Design and Analysis of a Miniaturized Triple-Band Implantable Antenna for Biomedical Applications

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Abstract: *This paper presents the design and simulation of a compact F-shaped patch antenna for implantable biomedical applications. The antenna is optimized to operate at three key frequency bands: 401–406 MHz (MICS), 1.395–1.432 GHz (WMTS), and 2.4–2.5 GHz (ISM). A progressive design approach—starting from an I-shape and evolving to an F-shape with a shorting pin—was employed to achieve multiband operation and circular polarization. Full-wave simulations were performed using CST with a realistic three-layer human tissue phantom based on the Zubal model. The final design exhibits return loss below –10 dB, stable VSWR, gain consistency, and radiation efficiency above –15 dB across all bands. Radiation pattern analysis shows a transition from omnidirectional to directional as frequency increases. The antenna also maintains robustness against implantation depth variation and supports communication distances up to 15 meters. These results demonstrate the antenna's potential for reliable, efficient in-body wireless communication.*

Keywords: Implant antenna; Triple-band; Patch antenna; Biomedical; Miniaturized.

1. INTRODUCTION

The rapid advancement of biomedical technology has significantly increased the demand for compact, efficient, and reliable wireless communication systems that can be seamlessly integrated into implantable medical devices. These systems are essential for supporting real-time monitoring and communication of critical health parameters, such as ECG, blood pressure, temperature, oxygen saturation, and artificial pancreas activity [1-3]. sEMG-based telerehabilitation [4] underscores the need for reliable implantable antennas for continuous physiological monitoring.

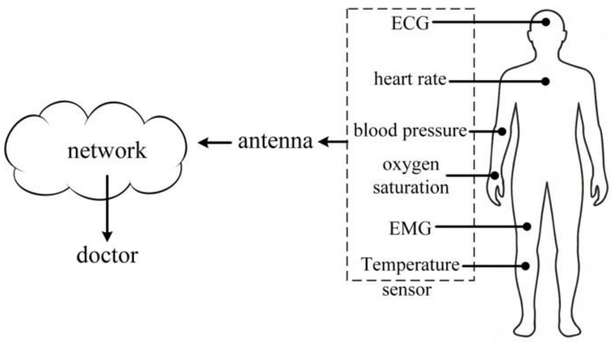


Fig.1. concept of a biomedical body area network

Fig.1 illustrates the concept of a biomedical body area network, where sensors and implantable antennas transmit data wirelessly to external devices and network, allowing doctors to remotely monitor patient health without needing to measure patients manually. By reducing the need for routine physical checks, antennas and wireless data transmission significantly lighten the workload of healthcare workers and streamline hospital operations. As personalized healthcare continues to evolve, implantable and wearable systems are increasingly relied upon for chronic disease management, emergency alerts, and continuous health tracking. Body Area Networks (BANs) are also expected to play a key role in telemedicine, enabling real-time data sharing during virtual consultations and supporting remote diagnosis, treatment, and chronic disease management.

These applications demand uninterrupted, secure, and adaptive wireless communication. Since various types of physiological data and medical protocols operate over different frequency bands, it becomes essential for antennas in these devices to support multi-band capability [5]. For example, the MICS band (401–406 MHz) is allocated specifically for implant communication due to its deep tissue penetration and low interference. The 1.395–1.432 GHz frequency band, designated for Wireless Medical Telemetry Service (WMTS), is used for transmitting real-time physiological data such as ECG and vital signs in healthcare environments, providing a stable, licensed communication channel that reduces the risk of interference. Meanwhile, the 2.4–2.5 GHz ISM band is a global standard for high-data-rate transmission in Wireless Body Area Networks (WBANs). Therefore, an antenna capable of covering these three frequency bands would offer versatility and compatibility across a broad range of biomedical applications. A Body Area Network (BAN) is a system of wearable and implantable sensors that collect physiological signals and transmit them wirelessly to external monitoring units. Such networks support continuous health tracking and enable real-time diagnostic feedback, forming the foundation of modern personalized healthcare systems, where sensors and implantable antennas transmit data wirelessly to external devices, base stations, and cloud platforms, allowing doctors to remotely monitor patient health.

One of the core challenges in this domain is designing antennas that are not only miniaturized but also capable of operating across multiple frequency bands required by modern medical applications. In particular, the Medical Implant Communication Service (MICS) band at 401–406 MHz is specifically allocated for implantable device communication due to its minimal interference and optimal propagation through human tissue. The 1.395–1.432 GHz band, designated for WMTS, is increasingly adopted for medical telemetry applications due to its licensing protection and reliability in clinical environments. Alongside this, the 2.4–2.5 GHz ISM band is widely used in Wireless Body Area Networks (WBANs) due to its global availability, adequate bandwidth, and support for high-data-rate transmission

To address these needs, our research focuses on the design and development of a Miniaturized F-Shaped Patch Antenna with Circular Polarization, specifically optimized for biomedical implant applications.

The proposed antenna is designed to operate across three critical frequency bands:

401–406 MHz (Medical Implant Communication Service: MICS): for reliable communication between implanted devices and external monitors.

1.395–1.432 GHz (WMTS band): for transmitting real-time medical telemetry such as ECG signals in clinical and hospital environments.

2.4–2.5 GHz (ISM band): commonly used in Wireless Body Area Networks (WBANs) for continuous data transmission.

To achieve this, the antenna employs a compact F-shaped patch structure with optimized slot geometry and metallic shorting pins. These features support circular polarization and multi-band functionality while minimizing antenna size. Circular polarization is particularly important in the human body due to tissue scattering and orientation variability, and it helps reduce polarization mismatch between the antenna and receiving systems.

While prior research has successfully demonstrated the use of miniaturized circularly polarized antennas at a single frequency band (e.g., 2.45 GHz) [6], our work extends this approach to support triple-band operation with improved impedance matching and radiation characteristics across MICS, WMTS, and ISM bands.

To evaluate the proposed antenna design, comprehensive full-wave simulations were conducted using CST Studio Suite. The antenna model was constructed using Rogers substrate, which is known for its low loss and stable dielectric properties, making it suitable for implantable applications. Additionally, the simulation incorporated a homogeneous three-layer phantom model—comprising skin, fat, and muscle layers—constructed in CST based on the Zubal human model, which accurately represents the dielectric properties of human tissue. This simulated environment was used to assess antenna performance under realistic biomedical conditions. All performance results presented are based solely on simulation data.

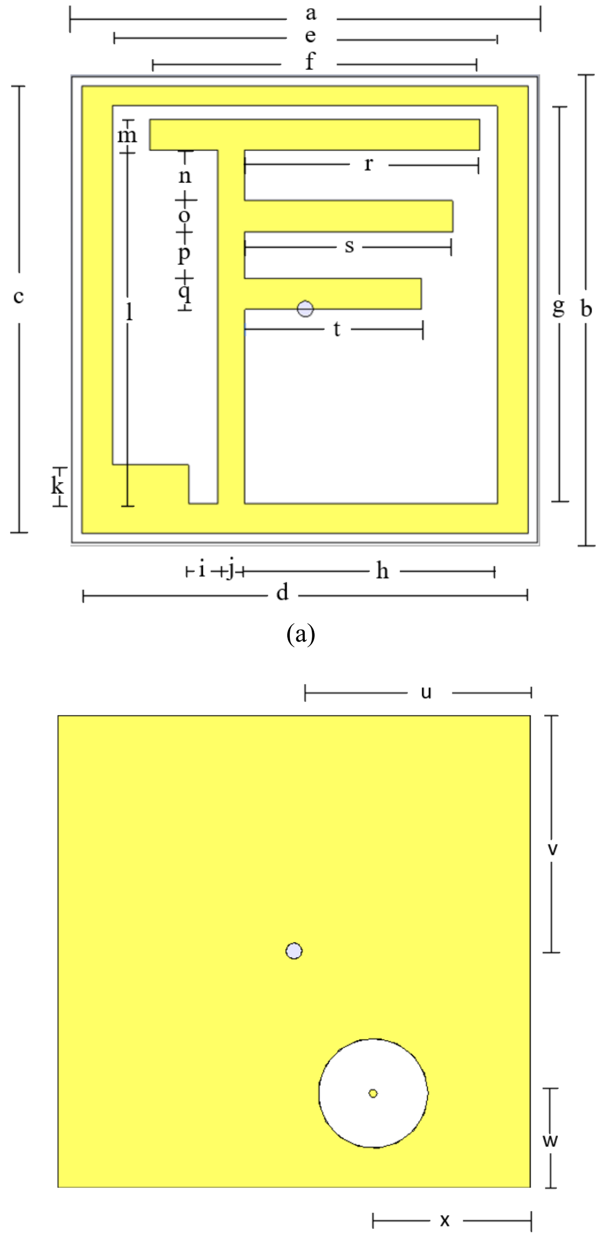
Recent studies in antenna research further support the importance of material and structure optimization in achieving high-performance designs. For instance, Didik Aprianto et al. [7] developed a microstrip patch antenna using a barium titanate-epoxy resin substrate, achieving a return loss of –42.52 dB at 5 GHz and proving the potential of composite dielectrics for compact antenna structures. In another study, Alam et al [8] proposed a triple-band substrate-integrated waveguide (SIW) antenna for high-frequency applications, demonstrating excellent gain and efficiency across K-band and Ka-band frequencies through a multilayer and ring-slot design.

By integrating compact size, multi-band operation, and stable circular polarization, the proposed antenna offers a promising solution for next-generation implantable biomedical devices, enabling safer, smarter, and more connected healthcare systems.

2. ANTENNA DESIGN AND ANALYSIS

2.1 Antenna Design

The design of a multiband antenna is achieved by shaping its geometry to support multiple resonant frequencies within the desired operating bands. The structure of the proposed triple-band implantable antenna is shown in Fig. 2.



(a)

(b)

Fig.2. Geometry of the proposed antenna: (a) radiation patch, (b) ground plane

Rogers 4053 material, characterized by high relative permittivity (ε_r = 3.55) and low loss tangent (tan δ = 0.0027), is used as both the substrate and superstrate.

This selection supports antenna miniaturization while providing insulation from the conductive properties of human tissue. The antenna design started with an initial I-shaped structure, which was then modified into an F-shaped configuration. A pin was subsequently added to improve impedance matching across all three target frequency bands. The final optimized dimensions of the proposed antenna, obtained using CST simulation software, are summarized in Table 1.

To closely replicate the real operating conditions of the proposed antenna, a homogeneous three-layer phantom model—comprising skin, fat, and muscle layers—is constructed in CST based on the Zubal human model. Since human tissues are lossy, electromagnetic waves experience attenuation as they propagate through the body. However, when the implanted antenna is placed at the center of a phantom with a cross-sectional width equal to a quarter-wavelength, the influence of surrounding tissue can be considered negligible [9-10].

Table 1. Optimized dimensions of the proposed antenna

Parameter	Length (mm)	Parameter	Length (mm)
a	12.0	m	0.8
b	12.0	n	1.3
c	11.5	o	0.8
d	11.5	p	1.2
e	9.9	q	0.8
f	8.5	r	6.05
g	9.25	s	5.35
h	6.5	t	4.55
i	0.75	u	6
j	0.7	v	6
k	1.0	w	2.9
l	9.35	x	4.32

To reduce simulation time, the phantom's dimensions are minimized while maintaining anatomical relevance. As a compromise, a phantom with dimensions of $100 \times 100 \times 58$ mm³ is used, as shown in Fig. 3. In physiological terms, the muscle layer is surrounded by connective tissues rich in capillaries and nerves, which are ideal for implantable medical devices (IMDs) to sense vital signals. Therefore, the proposed antenna is implanted in the muscle layer at a depth of dp = 4 mm. The dielectric properties of the three tissue layers at 0.4 GHz, 1.4 GHz, and 2.45 GHz are listed in Table 2.

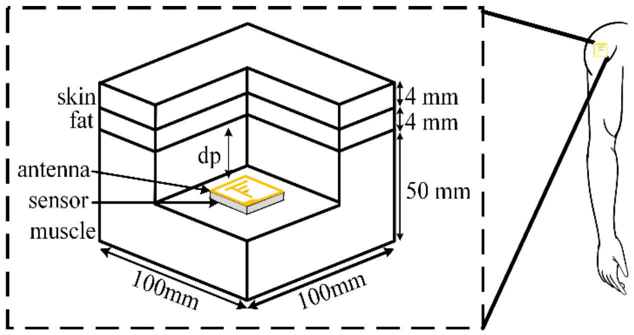


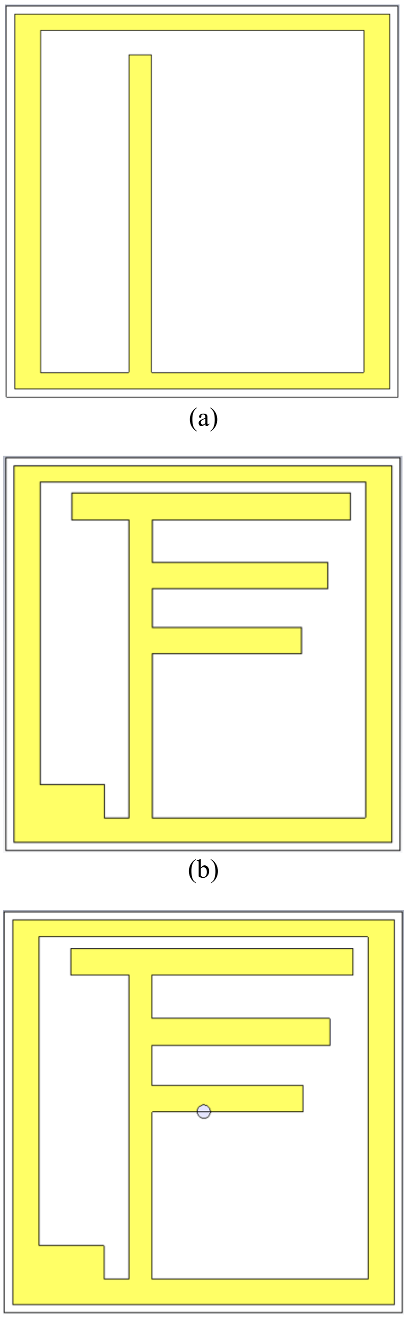
Fig.3. Simulation environment of the proposed antenna: Three - layer phantom model in CST

Table 2. Dielectric properties of the three-layer human tissue model

Tissue	0.4 GHz		1.4 GHz		2.45 GHz	
	ε_r	$\sigma\,(s/m)$	ε_r	$\sigma\,(s/m)$	ε_r	$\sigma\,(s/m)$
Skin	46.7	0.69	39.66	1.04	38.0	1.46
Fat	5.58	0.04	5.57	0.04	5.28	0.10
Muscle	57.1	0.80	54.11	1.14	52.7	1.74

2.2 Operating mechanism

To clarify the evolution of the antenna structure toward achieving the targeted multiband performance, three design cases (Case 1 to Case 3) were systematically developed and compared under identical simulation conditions, as illustrated in Fig. 4.



(a)

(b)

(c)

Fig.4. Evolution of the proposed antenna topology from (a) Case 1 and (b) Case 2, to (c) Case 3

In Case 1 (Fig. 4(a)), the antenna is initially designed with a compact square layout measuring 12 mm × 12 mm, corresponding to the intended size constraint for biomedical implantation. The radiating element adopts a simple I-shaped geometry, with the design parameters j and l being optimized to generate two distinct resonances. These resonant frequencies are observed at approximately 0.25 GHz and 2.9 GHz, which indicates preliminary dual-band behavior but falls outside the desired operational bands.

In Case 2 (Fig. 4(b)), the geometry has evolved into an F-shaped structure to further support the development of a triple-band response. The F-shape introduces asymmetrical and multiple current paths, which effectively enables the excitation of additional resonant modes. By tuning the structural parameters m, n, o, p, q, r, s and t, a third resonance is achieved. However, the resulting resonant frequencies still do not align with the medically significant target bands.

To refine the response and precisely align the resonances with the required frequency bands, Case 3 (Fig. 4(c)) introduces an additional shorting pin into the structure. The pin is strategically positioned and optimized to fine-tune the impedance characteristics. This final configuration successfully achieves resonances at the three target frequency bands: 401–406 MHz (MICS), 1.395–1.432 GHz (WMTS) and 2.4–2.5 GHz (ISM).

The return loss response of all three cases is compared in Fig.5, where Case 3 exhibits significant improvement, with all three resonances achieving return loss values below –10 dB, indicating effective impedance matching and suitability for biomedical communication applications.

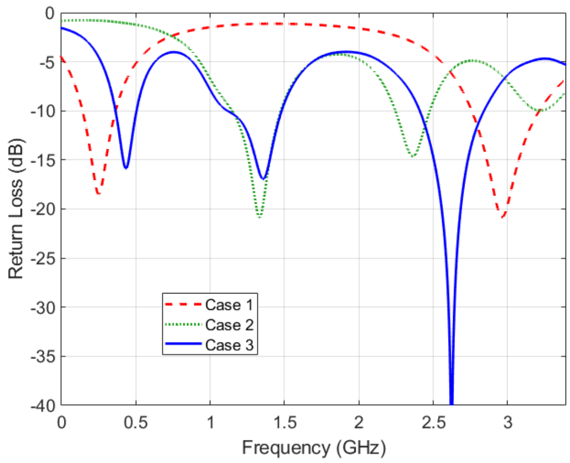


Fig.5. Return Loss comparison in the evolution process

2.3 Performance Analysis

In this section, the performance of the proposed miniaturized triple-band implantable antenna is evaluated using key parameters that are essential in assessing antenna efficiency and suitability for biomedical applications. These include Voltage Standing Wave Ratio (VSWR), gain, radiation efficiency, and 3D radiation patterns at the target frequency bands of 401–406 MHz, 1.395–1.432 GHz, and 2.4–2.5 GHz.

As shown in Fig.6, the VSWR performance varies significantly across the three cases. In Case 1, the antenna exhibits poor impedance matching with high VSWR values exceeding 10 across most of the frequency range, indicating strong signal reflection and low efficiency.

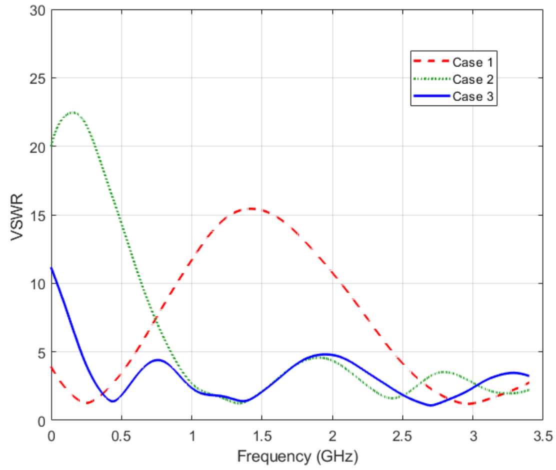


Fig.6. VSWR comparison in the evolution process

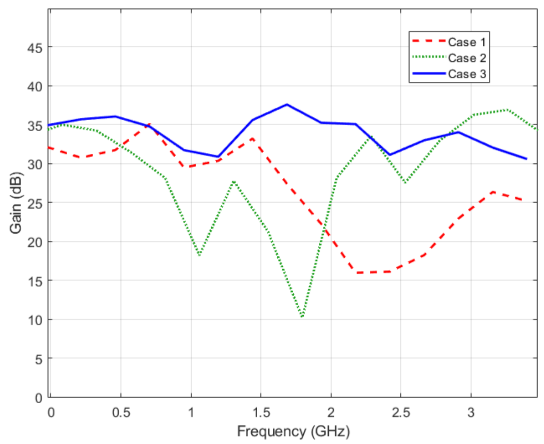


Fig.7. Gain comparison in the evolution process

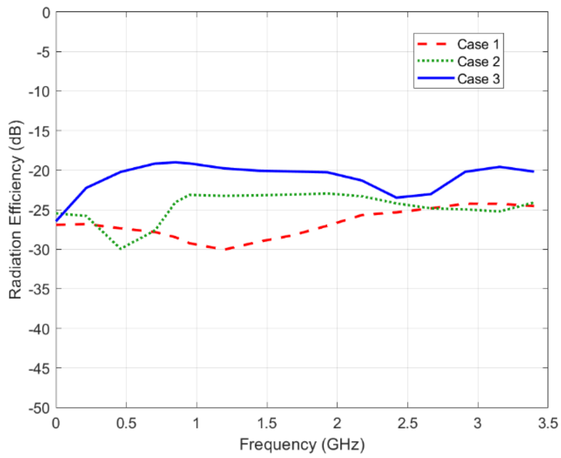
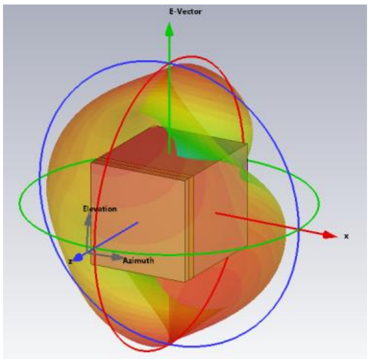
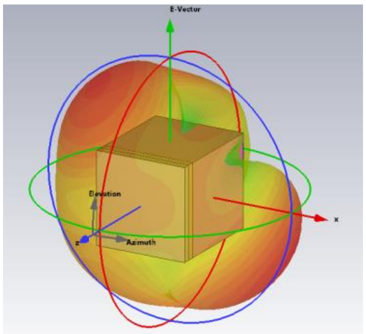


Fig.8. Radiation efficiency

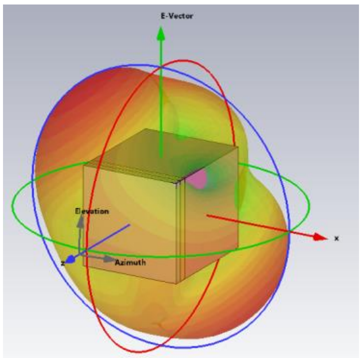
The introduction of an F-shaped structure in Case 2 yields moderate improvement, achieving multiple resonant frequencies with VSWR values reduced to below 5 in certain bands. However, the design still lacks optimal matching across all target frequencies. The addition of a shorting pin in Case 3 significantly enhances the antenna’s impedance characteristics, resulting in VSWR values below 2 across the desired frequency bands—401–406 MHz, 1.395–1.432 GHz, and 2.4–2.5 GHz—thus confirming effective multiband operation and minimal signal reflection.



(a)



(b)



(c)

Fig.9. 3-D radiation patterns of the proposed antenna for the arm implanted configuration. (a) 0.4 GHz (b) 1.4 GHz (c) 2.45 GHz

The simulated gain response, illustrated in Fig.7, further emphasizes the superiority of Case 3. Case 1 demonstrates relatively low gain, with values ranging from 25–32 dB, and noticeable dips at mid-range frequencies. While Case 2 exhibits a slightly improved gain profile, it suffers from instability and abrupt drops near 1.5 GHz and 2.0 GHz. In contrast, Case 3 maintains a more uniform and elevated gain performance throughout the 0.4–3.0 GHz spectrum, with gain levels consistently above 30 dB. This enhanced and stable gain profile supports more robust signal transmission and improved link quality in biomedical communication scenarios.

Radiation efficiency, shown in Fig.8, highlights the impact of structural improvements on power conversion in the lossy environment of human tissues. Case 1 shows the lowest efficiency, often below –25 dB, due to its basic geometry and poor impedance matching. Case 2 achieves better efficiency, particularly around 1.5–2.5 GHz, with values improving to around –18 dB. Case 3, however, achieves the best performance, maintaining radiation efficiency between –10 dB and –15 dB across the frequency range, signifying more effective power radiation and less dissipation in surrounding tissues.

Figure 9 illustrates the 3D radiation patterns of the proposed antenna at the three target frequency bands: 0.4 GHz, 1.4 GHz, and 2.45 GHz. At 0.4 GHz (Fig.9a), the antenna exhibits an omnidirectional radiation pattern, radiating uniformly in all directions. This is highly desirable for implantable applications, as the antenna orientation relative to external receivers may vary within the body.

At 1.4 GHz (Fig.9b), the antenna maintains a generally spherical radiation pattern but with enhanced lobes in certain directions, indicating increased gain and improved coverage for telemetry communication in clinical environments.

At the higher frequency of 2.45 GHz (Fig.9c), the antenna shows a more directional radiation pattern with well-defined main lobes. This behavior is consistent with expectations for higher-frequency operation, where shorter wavelengths enable focused radiation. Despite this directivity, the antenna still offers adequate spatial coverage for communication with nearby wearable or external monitoring devices.

Overall, the radiation pattern transitions from omnidirectional to directional as frequency increases, consistent with electromagnetic theory. These results confirm that the antenna supports stable and effective wireless communication across all three frequency bands when implanted in the arm.

2.4 Effect of Implantation Depth

Since the proposed antenna is intended for implantation in lossy human tissues, the implantation depth (dp) plays a critical role in determining its performance. Additionally, due to the antenna's compact dimensions, fabrication accuracy becomes equally important to ensure that simulated and measured results closely match. To assess these factors, a parametric sweep was conducted to evaluate the impact of implantation depth and fabrication tolerance. As shown in Fig.10, the reflection coefficient (S11) remains relatively stable across varying implantation depths.

This demonstrates the robustness of the antenna design in maintaining impedance matching and resonant characteristics, regardless of minor deviations in implant positioning.

Such depth insensitivity is advantageous in practical biomedical applications, where surgical variability is common. The results suggest that the antenna can consistently operate across the intended frequency bands, even when implantation depth varies within a clinically acceptable range.

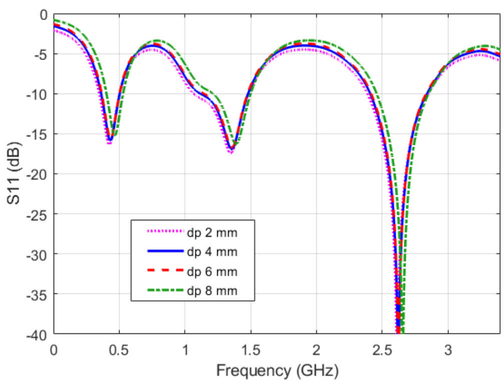


Fig.10. Effects of implantation depth on S11

2.5 Link margin

To evaluate the effective communication distance between the implantable antenna and the external receiver, the communication link margin (LM) is analyzed. LM quantifies the excess signal power available above the minimum required by the receiver, thereby ensuring reliable data transmission even in the presence of signal losses, noise, or environmental interference. The link margin is calculated using the following equation

$$LM = P_t + G_t + G_r - L_p - P_{min} \quad (1)$$

Where

P_t is the transmitted power (dBm)

G_t is the gain of transmitting (implantable) antenna (dBi)

G_r is the gain of receiving antenna (dBi)

L_p is the path loss (dB)

P_{min} is the minimum receiver sensitivity (dBm)

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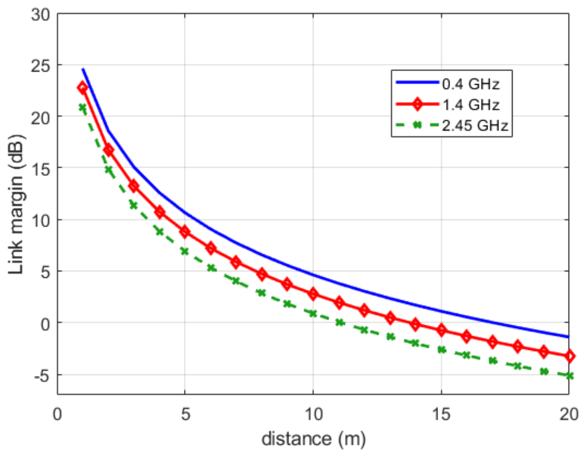

Fig.10. Link margins of the proposed antenna at 0.4 GHz, 1.4 GHz, and 2.45 GHz

3. CONCLUSION

This paper presented the design and performance evaluation of a miniaturizedtriple-band circularly polarized implantable antenna for biomedical applications. The antenna was specifically engineered to operate efficiently at three medically significant frequency bands: 401–406 MHz (MICS), 1.395–1.432 GHz (WMTS), and 2.4–2.5 GHz (ISM). The proposed structure, based on an F-shaped patch geometry, was developed through a progressive design process—starting from an I-shaped configuration (Case 1), evolving into an F-shaped structure (Case 2), and finally integrating a shorting pin (Case 3) to optimize matching and multiband operation.

Full-wave simulations in CST Studio Suite were conducted using a homogeneous three-layer phantom model based on the Zubal human body model, comprising skin, fat, and muscle layers, to emulate realistic implant environments. The final antenna design achieved return loss values below –10 dB across all target frequency bands, indicating good impedance matching. Additional performance evaluations confirmed stable VSWR, radiation efficiency up to –10 dB, and consistent gain across the bands.

The 3D radiation pattern analysis demonstrated omnidirectional behavior at lower frequencies (0.4 GHz), transitioning to more directional patterns at higher frequencies (2.45 GHz), aligning with theoretical expectations. This ensures the antenna's reliability under various implant orientations and communication distances. Moreover, the antenna's robustness against variations in implantation depth was confirmed, further supporting its practical applicability in clinical scenarios. Link margin analysis showed that the antenna can maintain a reliable wireless communication link at distances up to 11–15 meters, depending on the frequency, while complying with specific absorption rate (SAR) limits for implantable devices.

In conclusion, the proposed triple-band F-shaped implantable antenna demonstrates compact size, multi-band operation, and stable performance in realistic tissue environments, making it a promising solution for next-generation biomedical telemetry, remote monitoring, and wireless body area networks (WBANs).

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