analyzer) testing, the comparison between the normal condition and bend condition of an inverted U-slot patch antenna would also focus on the dB values at a specific frequency, such as 2.4GHz as shown in Figures 25 and 26. When conducting VNA testing, the dB value reflects the strength or attenuation of the signal, which can indicate the antenna's performance under different conditions. A higher dB value, such as -30 dB in the bend condition compared to -20 dB in the normal condition, suggests that the antenna performs better or has lower signal losses when bent. By analyzing the VNA testing results, you can gain insights into how bending affects the antenna's impedance, return loss and other parameters crucial for its functionality. This comparison helps in evaluating the antenna's robustness and performance in real-world scenarios where bending or deformation may occur. The below Figure 27 shows the output for inverted U-slot antenna under full bending condition.

Figure 25: Graphical Output of the Inverted U-Slot Antenna under Full Bending Position

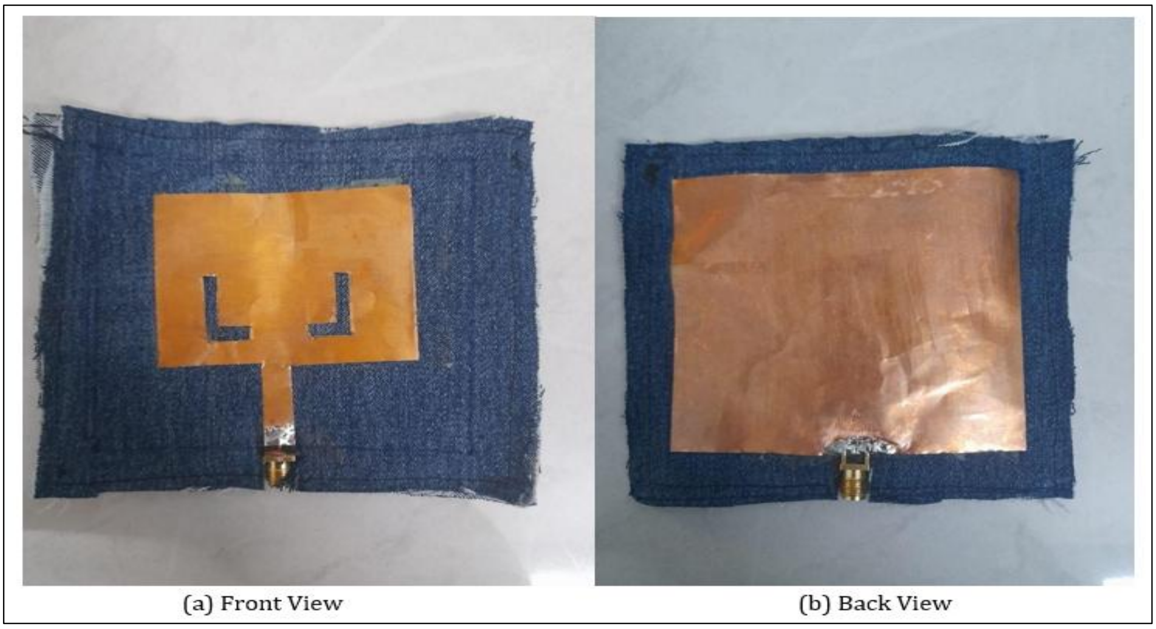


Figure 26: Double L -Slot Patch Antenna. Hardware Design of Double L-Slot Patch Antenna

After the creation process is complete, Figure 28 depicts the next phase, which consists of a detailed study using a scalar network analyzer. The test results indicate a -30 dB return loss at 2.425 GHz. Both the produced and simulated outputs bear a strong resemblance. The actual occurrences and predicted outcomes fluctuate slightly for a variety of reasons.

Figure 27: Slight Bending Condition of the Double L-Slot Antenna

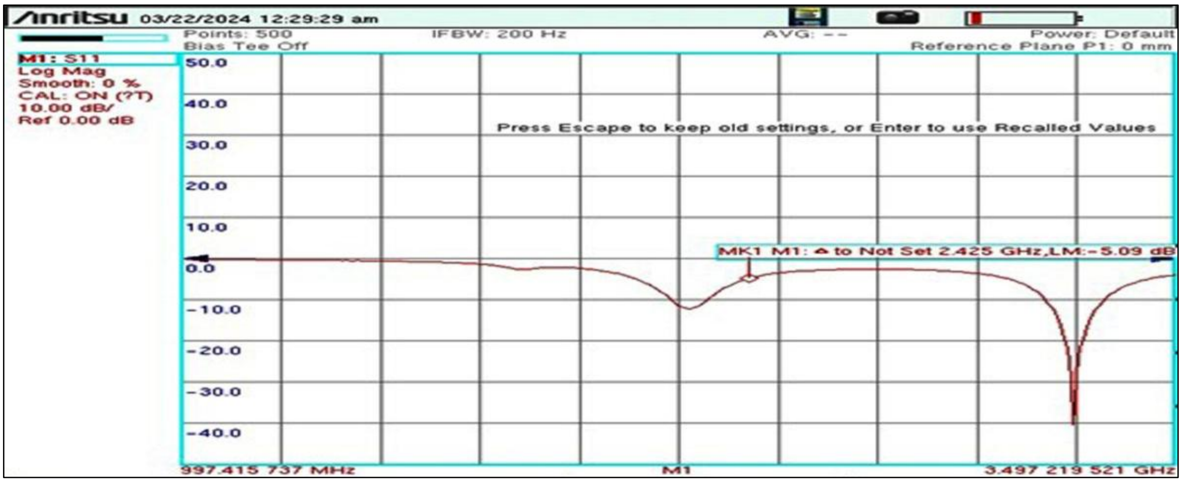


Figure 28: Graphical Output of the Double L-Slot Antenna under Slight Bending Condition

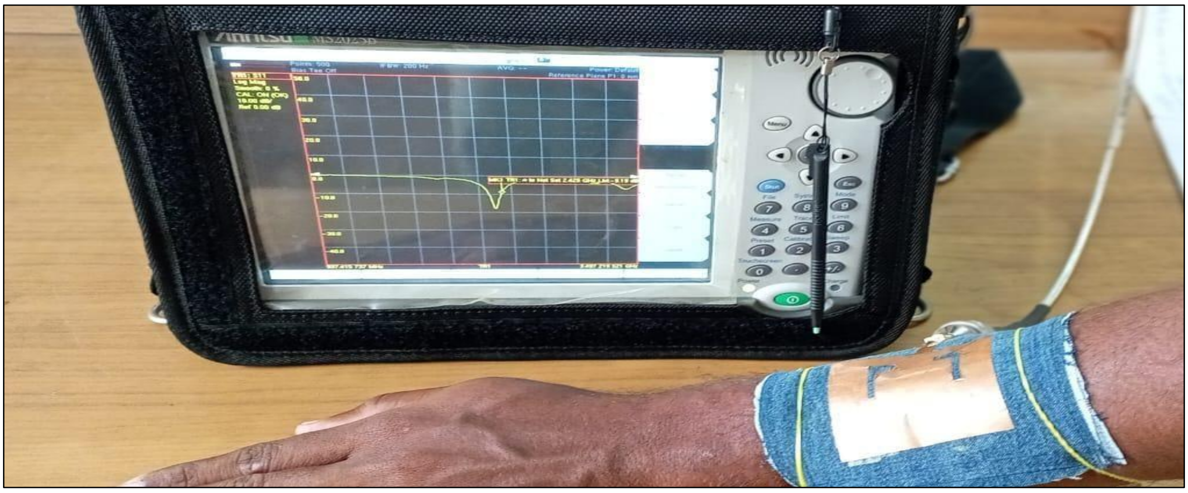


Figure 29: Full Bending Condition of the Double L-Slot Antenna

The closeness of wearable microstrip patch antennas to the body significantly influences their efficacy and the signals transmitted. The epidermis differs from other dielectrics. This absorption diminishes the antenna's efficacy and may alter the discharge pattern. Your location and travel speed can both affect the antenna's effectiveness.

Figure 30: Graphical Output of the Double L-Slot Antenna under Full Bending Condition

In VNA (Vector Network Analyzer) testing, the comparison between the slight bend condition and full bend condition of an double L-slot patch antenna would also focus on the dB values at a specific frequency, such as 2.425 GHz as shown in above Figures 29 and 30.When conducting VNA testing, the dB value reflects the strength or attenuation of the signal, which can indicate the antenna's performance under different conditions. A higher dB value, such as -30 dB in the slight bend condition compared to -20 dB in the full bend condition, suggests that the antenna performs better or has lower signal losses when bent. The below Figure 31 shows the output of in double L-slot antenna under normal condition. The research employed a vector network analyzer to evaluate the efficacy of simulated antennas in a regulated environment. The most significant characteristics examined were the gain, voltage standing wave ratio (VSWR), return loss, and radiation pattern. The portable antenna has shown efficacy for wireless body area networks. It sustained a consistent frequency of 2.4 GHz while delivering a 20 dB enhancement. We found the models and readings to be relatively comparable.

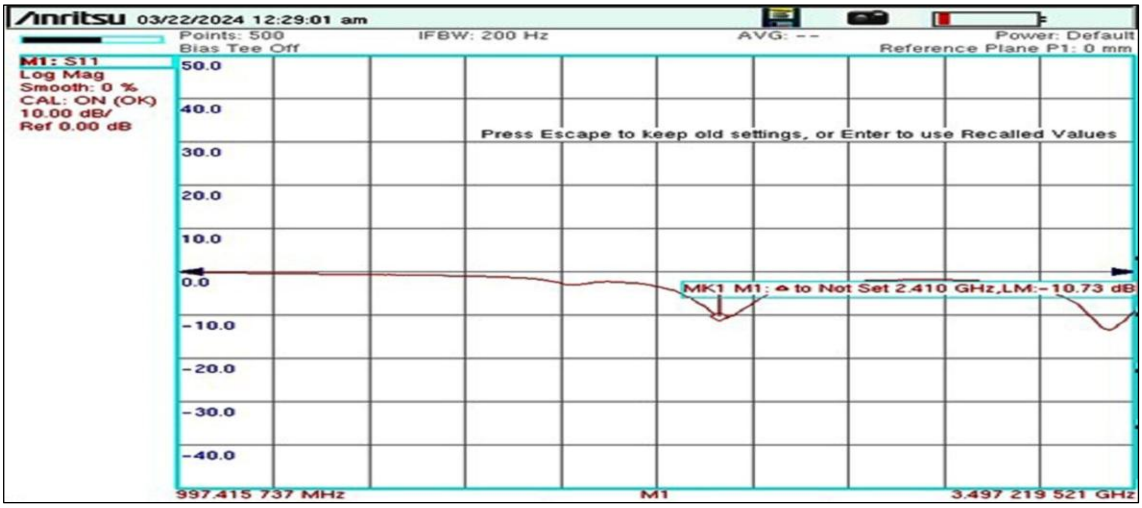


Figure 31: Graphical Output of the Double L-Slot Antenna under Normal Condition

Conclusion

In The conclusion for designing inverted U-slot and double L-slot patch antennas operating at 2.4 GHz using jeans as a substrate encompasses several crucial aspects that warrant further elaboration. Firstly, the selection of jeans material as a substrate introduces unique characteristics to the antennas. Jeans, being a fabric-based substrate, offers flexibility and comfort, making it an attractive choice for wearable applications. Moreover, the comfort aspect is vital for user acceptance, especially in applications where the antennas are in direct contact with the skin or clothing. Secondly, the choice of operating frequency at 2.4 GHz aligns with common standards and applications such as Bluetooth, Wi-Fi and some RFID systems. This frequency band is widely used in wireless communication, IoT devices and smart wearable, making it a practical choice for the antenna's operational frequency. Thirdly, the inverted U-slot and double L-slot designs offer distinct performance characteristics. The inverted U-slot design typically exhibits better impedance matching and radiation properties compared to the double L-slot design. This difference arises from the specific geometry and arrangement of the slots, which influence the antenna's resonance and radiation pattern. The software simulation and hardware testing results for the antenna were identical. They both operated at 2.4 GHz and achieved a gain of 20 dB. However, the choice between these designs depends on the application requirements, such as bandwidth, gain, and radiation directionality. Simulation tools like HFSS (High-Frequency Structure Simulator) can provide insights into the antenna's electrical properties, radiation patterns, and impedance matching. Further optimization of the antennas on jeans substrate may involve fine-tuning the dimensions of the slots, optimizing the substrate's dielectric properties, and exploring advanced manufacturing techniques like inkjet printing or embroidery for seamless integration into clothing or wearable devices. These optimizations aim to enhance the antennas' overall performance, reliability and suitability for specific applications in communication systems, IoT devices, healthcare monitoring and other wearable technology domains.

Abbreviation

Nil.

Acknowledgement

Nil.

Author Contributions

All authors contributed equally.

Conflict of Interest

The authors declare no conflicts of interest.

Ethics Approval

Not applicable.

Funding

Nil.

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