Semnan University

Mechanics of Advanced Composite Structures

Journal homepage: https://macs.semnan.ac.ir/

ISSN: 2423-7043

Research Article - Part of the Special Issue on Mechanics of Advanced Fiber-Reinforced Composite Structures

Complementary Split Ring Resonator-Inspired Antenna for Wearable Multiband Applications Using Biodegradable Polylactic Acid

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ARTICLE INFO

Article history:

Received: 2024-04-21
Revised: 2024-08-03
Accepted: 2024-08-15

Keywords:

Multi-Band;
Biodegradable;
Flexible;
Metamaterial;
Lightweight;
Eco-Friendly;
Hexagonal patch antenna.

ABSTRACT

In this manuscript, replacing traditional antennas with biodegradable PLA substrates aims to reduce e-waste in today's technologically advanced age. This work achieves its objectives by designing the miniaturized (56 x 56 x 1.6) mm3 hexagonal patch antenna with partial ground (18.2 x 52) mm2 and incorporating complementary split ring resonators (CSRRs) in the HFSS (High-Frequency Structure Simulator). This innovative approach combines unconventional antenna design with metamaterial technology to enhance antenna performance, making it flexible, lightweight, and suitable for multi-band applications. An evaluation of PLA compared to other substrates revealed that PLA is more suitable for its eco-friendliness, and the simulation result is also satisfactory for bandwidth, return loss, VSWR, directivity, efficiency, and other parameters. Additionally, the integration of taffeta fabric as a conductive patch material provided elasticity and enhanced wearability. Using this unique method, the proposed antenna resonates at multiband frequencies of 2.6 GHz, 8.6 GHz, 10.5 GHz, 12.4 GHz, and 15.3 GHz, which gives return losses of -26.84 dB, -22.16 dB, -29.87 dB, -39.43 dB, and -26.35 dB, respectively. In addition to its biocompatibility and achievement of the SAR threshold, the antenna serves as a long-term solution for multi-band wireless applications. This further advances the realm of environmentally friendly wearable technology.

1. Introduction

Modern society has seen a growing number of wearable gadgets integrating wireless communication technologies, which has increased demand for small, effective antennas that can function in numerous frequency bands. The antenna is designed using biodegradable [1] Polylactic Acid (PLA) to align with the growing trend of environmentally friendly materials in electronics. The application of CSRR, a well-known electromagnetic structure, results in special electromagnetic qualities that improve the antenna's performance over a range of frequency bands. The use of PLA [2] as the substrate supports environmental sustainability in addition to enhancing the mechanical flexibility of the antenna, which is essential for wearables. This aims to address the challenges of efficiency and reduction in size in wearable antennas by creating a solution that satisfies both the worldwide demand for biodegradability and the technical specifications of multiband communication. This provides a viable path for

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Cite this article as:

Srinivasan, S., Selvaraj, H., Pitchaimani, G. and Bishnoi, K., 2025. Complementary Split Ring Resonator-Inspired Antenna for Wearable Multiband Applications Using Biodegradable Polylactic Acid. *Mechanics of Advanced Composite Structures*, 12(2), pp. 339-352.
https://doi.org/10.22075/MACS.2024.33850.1658

the creation of next-generation, environmentally friendly wearable antennas with multiband capabilities and contributes to the continuing conversation about the convergence of wireless communication, [3] wearable technology, and environmental consciousness. [4] The article is about a special guitar-shaped antenna for super-fast 5G internet. It works well in 5G and has a good range. When they built a real one, it worked just as they expected. So, this guitar-shaped antenna is a good choice for super-speedy 5G internet. This design is used as a proposed design with some novelty. Testing a plant-based material called PLA for simple Micro patch antennas in smartwatches. The plant-based antennas performed better and are better for the environment when compared to a common material called FR-4. So, using PLA for antennas in wearable devices could make them work better and be more eco-friendly [2]. A type of eco-friendly synthetic fiber called PLA is made from plants. It's used in medical, packaging, and clothing stuff. It's easy to make, has special qualities, and can be recycled. The review is split into two parts. [4] The first part talks about how it's made, its qualities, how it performs, and its environmental impact. It's gaining popularity in different textile industries. This helps to study deeply about PLA. This thesis discusses the reason for better performance with [5] Taffeta due to its highest conductivity among the tested fabrics. It has quite low surface resistivity of less than 0.05 Ohms/sq which makes it well suited for highly efficient RF devices. It is also Lightweight with a weight of 72g/m2 and a thickness of 0.08mm. It is also highly tear-resistant.

2. CSRR Enhanced Design

The growth of wireless communication systems operating across multiple frequency bands has increased demand for multiband antennas. [1] In today's modern telecommunications, these antennas are essential for supporting various applications, including satellite communication, Wi-Fi, Bluetooth, GPS, and cellular networks. [4] Several techniques are employed to design multiband antennas, including resonant frequency adjustment, [6], [7], [8] metamaterials, SIW, matching networks, reconfigurable elements, and slot antennas. Among these techniques, the shift towards a newer antenna design, particularly leveraging metamaterial-based structures like CSRRs, provides distinct advantages for multiband antenna design.

It provides frequency tunability, enabling precise control over resonant frequencies to achieve multiband operation. [9] The rationale for selecting the CSRR design stems from its potential to enhance electric near-field effects through resonant excitation in a double-layer dielectric metasurface. While various geometrical designs for metamaterials and slot antennas have been documented, the CSRR design offers distinct advantages that warrant specific comparison and reference. This includes its ability to split Rayleigh-Wood anomalies into multiple modes and broaden spectral characteristics, as observed in numerical and experimental studies. Additionally, CSRRs are known for their ability to manipulate electromagnetic waves, particularly in achieving resonance and enhancing electric near-field effects. This capability is crucial in optimizing antenna characteristics such as impedance matching, bandwidth efficiency, and radiation pattern control. By integrating CSRRs into the PLA substrate, this manuscript aims to leverage these properties to achieve superior antenna performance across desired frequency bands, ensuring effective signal transmission and reception for wearable applications. Additionally, they maintain a compact size, making them suitable for integration into small-form-factor devices like wearable technology. [1], [4] Moreover, CSRRs enhance antenna performance by improving impedance matching, reducing cross-polarization, and increasing bandwidth. Their design parameters are flexible, allowing engineers to modify antenna features to suit performance needs for multiband operation. By harnessing these benefits, metamaterial-based CSRR antennas provide higher performance and versatility, making them ideal for multiband applications in modern wireless communication systems. In summary, [4] CSRRs play a pivotal role in modern antenna innovation, enabling heightened performance, adaptability, and efficiency in wireless communication. The incorporated CSRR in the proposed antenna is shown in Fig. 1 and the dimensions used are listed in Table 1. The equivalent circuit of CSRRs is mentioned in Fig. 2 and typically consists of inductors and capacitors, representing the resonant behavior of the structure. The split ring induces inductance, while the gap acts as a capacitor, forming a resonant LC circuit. This equivalent circuit model allows engineers to analyze and predict the behavior of CSRRs in antenna designs, aiding in the optimization of performance characteristics such as frequency response, bandwidth, and impedance matching.

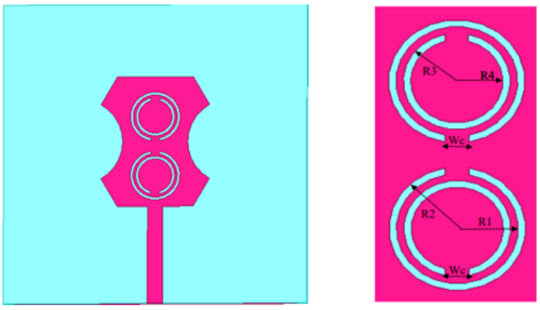


Fig. 1. Layout of Proposed Antenna with CSRR

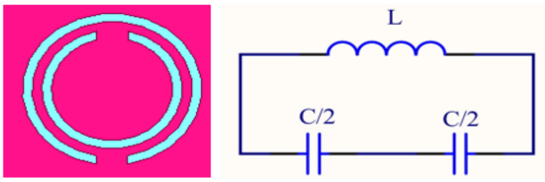


Fig. 2. Equivalent circuit of CSRR

2.1. Substrate Analysis

In this work, [2] Polylactic Acid (PLA) serves as the primary substrate, chosen for its eco-friendly and biodegradable characteristics.

Table 1. Dimensions of the CSRR

CSRR Parameters	Dimensions (in mm)
Wc	1.6
R1	4
R2	4.5
R3	3
R4	3.5

This involves a comparative analysis with alternative substrates, including denim (Jean), [10] Kapton, [11] Polydimethylsiloxane (PDMS), and Polytetrafluoroethylene (Teflon). The choice to specifically compare PLA with these materials in antenna substrate material selection is driven by several pivotal reasons. Firstly, these materials are readily available and commonly utilized across various industries, ensuring easy accessibility for comparison studies. [1] Moreover, each material boasts unique physical and electrical properties, encompassing factors such as [12] flexibility, eco-friendliness, thermal stability, dielectric constant, and moisture resistance.

The properties are discussed in Table 2. As these properties greatly influence antenna performance, evaluating PLA against a diverse array of materials allows for a thorough assessment of its suitability across different performance criteria. The investigation aims to elucidate how these materials impact the performance of the wearable antenna with its parameters, offering insights into their suitability for specific applications in the fields of electronics, fashion, and beyond.

2.1.1. Denim (Jean Material)

Denim, a rugged cotton fabric with a twill weave, possesses enduring qualities, making it a staple in the fashion industry. While denim offers durability and breathability, its electrical properties like low permittivity of 1.7, 1.8, or 2 and the loss tangent of 0.025 were used in this work, and suitability for electronic applications may pose challenges.

2.1.2. Polydimethylsiloxane (PDMS)

Polydimethylsiloxane, commonly known as PDMS, is a versatile silicone-based polymer with notable transparency, and biocompatibility. Ideal for microfluidic devices and biomedical applications, [11]PDMS offers unique advantages in terms of elasticity. It has a permittivity of 2.8, 3, or 3.4, and a loss tangent range from 0.01 - 0.05 was used in this work. However, its mechanical robustness may be a consideration in certain applications.

2.1.3. Kapton (Polyimide Film)

Kapton, a polyimide film developed by DuPont, stands out for its exceptional thermal stability, chemical resistance, and electrical insulation properties. [10] It has a relative permittivity of range from 3 - 4 and a loss tangent of 0.004 were used in this work. Widely utilized in aerospace, electronics, and automotive industries, Kapton's thin yet durable structure makes it a preferred choice for flexible circuits and applications requiring resilience in extreme conditions.

2.1.4. Teflon (Polytetrafluoroethylene - PTFE)

Teflon, or polytetrafluoroethylene (PTFE), boasts non-stick attributes, low friction, and chemical inertness. This has the permittivity value of 2, 2.02, 2.12, or 2.5, and a loss tangent of 0.00028 were used in this work. Widely recognized for its use in cookware, Teflon's limitations in flexibility and potential trade-offs in certain electronic applications should be considered.

2.1.5. Polylactic Acid (PLA)

A biodegradable polymer made from plants, polylactic acid (PLA) is sourced from renewable resources such as sugar cane, corn, and wheat. [1], [2] PLA has been employed in the biomedical, textile, optical, food packaging, and tissue engineering industries. It assumes specific characteristics such as biodegradability, biocompatibility, good mechanical capabilities, and electrical properties are listed in Table 3. However, PLA has certain disadvantages, including low impact strength, low glass transition temperature, moisture sensitivity, brittleness, and poor electrical conductivity. To enhance PLA's qualities, particularly its flexibility, thermal stability, and electric conductivity, numerous studies have been conducted in the areas of polymer alloy technology, blending, plasticization, copolymerization, and composite manufacture. The production process of Polylactic Acid (PLA) involves several stages, beginning with the extraction of raw materials from renewable sources. Typically derived from crops like corn or sugarcane, the first step is to harvest and process these plants into fermentable sugars, which serve as the foundation for PLA production. The extracted sugars undergo fermentation by lactic acid bacteria, converting them into lactic acid. Subsequently, lactic acid undergoes polymerization, a chemical reaction that links individual molecules into long chains, forming the PLA polymer. This process can be accomplished through either direct condensation or a two-step process involving lactide intermediates. Once the PLA polymer is synthesized, it is then processed into granules or pellets, which can be used as feedstock for various manufacturing applications. The final PLA products, ranging from packaging materials to [13] 3D printing filaments are fabricated using conventional plastic processing techniques like extrusion, injection molding, or thermoforming. Overall, the process of making PLA underscores its bio-based origin, renewable nature, and potential for reduced environmental impact in comparison to conventional plastics. The life cycle of Polylactic Acid (PLA) is discussed below in Fig. 3.

Fig. 3. The life cycle of PLA [13]

A conducting substance is required for both the radiating element and the ground plane in all antennas. The electrical conductivity of the substance affects the current that flows through the conductor that radiates. In the proposed antenna, [5] taffeta electro textile, which has the highest conductivity and a relatively low surface resistivity of less than 0.01Ω/sq, is used as the ground plane and radiating patch in the proposed antenna. This makes it suitable for efficient wearable antennas as well as other RF circuits and devices at wireless communication frequencies. It weighs 72 grams per square meter and is 0.08 mm thick. It is durable, incredibly resilient to tearing, and simple to mold and work with. There are several notable advantages to using "Pure Copper Polyester Taffeta" instead of standard copper as the conducting material for the patch. By fusing the electrical conductivity of copper with the flexibility and low weight of polyester, pure copper polyester taffeta offers a flexible substitute for [14] wearable technology. Furthermore, [2], [5] the PLA and Pure Copper Polyester Taffeta combination helps the antenna maintain a lightweight profile, which is important in wearable applications where low weight is necessary for user comfort.

2.2. Design Evolution

The antenna design involves a series of steps. Initially, a hexagonal shape is created for the patch. This first step of the antenna is shown as (a) Antenna 1 in Fig. 4. In the next step, the circle with radius is determined and the patch is cut to resemble a guitar shape, with cuts on the right and left from the center. This second step of the antenna is shown as (b) Antenna 2 in Fig. 4. Moving on to the third step, a single Complementary Split Ring Resonator (CSRR) is added to the design, imparting specific electromagnetic properties. This third step of the antenna is shown as (c) Antenna 3 in Fig. 4. In the fourth step, another CSRR is introduced, further enhancing the antenna's performance. This fourth step of the antenna is shown as (d) Antenna 4 in Fig. 4. [4] This detailed design process combines precise geometry with electromagnetic tuning, improving the antenna's ability to receive and transmit signals effectively.

2.3. Design Specification

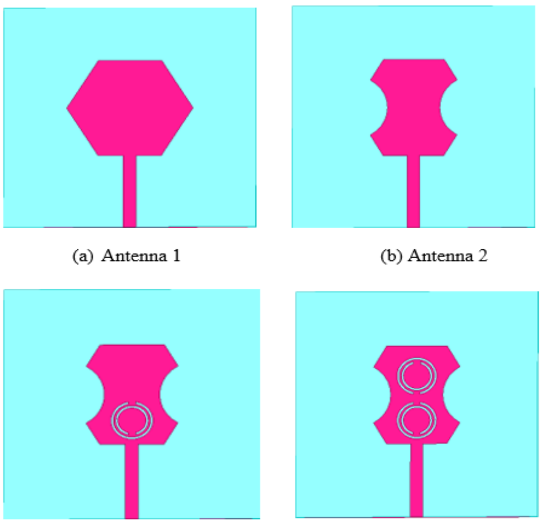
The proposed final evolution of the antenna is mentioned in Fig. 5, with the respective dimensions which are listed in Table 3.

Table 2. Properties of Substrate Materials

Physical and Electrical Properties					
Materials	**Permittivity [ε]**	**Loss tangent [tanδ]**	**Thermal Stability**	**Nature**	**Moisture Resistant**
PLA	3.1	0.006-0.01	160°C to 180°C	compostable	Moderate
Denim	1.8	0.025	200°C	de-compostable	Moderate
Kapton	3 - 4	0.004	-269°C to 400°C	de-compostable	High
PDMS	2.8	0.01 – 0.05	250°C	de-compostable	High
Teflon	2	0.00028	260°C	de-compostable	High

Table 3. Dimensions of the Proposed Antenna

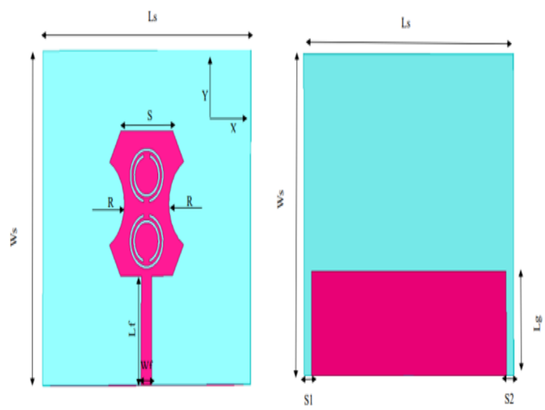
Antenna Parameters	Dimensions (Mm)
Ls, length of the substrate	56
Ws, width of the substrate	56
S, side of the patch	14
R, radius of the circles	8w
Lf, length of the feedline	18.2
Wf, width of the feedline	2.8
Lg, length of the ground	18.2
S1 & S2	2



(a) Antenna 1 (b) Antenna 2

(c) Antenna 3 (d) Antenna 4

Fig. 4. a, b, c, d - Evolution of Proposed Antenna



(a) (b)

Fig. 5. Layout of Proposed Antenna (a) top view, (b) bottom view

The design process involves a series of calculations to optimize antenna performance for specific requirements using Ansys HFSS Software. This includes determining the effective wavelength, setting up parameters for length variations, and performing parametric sweeps to analyze and enhance the antenna's efficiency and functionality.

HFSS provides precise electromagnetic field simulations, crucial for high-frequency design validation, enabling engineers to model, simulate, and refine complex RF and microwave components accurately. [1] Key considerations include frequency, bandwidth, radiation pattern, gain, impedance matching, and size constraints.

$$(\epsilon_r) = 3.1 \quad (1)$$

$$C = 3 * 10^{8} \quad (2)$$

$$w = \frac{C}{2f\sqrt{\frac{(\epsilon_r + 1)}{2}}} \quad (3)$$

$$\epsilon_r\ eff = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-\frac{1}{2}} \quad (4)$$

$$Leff = \frac{C}{2f\sqrt{\epsilon_r\ eff}} \quad (5)$$

$$\Delta L = 0.412h\frac{(\epsilon_r\ eff + 0.3)(\frac{w}{h} + 0.264)}{(\epsilon_r\ eff - 0.258)(\frac{w}{h} - 0.8)} \quad (6)$$

$$incrementsL = Leff - 2\Delta L \quad (7)$$

$$Wg = 6h + W \quad (8)$$

$$Lg = 6h + L \quad (9)$$

where the above equations from 1 to 9 describe the Resonant frequency f (in Hz), C is the Speed of the light (in m/s), w is the width of the patch (in meters), ϵ_r is the Relative permittivity of the substrate, Leff is Effective length of the patch (in meters), ΔL_ is Delta length, L is the length of the patch (in meters), Wg is the Width of the ground (in meters), and Lg is the Length of the ground (in meters).

3. Results & Discussions

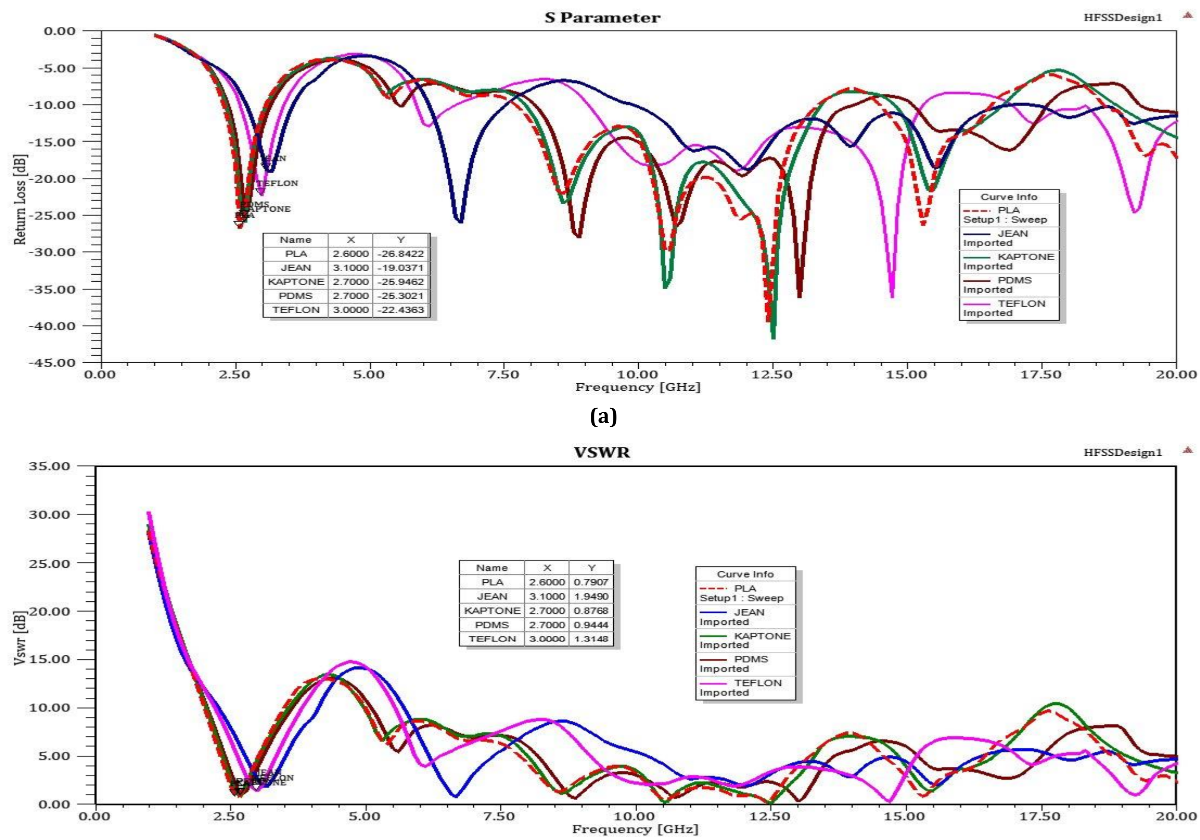
In this section, the results were analyzed and discussed for substrate comparative and evolutional design with [15] antenna measurements.

3.1. Comparative Analysis

Wearable antennas are integral to the advancement of wearable technology, enabling seamless integration of communication and sensing functionalities into everyday clothing and accessories. The selection of PLA (Polylactic Acid) as a substrate in this context offers several significant advantages over other potential substrates. PLA is a biodegradable, environmentally friendly material, aligning with the increasing demand for sustainable technologies. Its mechanical flexibility and lightweight nature make it ideal for comfortable, unobtrusive wearable devices. Furthermore, PLA exhibits excellent dielectric properties, ensuring efficient electromagnetic wave propagation and minimal signal loss. Additionally, PLA's compatibility with 3D printing technologies allows for precise, customizable antenna designs, enhancing the overall functionality and adaptability of wearable antennas in various applications. In a comprehensive analysis, the comparison focused on [15] critical parameters such as return loss, VSWR, gain, directivity, efficiency, and other parameters to determine the most suitable substrate for the design of a wearable antenna. Among the substrates, PLA exhibited a resonance frequency of 2.6 GHz, accompanied by an impressive return loss of -26 dB and a VSWR of 0.79 dB. On the other hand, Jean resonated at 3.1 GHz with a return loss of -19 dB and a VSWR of 1.94 dB. Whereas Kapton resonance at 2.7 GHz, yielded a return loss of -25 dB and a VSWR of 0.87 dB. PDMS resonated at 2.7 GHz with a return loss of -25 dB and a VSWR of 0.94 dB, and Teflon resonated at 3 GHz with a return loss of -22 dB and a VSWR of 1.31 dB. The PLA's resonance at 2.6 GHz, coupled with an exceptional return loss of -26 dB and a low VSWR of 0.79 dB, signifies superior performance in terms of impedance matching and signal efficiency.

The S-Parameter and VSWR analysis are shown in Fig. 6. Additionally, the other parameters were analyzed and the proposed antenna resonates in multiband frequencies which range from 2 GHz to 15 GHz with applications like WiFi, Bluetooth, Radar, and Satellite Communications.

However, since the focus is on wearable technology, the operating frequency selected is specifically tailored for wearable applications, and the analysis has been conducted accordingly which is discussed in Table 4.



(b)

Fig. 6. S-Parameter (a) & VSWR, (b) for PLA and Various Substrates

Table 4. Comparative Analysis of parameters for various substrates

Substrates	Multiband Frequencies [Ghz]	Return Loss [dB]	VSWR [dB]	Gain [dB]	Directivity [dB]	Efficiency [%]	Bandwidth [MHz]
PLA	**2.6**, 8.6, 10.5, 12.4, 15.3	-26.84	0.7907	1.6397	1.843	92	870
Jean	**3.1,** 6.7, 12, 15.5	-19.03	1.9490	1.6619	1.8376	90	870
Kaptone	**2.7,** 8.6, 10.5, 12.5, 15.4	-25.94	0.8768	1.7152	1.8366	92	790
PDMS	**2.7,** 8.9, 10.7, 13	-25.30	0.9444	1.700	1.8475	92	820
Teflon	**3,** 14.7, 19.2	-22.43	1.3148	1.7038	1.854	91	830

In comparison, Jean, Kapton, PDMS, and Teflon, while exhibiting certain merits, with slight variations do not match the combined excellence of PLA in return loss, VSWR, and other parameters. Comparing these findings, it is evident that PLA stands out as the substrate with the lowest resonant frequency and the highest return loss, making it a favorable choice for the wearable antenna[16], [17] design, offering an ideal balance between resonance characteristics and impedance matching for effective signal transmission and reception in wearable applications.

3.2. Evolutional Analysis

The iterative evolution of the antenna designs was systematically examined through a comprehensive parametric analysis, with a specific focus on understanding the S11 dB characteristics, VSWR, and such parametric of the proposed guitar-shaped antenna. [18] This analytical approach aimed to reveal the antenna's performance at various stages of optimization. Commencing with Antenna 1 in the design evolution, the parametric analysis revealed a return loss of -16 dB at 2.9 GHz, setting the initial norm for further improvements and establishing the initial performance baseline. Advancing to the second design iteration Antenna 2, by determining the circle radius of 8mm and implementing cuts to create the desired shape, the antenna exhibited improved characteristics. The return losses saw a notable enhancement, improving at -19 dB at 2.7 GHz. This refinement underscored the impact of geometric modifications on the antenna's frequency response.

Transitioning to Antenna 3 in the evolutionary process, the careful evaluation revealed a significant improvement, with the return loss reaching -24 dB at 2.6 GHz. This indicated the effectiveness of introducing resonators for enhanced performance. In the Antenna 4, which made final improvements by adding another CSRR. This had a big impact and helped the antenna perform well, with a fantastic return loss of -26 dB at 2.6 GHz, aligning closely with the desired operating frequency. A higher Return Loss value indicates minimal power reflection, signifying superior impedance matching and optimized power transfer.

The S-parameter of the evolution of the proposed antenna is shown in Fig. 7. Similarly, the VSWR analysis at each evolutionary step of the antenna design revealed insightful performance improvements [19]. Finally, Antenna 4, featuring an additional CSRR, demonstrated impressive performance,

Reducing a VSWR value of 0.79 dB at 2.6 GHz signifies a superior impedance-matching performance compared to the earlier design iterations. [20] The lower VSWR indicates minimal signal reflection and better alignment between the antenna and the transmission line, resulting in improved efficiency and signal transmission capabilities.

Therefore, the Antenna 4 can be considered a satisfactory design in the evolutionary stages. The VSWR of this evolution of the proposed antenna is shown in Fig. 8. Additionally, the bandwidth, efficiency, gain, and other parameters are also obtained for the proposed antenna's evolution and listed in Table 5.

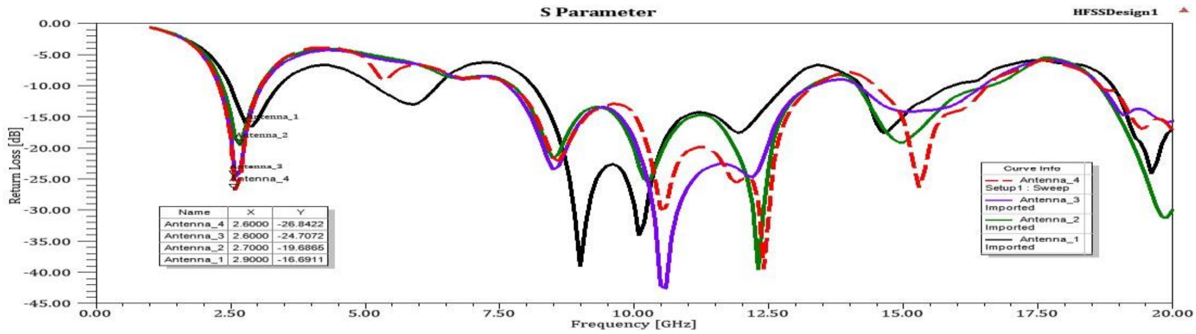


Fig. 7. S-Parameter for Evolution of Proposed Antenna

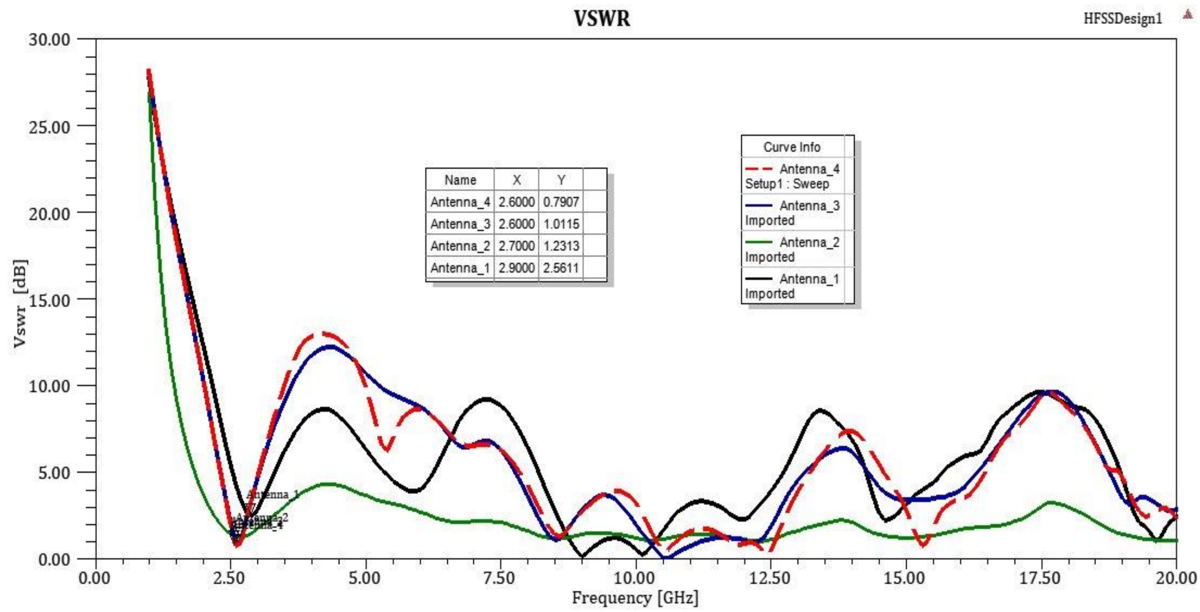
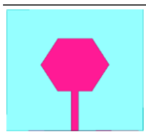
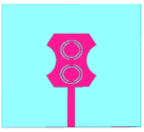


Fig. 8. VSWR for Evolution of Proposed Antenna

Table 5. Analysis of Antenna Evolution parameters

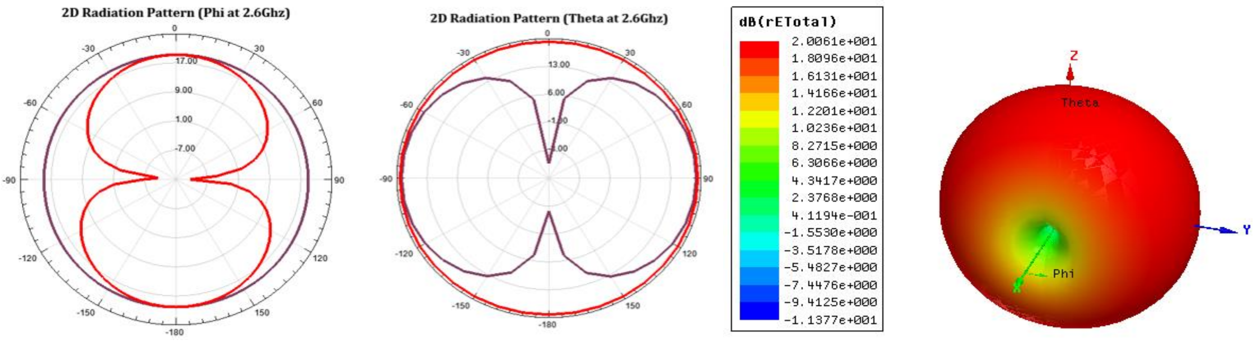
Evolution	**Multiband requencies [GHz]**	**Return Loss [dB]**	**VSWR [dB]**	**Gain [dB]**	**Directivity [dB]**	**Efficiency [%]**	**Bandwidth [MHz]**
	2.9, 9, 10.1, 19.6	-16.69	2.561	1.774	1.8806	94	930
	2.7, 8.5, 10.5, 12.2, 15	-21.78	1.231	1.7256	1.8354	94	720
	2.6, 8.5, 10.4, 12.2	-24.70	1.01	1.7149	1.858	92	820
	2.6, 8.6, 10.5, 12.4, 15.3	-26.84	0.7907	1.6397	1.843	92	870

3.3. Measurements of the Proposed Antenna

In continuation with S11 and VSWR, the antenna measurements such as Radiation Pattern, gain, directivity, bandwidth, and efficiency are the key characteristics, that define the performance and behavior of an antenna in various communication systems. [21] These parameters play a crucial role in ensuring efficient signal transmission and reception.

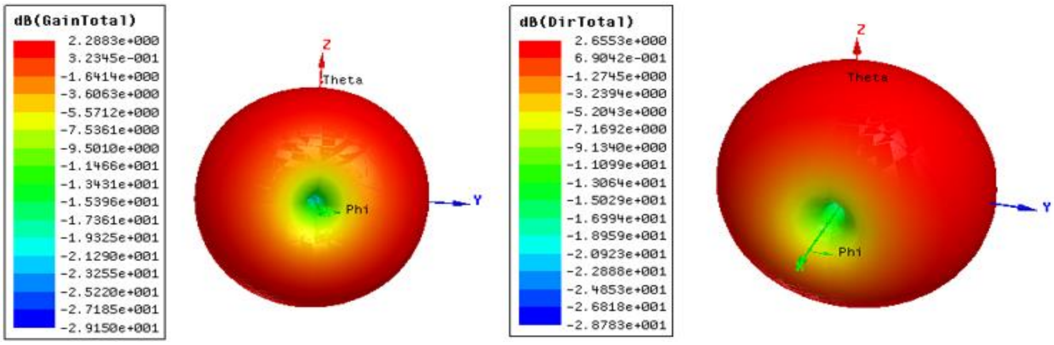
The radiation pattern of an antenna illustrates how electromagnetic energy is distributed in space. In the analysis, the evaluation of the radiation pattern was undertaken through 2D plots (for both E and H planes in terms of phi and theta) and 3D plots at the operating frequency of 2.6 GHz.

The results revealed that the proposed antenna achieved a maximum radiation efficiency of 20.061 dB, which radiates in Bidirectional. These results are depicted in Fig. 9. The analysis of gain and directivity plots at the 2.6 GHz operating frequency was obtained for the proposed antenna design.



(a) (b) (c)

Fig. 9. E & H planes (a), (b) and 3D plot, (c) of Radiation Pattern



(a) (b)

Fig. 10. Gain (a) and Directivity, (b) plot of the proposed antenna

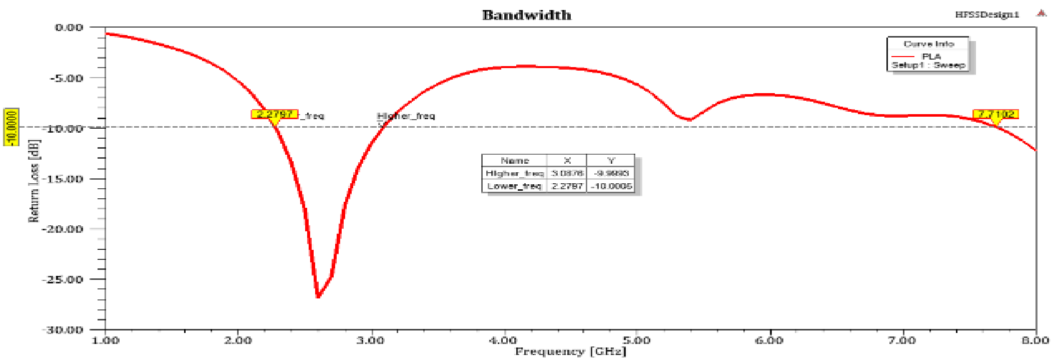
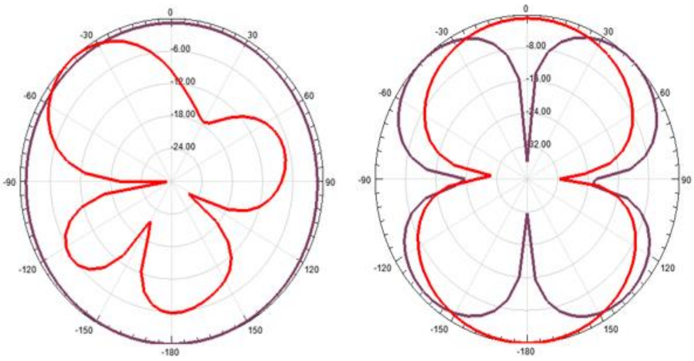


Fig. 11. Bandwidth plot of proposed antenna at -10 dB

The results revealed an impressive maximum gain of 2.2883 dB and a maximum directivity of 2.6553 dB is represented in Fig. 10. This gain indicates the antenna's effectiveness in amplifying signals, contributing to improved communication performance. Additionally, the obtained directivity suggests that the antenna efficiently focuses radiation in specific directions. Therefore, the proposed antenna design demonstrates a good balance between gain and directivity, making it suitable for practical wearable applications. The proposed antenna achieved radiation efficiency in terms of peak gain and peak directivity while the gain and directivity are proportional to each other and equal to efficiency. Thus, the radiation efficiency obtained an impressive value of 92%, showcasing the antenna's efficiency in converting input power into radiated energy. These results collectively affirm the effectiveness of the antenna design, demonstrating high radiation efficiency, substantial gain, and directed signal propagation.

Bandwidth in antenna design refers to the range of frequencies over which the antenna can effectively transmit and receive signals. The bandwidth of the proposed antenna is calculated as 808.2 MHz at -10 dB and represented in Fig. 11.

In the context of wearable devices[22], [23], where compactness and versatility are key considerations, an 808.2 MHz bandwidth provides substantial coverage for various communication protocols and frequency bands. This wide bandwidth ensures that the antenna is capable of accommodating diverse wireless communication standards, making it well-suited for applications in wearable technology.



(a) **(b)**

Fig. 12. (a) E & H plane Co polarization, (b) E & H plane Cross polarization

The obtained 2D radiation patterns of Co-Cross polarization for both the E-plane and H-plane are shown in Fig. 12, for 2.6 GHz operating frequency. [24]The theta (θ) and phi (φ) are the spherical coordinates to the Cartesian axis alignments such as, when φ is equal to 0 and sweeps θ from 0 to 360 is called an E-plane. On the other hand, when φ is equal to 90 and sweeps θ from 0 to 360 is called an H-plane.

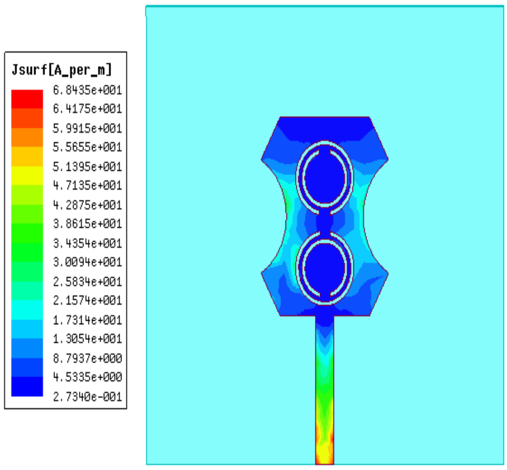


Fig. 13. The current distribution of the proposed antenna

Understanding the Current distribution is crucial for [25] optimizing antenna performance. The current distribution of the proposed antenna is represented in Fig. 13, revealing the highest intensity of current within the antenna structure, and providing insights into the spatial distribution of electrical flow through the feed line. This maximum value of current distribution suggests efficient energy utilization within the design, contributing to improved antenna performance.

Impedance matching is a crucial aspect of antenna design, ensuring efficient power transfer between the transmission line and the antenna itself. Achieving impedance matching is essential for minimizing signal loss and maximizing the effectiveness of the antenna system in various communication applications. In the analysis, the proposed antenna achieved a 50-ohm impedance represented in Fig. 14, which signifies a successful impedance match, as it corresponds to the standard impedance commonly used in radio frequency systems. This alignment ensures optimal power transfer between the antenna and the transmission line, indicating that the antenna is well-matched to the [26] desired impedance specifications.

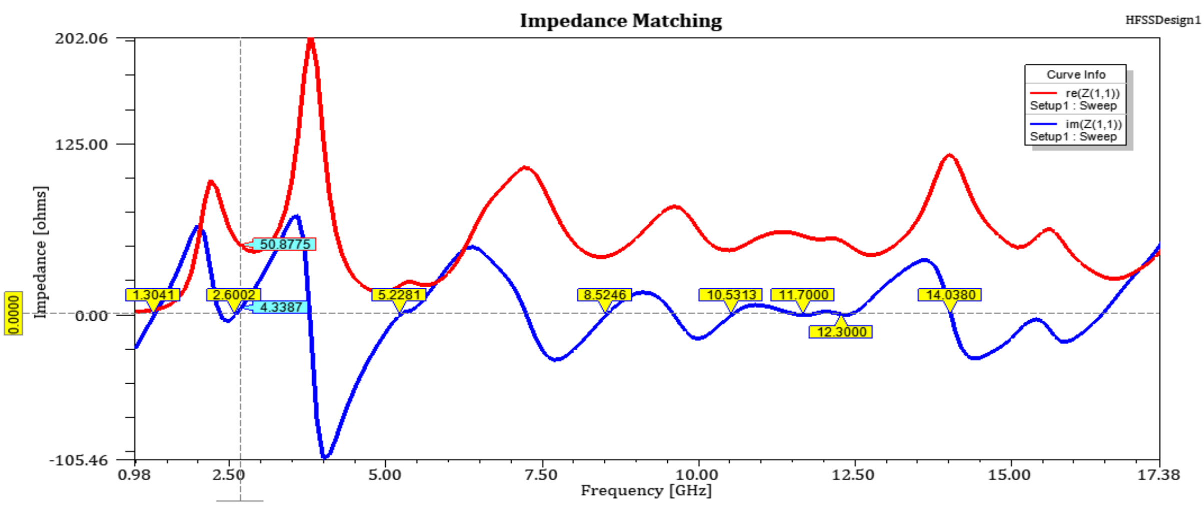


Fig. 14. Impedance plot of proposed antenna for 2.6 GHz

3.3.1. SAR and Conformal Analysis

The SAR [15] (Specific Absorption Rate) test measures the rate at which the human body absorbs RF (radio frequency) energy from wireless devices, ensuring compliance with safety standards. In this proposed, the SAR analysis is conducted with a human hand model at a distance of approximately 8.5 mm from the antenna over 1 gram of tissue, as represented in Fig. 15.

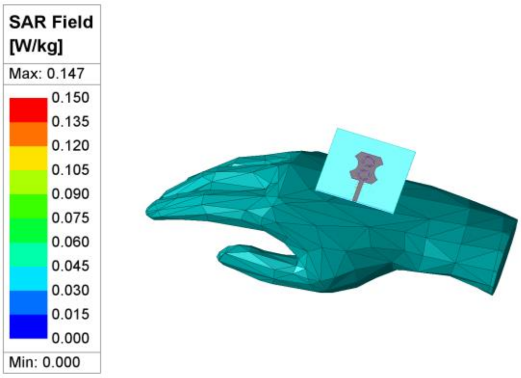


Fig. 15. SAR analysis for the proposed wearable antenna at 2.6 GHz

The test yielded a result of 0.147 W/Kg for the operating frequency of 2.6 GHz, which falls within the acceptable range for wearable technology applications. The Federal Communications Commission (FCC) mandates that SAR levels for mobile devices should not exceed 1.6 W/kg averaged over 1 gram of tissue, while the International Commission on Non-Ionizing Radiation Protection (ICNIRP) sets a limit of 2 W/kg averaged over 10 grams of tissue. This ensures compliance with safety standards, suggesting that the proposed antenna design poses minimal risk of excessive electromagnetic energy absorption by the human body. Consequently, the antenna meets safety standards and is suitable for integration into [22] wearable devices.

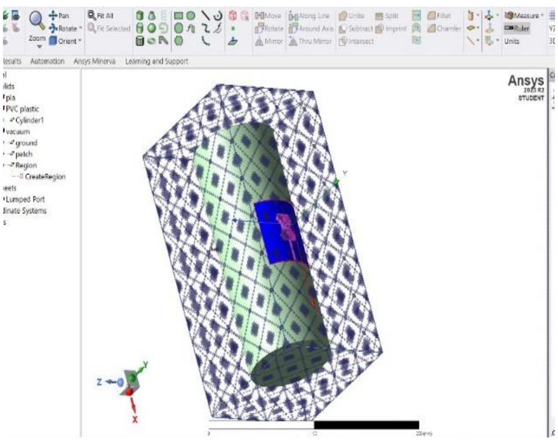
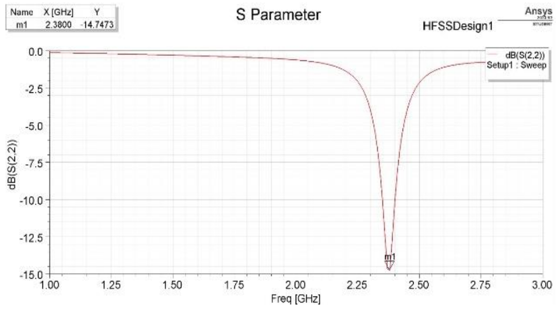


Fig. 16. Conformal analysis for the proposed wearable antenna

Additionally, by analyzing the conformal test, [22], [23] it was observed that antenna parameters remain consistent before and after bending. However, slight bending of the antenna in the X-bend and Y-bend directions resulted in adjustments in return loss, as depicted in Fig. 16, and Fig. 17, although still within the same operating frequency range. The antenna demonstrates its capability to withstand bending without losing efficiency, showcasing performance and adaptability to deformation.



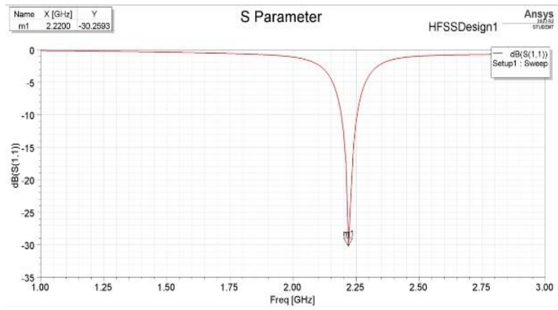


Fig. 17. S11 for (a) X-bending, (b) Y-bending Conformal analysis for the proposed wearable antenna

4. Limitations & Scope

The current antenna design may face challenges related to bandwidth limitations, size constraints, and manufacturing complexity, which could affect its performance across a wide frequency range and scalability [6]. Moreover, the long-term durability of the PLA substrate in varying environmental conditions like temperature and humidity remains a concern. To address these issues, future improvements could focus on enhancing bandwidth capabilities, optimizing size and form factors for easier integration, and simplifying manufacturing processes [27]. Additionally, exploring alternative biodegradable materials and advanced fabrication techniques could further enhance antenna performance and durability. These advancements would enable the antenna to achieve greater versatility, efficiency, and cost-effectiveness, thereby facilitating broader adoption in wireless communication and wearable technology applications.

5. Conclusions

In conclusion, the proposed design for wearable multiband applications using PLA represents significant progress in antenna design and sustainable technology. Through a precise iterative process, the antenna evolved in four stages, each contributing to enhanced performance and versatility. Antenna 1 resonates across four multi-band spanning from 2 to 19 GHz, exhibiting lower return losses but acceptable parameters such as a maximum gain of 1.774 dB and 94% efficiency. Antenna 2 covers five bands from 2 to 15 GHz, maintaining acceptable parameters. Antenna 3 operates across four bands, from 2 to 12 GHz. The final evolution design stands out for its remarkable performance, resonating across five bands from 2 to 15 GHz, with each band achieving maximum gain ranging from 2 to 5 dB, good VSWRs, high directivity, and an efficiency range of 90% to 98%, along with satisfactory bandwidths. Furthermore, the comparative analysis of substrates, particularly with the primary substrate PLA, corroborates these findings. PLA exhibited the lowest resonant frequency with the wearable band and the very minimal return loss, indicating superior impedance matching and signal efficiency. Compared to standard materials like Jean, Kapton, PDMS, and Teflon, PLA demonstrated better overall performance by highlighting its superior performance and suitability for the design of wearable antennas. Additionally, to ensure suitability for wearable applications, SAR analysis indicated compliance with safety standards, with values below 1.5. Bending analysis yielded satisfactory results, affirming the antenna's robustness and practical applicability. Therefore, PLA stands out as the most suitable substrate for the wearable antenna design, offering an ideal balance between resonance characteristics and impedance matching for effective signal transmission and reception in wearable applications.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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