Miniaturized Antenna for High Data Rate Implantable Brain-Machine Interfaces

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This work was supported by the Institute for Information & Communications Technology Promotion (IITP) grant funded by the Korean Government [Ministry of Science, and ICT and Future Planning (MSIP)] under Grant 2022-0-00310

\section*{ABSTRACT}

Technological advancements in medical care have necessitated the development of efficient and miniaturized implantable medical devices. This paper presents an ultra-wide-band implantable antenna for use in scalp-based biomedical applications covering the industrial, scientific, and medical (ISM) (2.4–2.48 GHz) band. The proposed antenna is mounted on a 0.1–mm thick liquid crystalline polymer (LCP) Roger ULTRALAM (tanδ = 0.0025 and ε\textsubscript{r} = 2.9), serving as a dielectric material for both the superstrate and substrate layers. LCP materials are widely used in manufacturing electronic devices owing to their desirable properties, including flexibility, conformable structure, and biocompatibility. To preserve the capability of an electrically small radiator and achieve optimum performance, the proposed antenna is designed to have a volume of 9.8 mm\textsuperscript{3} (7 mm × 7 mm × 0.2 mm). The addition of a shorting pin and open-ended slots in the radiating patch, and close-ended slots in the ground plane facilitates antenna miniaturization, impedance matching, and bandwidth expansion. Notably, the antenna exhibits a peak gain of −20.71 dBi and impedance-matched bandwidth of 1038.7 MHz in the ISM band. Moreover, the antenna is safe to use according to the IEEE C905.1-2005 safety guidelines based on low specific absorption rates. To evaluate the performance of the implantable antenna, finite-element simulation was performed in homogeneous and heterogeneous environments. For validation, measurements were performed in a minced pork-filled container. The simulation results are consistent with the measurements. In addition, a link budget analysis is performed to confirm the robustness and reliability of the wireless telemetric link and determine the range of the implantable antenna.

\section*{INDEX TERMS}

Implantable antenna, high gain, novel shaped, specific absorption rate, ultra-wide band.

\section*{I. INTRODUCTION}

Implantable medical devices (IMDs) enable early diagnosis of human diseases and play a significant role in several biomedical applications, such as intracranial pressure detection, glucose monitoring, capsule endoscopy, and cardiac pacemakers \cite{1} \cite{2}. These devices can be used to continuously monitor human health and facilitate the exchange of various physiological information using an external controller \cite{3}. To integrate wireless capabilities in an IMD, a small and efficient implantable antenna that enables the device to establish a real-time biotelemetric link is required \cite{4} with an on-body wearable and body-centric devices with high-performance antenna systems \cite{5}–\cite{7}. Medical professionals can remotely analyze this information and provide necessary treatment using high data rate MIMO-based biomedical devices \cite{8}–\cite{10}, thereby improving the quality of life.

Several frequency bands are regulated by the Federal Communications Commission (FCC) for use in biomedical applications, including medical implant communications service (MICS, 402–405 MHz), improved MICS, called the medical device radio communication Service (MedRadio, 401–406 MHz) \cite{11}, and industrial, scientific, and medical (ISM, 433–438 MHz; 902–928 MHz; 2.4–2.48 GHz; and 5.725–5.875 GHz) bands. To extend the device lifetime and battery energy, a sleep-wakeup mode is utilized at 2.45 GHz.
as the IMDs consume less power in the sleep mode than in the wake-up mode. Moreover, the ISM band of 2.45 GHz is primarily used in biomedical applications owing to the increased radiated power at high frequencies.

Typically, the implantable antennas are placed inside the human body, which is heterogeneous and lossy by nature. The differences in the permittivity and conductivity values of different human tissues impose serious challenges on implantable antennas face, such as impedance mismatching and detuning effects. To address these problems, an implantable antenna with wide bandwidth is preferred. Moreover, several additional challenges must be addressed, following the guidelines reported in [16], to develop an implantable antenna, including size restriction, bandwidth, biocompatibility, patient safety, and reliable telemetry.

Recently, numerous implantable antennas have been developed for biomedical applications. A multiple-input multiple-output (MIMO) antenna with an electromagnetic bandgap structure was proposed in [17]. Despite the isolation attained by the EBGs and large structural dimensions (18.5×18.5×1.27 mm³), the antenna exhibited a simulated bandwidth of 440 MHz and a peak gain of −15.18 dBi in the ISM band. Moreover, the MIMO technique is an unrealistic approach to IMD owing to its limited power resources. An implantable antenna for the MedRadio band was designed in [18]. However, the structure had a large area of 66.89 mm² and exhibited a comparatively low bandwidth (139.6 MHz). A circularly polarized (CP) implantable antenna was designed at the 2.4 GHz ISM band for cardiac pacemaker applications [19]. Although the gain (−15.87 dBi) and bandwidth (890 MHz) were satisfactory, the antenna had a large footprint (40×40×1.27 mm³). In [20], a triple-band implantable antenna for multiple biomedical applications was proposed in the ISM (915 MHz and 2.45 GHz) and midfield (1824–1980 MHz) bands. However, it exhibits lower bandwidths and gain values in the ISM and midfield bands. Similarly, a dual-band implantable antenna operating in the ISM and MedRadio bands was proposed in [21]. The antenna offered an unsatisfactory bandwidth and had a large footprint. In [22], a single-band implantable antenna operating in the ISM (2.4–2.48 GHz) band was designed for glucose monitoring. Although the gain (−17 dBi) was high, the structure had a large volume (91.7575 mm³) and a lower bandwidth (300 MHz). A novel shaped antenna operating in the ISM and MICS bands was proposed for pacemakers [14]. However, the antenna had a complex geometry, large dimensions, and low gain values. In [23], a flexible slot antenna integrated with a metamaterial (MTM) array was proposed for biotelemetry applications. To enhance the gain of the antenna, an MTM array with epsilon very large (EVL) properties was utilized in the superstrate of the antenna. Although the EVL-based MTM array improved the gain by 3 dBi, it increased the overall volume of the antenna. Similarly, in [24], a CP implantable microstrip patch antenna (MPA) operating in the ISM band was presented. Two high-order degenerate modes were excited in the MPA to generate CP radiating waves at low-gain values. In addition to the complex geometry of the antenna, its dimensions were large. These observations indicate that antennas developed for biomedical applications at various frequencies have several limitations and are unsuitable for use in IMDs. Therefore, further research is required to develop an efficient implantable antenna with a small volume, high gain, large bandwidth, low SAR, and reliable telemetric capability.

This study developed an ultrawideband implantable antenna for biotelemetric IMDs implanted under the scalp. The proposed antenna has a volume of 9.8 mm³ and is characterized by its single operating mode: data telemetry in the ISM band (2.4–2.48 GHz). To achieve optimum performance on a miniature structure comprising a radiating element and ground plane embedded in the LCP Rogers ULTRALAM substrate and superstrate layers, several miniaturizing techniques were employed in the design. In addition to the increment in the electrical length, impedance improvement
TABLE 1. Comparison with the previous work

| Ref | Volume [mm³] | Frequency [GHz] | SAR (W/Kg) | Bandwidth [MHz] | Gain [dBi] | Dielectric Material | Patch Shape | Shorting Pin |
|-----|--------------|----------------|------------|----------------|-----------|-------------------|-------------|--------------|
| [1] | 17.15        | 0.402          | 388        | 148            | −30.5     | Rogers RT/ Duroid 6010 | Zig Zag     | Yes          |
| [19] | 21           | 2.45           | 217.849    | 890            | −20.47    | Rogers RT/ Duroid 6010 | Zig Zag     | No           |
| [20] | 66.41        | 2.45           | 217        | 80             | −10.3     | TMM 13i            | Zig Zag     | Yes          |
| [21] | 31.5         | 2.8            | 778.1      | 115            | −10.3     | Rogers 6010        | Spiral      | Yes          |
| [22] | 91.75        | 2.45           | 303        | 300            | −17       | Rogers 3210        | Circular    | No           |
| [25] | 52.5         | 0.4015         | 665.35     | 64             | −40.8     | Rogers 6010        | Zig Zag     | Yes          |
| [26] | 67.8         | 2.45           | 238.9      | 980            | −19.2     | Rogers 3010        | Rectangular | Yes          |
| [27] | 161.29       | 2.45           | 213        | 190            | −22       | Rogers 3010        | Rectangular | No           |
| [28] | 434.65       | 2.45           | 1.3        | 440            | −15.8     | Rogers 6010LM      | Spiral      | Yes          |
| [29] | 254          | 2.45           | 382        | 60             | −15       | Rogers 3210        | Jr-Shape    | Yes          |
| [30] | 203.6        | 0.015          | 679.797    | 40             | −16       | Rogers RO3010      | Meandered   | Yes          |
| [31] | 127          | 2.45           | 254.74     | 390            | −17.2     | Rogers 3010        | WallitCe    | No           |
| Proposed Work | 9.8 | 2.45 | 289.76 | 1038.7 | −20.71 | Ultralam | Square | Yes |
TABLE 2. Parameters of the proposed antenna (Units: mm)

| Parameters | Values | Parameters | Values | Parameters | Values |
|------------|--------|------------|--------|------------|--------|
| W          | 7.0    | w15        | 1.5    | h12        | 1.0    |
| H          | 7.0    | w16        | 5.0    | h13        | 2.0    |
| w1         | 5.0    | w17        | 1.0    | h14        | 1.5    |
| w2         | 2.7    | w18        | 3.0    | h15        | 1.0    |
| w3         | 1.5    | w19        | 1.5    | h16        | 2.0    |
| w4         | 2.5    | h1          | 0.5    | h17        | 1.5    |
| w5         | 1.5    | h2          | 0.5    | d1         | 1.0    |
| w6         | 0.8    | h3          | 1.0    | d2         | 0.6    |
| w7         | 0.5    | h4          | 0.5    | d3         | 1.6    |
| w8         | 1.24   | h5          | 0.5    | d4         | 1.5    |
| w9         | 0.45   | h6          | 0.5    | d5         | 1.3    |
| w10        | 2.9    | h7          | 1.5    | d6         | 1.64   |
| w11        | 2.0    | h8          | 0.8    | pxe        | 2.85   |
| w12        | 2.0    | h9          | 0.2    | pye        | −2.85  |
| w13        | 1.64   | h10         | 1.5    | vxe        | −1.4   |
| w14        | 4.5    | h11         | 2.0    | vye        | −3.18  |

B. SIMULATION SETUP

The initial simulation setup for the designed antenna is illustrated in Fig. 2. The proposed antenna was simulated in a HSP with dimensions of 100 mm × 100 mm × 100 mm in Ansoft HFSS. The antenna was placed at the center of a single-layer HSP model enclosed by an airbox that served as a radiation boundary. According to [22], the dielectric properties of human tissues are dependent on the operating frequency, which was 2.45 GHz in this study. A relative permittivity ($\varepsilon_r$) of 38 and an electrical conductivity of 1.46 S/m at 2.45 GHz were assigned to the HSP to mimic human skin tissue.

C. DESIGN STEPS

The antenna was developed in four steps to obtain optimum performance at the required resonance band (Fig. 3). Several rectangular slots and cuts were added to the patch and the ground plane to extend the electrical length of the antenna and achieve compactness.

A comparison of the reflection coefficients ($S_{11}$) for the different design steps utilized to develop the proposed wideband implantable antenna is shown in Fig. 4. The resonant frequency is in the 4.2 GHz region in the initial phase, with poor impedance-matching characteristics ($S_{11} > -10$ dB). At this stage, the frequency can easily be shifted to the lower region by increasing the dimensions of the antenna. However, large antennas are unsuitable for biomedical applications. Therefore, a few rectangular slots were created in the patch and ground plane to achieve the desired resonance. Despite having identical dimensions, an elongated path is established for the currents to flow over the surface of the radiating patch and ground plane, thereby shifting the frequency to a lower band [34]. This phenomenon can be observed from the $S_{11}$ graphs, which exhibit a dual resonance at 1.2 and 3.4 GHz achieved in the second and third steps with similar impedance-matching features. In the final design process, more slots were added to the center of the radiating patch. The insertion of slots creates small capacitive gaps on the radiator and ground plane, which improve impedance-matching characteristics. Moreover, parasitic capacitance aids in shifting the resonance to the lower side of the frequency spectrum [35]. Notably, the proposed antenna exhibited a perfectly matched impedance with minimal reflections at the desired 2.45 GHz ISM band, covering a large bandwidth of 874.3 MHz (from 1945 MHz to 2829 MHz).

D. PARAMETRIC ANALYSIS

The performance of an antenna is greatly influenced by the size and length of various parameters. Therefore, a parametric analysis was performed to optimize and tune the final antenna design. A few essential parameters were considered for performance evaluations, such as slot $w_1$ in the ground plane, circular cut with a diameter ($d_b$) and slot $w_{15}$ in the radiating element. Furthermore, the effect of the shorting position was investigated. In the simulation environment, the values of the critical parameters were varied to analyze their impacts on $S_{11}$, which was used to fine-tune the antenna.

1) Effect of varying the parameter $w_1$

Fig. 5 shows the effect of the variation in the slot parameter $w_1$ on the reflection coefficient. Increasing the value from 4 mm to 5.5 mm in steps of 0.5 mm, the resonance frequency is shifted towards the lower band. Further increments in $w_1$ cause the close-ended slot to become open-ended and split the current path in two directions near the feed port on the ground plane—one in the upward direction towards the shorting pin and the other in the lower-right direction.
When \( w_1 \) is extended to 5.5 mm, parameter \( w_1 \) vanishes. The two resonances occur at 1.7 GHz and 3.3 GHz in this case, implying that the length \( w_1 \) exerts a more significant influence on impedance matching and antenna tuning in the appropriate frequency band.

2) Effect of varying the parameter \( d_3 \)
Fig. 6 shows the effect of the circular cut \( (d_3) \) on \( S_{11} \), which ranges from 1.2 mm to 1.8 mm. Evidently, increasing the value of \( d_3 \) results in improved impedance matching. However, at \( d_3 = 1.8 \) mm, the resonance splits into two bands, eliminating the wideband characteristics of the proposed antenna. Therefore, the value of \( d_3 \) is set to 1.6 mm to obtain ultra-wide bandwidth.

3) Effect of varying the parameter \( w_{15} \)
The width of the rectangular cut \( w_{15} \) has a significant effect on the impedance matching and stability of the designed antenna. Fig. 7 shows the effect of the variation in the width of the side strip \( w_{15} \) on \( S_{11} \) of the antenna. First, return loss is observed without the side strip. The antenna resonates at 3.5 GHz, with a dip of \(-10 \) dB in the \( S_{11} \). Subsequently, a strip with a width in the range of 0.5–1.5 mm is added. At the lower values of the strip \( w_{15} \), the desired band is not achieved, and \( S_{11} \) exhibits a peak dip at 3.3 GHz. By increasing the size of \( w_{15} \), impedance matching is gradually improved, and the frequency is shifted to the lower side of the spectrum. Further increments in the width of the strip elongated the current path, and the required frequency band was achieved by setting \( w_{15} = 1.5 \) mm.

4) Effect of varying the shorting pin location
The effect of the shorting pin on the performance of the proposed antenna was also analyzed at four different locations (Fig. 8). Evidently, the shorting pin facilitates impedance matching and tuning of the implantable antenna. The antenna is completely mismatched when the shorting pin is placed near the feed port at the location \( P_1 \). The currents experience a small path on the main radiator shorted with the ground, causing a poor resonance at 4.5 GHz. When the shorting pin was moved to the location \( P_2 \), multiple current paths were created, causing weak \( (S_{11} > -10 \) dB\) resonances at multiple undesired frequencies. At \( P_3 \), where the shorting pin is moved to the upper-right corner of the antenna, dual bands are produced at 900 MHz and 3.15 GHz. Finally, the shorting pin is optimized at position \( P_4 \) where the antenna exhibits perfectly matched impedance and wideband characteristics at the desired frequency of 2.45 GHz. Generally, a shorting pin is added in the structure to short the radiator with the ground plane. Typically, the shorting pin is smaller in radius, which is usually between 0.1 to 0.3 mm. This radius is taken according to the trace width on the radiator. As long as the diameter of a shorting pin is not greater than the maximum width of the trace on which it is added, there is no affect on the \( S_{11} \) and gain of the implantable antenna. However, when the diameter of shorting pin is increased in such a way that it occupies two or more traces, there is effect on the \( S_{11} \) and gain of the implantable antenna. As more traces on the radiator are shorted with the ground plane, the frequency response is deteriorated. Therefore, in this study, the diameter of a shorting pin is restricted to 0.6 mm in diameter so that it can short a single trace on the radiator with the ground plane.

E. FABRICATION AND MEASUREMENTS
As previously mentioned, initial simulations were performed in FEM-based homogeneous model. To further inspect the sensitivity of antenna, numerical computations were conducted in the heterogeneous environment, such as head
model comprised of multiple human tissues. In both cases, the antenna was implanted at depth of \( d = 12 \text{ mm} \). For experimentation, the fabricated prototype of antenna is developed using photolithographic technique in which the metalizations of the slots and cuts on the radiating element and ground planes were chemically etched off. Afterward, the soldering process was adopted to connect an SMA cable with the fabricated antenna. To evaluate the simulated attributes, the real-time performance was analyzed by measuring the reflection coefficient and radiation pattern in a minced pork emulating human biological tissues. The realistic duke model, fabricated antenna, and measurement setup are shown in Fig. 9.

III. RESULTS AND DISCUSSION

The performance of the proposed implantable antenna was analyzed with respect to the reflection coefficient, far-field gain pattern, patient safety, and link budget. \( S_{11} \) of the proposed antenna in a HSP, homogeneous brain model, realistic heterogeneous head model, and minced pork are compared in Fig. 10. Evidently, that the proposed antenna exhibits ultra-wideband performance at a resonant frequency of 2.45 GHz. The antenna offers a \(-10\) dB bandwidth of 874 MHz \((1.945 \pm 2.829 \text{ GHz})\) and 792 MHz \((1.801 \pm 2.593 \text{ GHz})\). A slight shift in the frequency spectrum and dip in the return loss were observed because of the high permittivity of the brain compared to the skin. The antenna exhibits a band coverage of 801.2 MHz \((1.881 \pm 2.6817 \text{ GHz})\) in a heterogeneous head environment. The complex and diverse electrical properties existing in a realistic human head model cause a slight shift in resonant frequency. The antenna offers a \(-10\) dB bandwidth of 1038.7 MHz \((1.868 \pm 2.925 \text{ GHz})\) in this realistic environment. Owing to fabrication tolerances and human procedural errors, a slight shift in the simulated and measured values was observed. However, these effects are negligible, as the antenna covers the desired band (2.45 GHz) in all scenarios.

The current distribution in the proposed antenna in the four successive phases is shown in Fig. 11. \( \theta = 0^\circ \) and \( 180^\circ \), the currents flow primarily around the feed point; however, the polarity is opposite in both cases. The flow of currents
from the feed towards the shorting pin on the ground plane increases at $\theta = 90^\circ$ indicating that the charge is coupled between the ground plane and radiator, thereby elongating the current path. The same phenomenon was observed at $\theta = 270^\circ$ wherein the currents flowed in the opposite direction to that at $\theta = 90^\circ$. Notably, a half-wavelength dipole mode was observed at 2.45 GHz in all cases.

Owing to signal transmission through lossy tissues in the human body, the gain of implantable antennas is substantially lower than that of free-space antennas. Fig. 12 shows the radiation patterns of the proposed implantable antenna. The H-plane and E-plane radiation patterns of the designed antenna depend on the human body tissue in which the antenna is implanted [34]. Realized peak gain values of $-19.06$, $-19.57$, $-19.36$, and $-20.71$ dBi were attained in the skin, brain, head, and minced pork, respectively. The realized gain in different environments corresponds to the desired gain of implantable antennas in the ISM band [36]. Furthermore, the E- and H-plane gain patterns were omnidirectional in the HSP.

The implantable antenna uses electromagnetic (EM) waves to transfer biotelemetric data. Therefore, considering SAR is crucial for measuring the EM power absorbed by the body per unit mass. According to the two IEEE standards, IEEE C95.1–1999 and IEEE C95.1–2005, the safety limits are 1.6 and 2 W/kg averaged over 1 and 10 g of human tissues, respectively. By setting the input power to 1 W, a peak SAR value of 350.81 W/kg (1 g) was obtained at 2.45 GHz (Fig. 13). To maintain the radiator under the safety limit, the net input power to the antenna should not exceed 4.56 mW, as it is the critical value at which the peak SAR value reaches the critical limit of 1.6 W/kg. The results of the safety analysis performed using the proposed implantable antenna listed in Table 3 indicate that the SAR is not an issue of concern.

IV. LINK BUDGET ANALYSIS OF THE PROPOSED ANTENNA

A link budget analysis was performed to exchange physiological data between the implantable antenna and the external controller. The development of a robust and reliable link based on link budget calculations proves a challenge because of the presence of different types of attenuations, including cable and connector losses, path loss, and antenna losses (mismatch and material) [37]. For a stable biotelemetric link, the difference between the antenna power ($A_P$) and the required power ($R_P$), known as the link margin, should be greater than 0. However, this study considered a link margin of 10 dB for improved reliability. The required antenna power is calculated as follows:

$$R_P = \frac{E_o}{N_o} + KT + B_r,$$

where $E_o/N_o$ is the ideal phase-shift keying with a value of 9.6 dB, $K$ is the Boltzmann’s constant ($1.38 \times 10^{-23}$), $T_o$ is the temperature ($K$), and $B_r$ is the bit rate in Kbps/Mbps. The important parameters in the calculation of the link budget are listed in Table 4. According to IEEE safety limits, the input power to the implantable device is restricted to 25 $\mu$W ($-16$ dBm). To ensure safety, the effective isotropic radiated power (EIRP) of the implanted antenna must be less than or equal to $EIRP_{max}$. The $EIRP_{max}$ for the ISM (2.45 GHz) band is 20 dBm [38]. In this study, the transmitted power $P_a$ was assumed to be -16 dBm. Similarly, a bit rate $B_r$ of
be safely implanted in patients. The antenna exhibits several essential features, including ultra-compact size, ultra-wide bandwidth, perfect impedance matching, high gain, omnidirectional radiation pattern, patient safety, and biotelemetric capability. Furthermore, the results of the comparative analysis demonstrate that proposed antenna offers superior performance compared to existing state-of-the-art implantable antennas.

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