An Ultra-Miniaturized Antenna Using Loading Circuit Method for Medical Implant Applications

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ABSTRACT In this paper, an ultra-miniaturized implantable antenna is proposed for biomedical applications, which operates in frequency of the industrial, scientific, and medical bands of 2.4 GHz. The miniaturization of the proposed antenna is obtained by using a meander line as radiating patch, introducing a 1.2 Ω chip resistor, and two pairs of a rectangle slot are etched on the ground plane to expand the antenna impedance bandwidth. The antenna has an ultra-compact size with a width and length of 2.5 mm and a thickness of 0.64 mm (the total dimension of 2.5 mm × 2.5 mm × 1.28 mm³). To validate the antenna structure, the optimal design is fabricated and experimentally measured. A low loss, flexible, and biocompatible PCB material, Taconic CER-10 (εᵣ = 10.2, σ = 0.0035) is adopted as both the substrate and superstrate. The experiment results imply that the proposed antenna produces a good impedance matching at 2.4 GHz with a bandwidth of 16.6 % and a maximum peak gain of −18.3 dBi. In addition, to further prove the performance of the designed biomedical implantable antenna, the effects of a coaxial cable and the simulations in the environment of the human tissue models (head, arm, and leg) are established. The antenna provides a low specific absorption rate (SAR) with the value compliance the IEEE standard safety guidelines. To the best of our knowledge, the proposed antenna is the smallest dimension (in width and length) with high performance compared to previously reported works. Thus, the antenna is a potential candidate and suitable for the biomedical applications.

INDEX TERMS Biocompatible, biomedical, chip resistor, meander line, implantable antenna, specific absorption rate (SAR).

I. INTRODUCTION Nowadays implantable medical devices (IMDs) have played an important role in academia and industry. It is utilized for brain implant technology [1], real-time glucose monitoring [2], heat failure detection [3], retinal prosthesis [4] and capsule endoscopy [5]. The IMDs are designed with the purpose to continuously monitor various activities inside the human body and wirelessly communicate with the receivers equipment outside the human body. Therefore, an implantable antenna is necessary. Unlike the traditional antennas which operate in free space, the antennas use inside the body have the different radiation characteristics, need to satisfy many conditions [6], and have to address the patient safety [7], [8]. Several frequency rangers are approved and currently used in different medical implant applications. These bands include Medical Device Radio Communication Service (MedRadio, 401-406 MHz [9]–[12]) and Industrial Scientific Medical (ISM)(433-438 MHz [13], [14]; 886-906 MHz [13]; 2.4-2.48 GHz [15]–[17]; and 5.725-5.875 GHz) and Wireless Medical Telemetry Service (WMTS) [8]. Although the signal propagation in human body is better at lower frequencies, the radiated power allowed in the higher bands is bigger than lower frequency bands [18]. Among these bands, the band of 2.4 GHz is mostly used for IMD applications.

The fundamental requirements for designing a biomedical implantable antennas are flexible, sufficient gain, high bandwidth, low specific absorption rate (SAR), and compact size. Recently, various techniques of implantable antenna size reduction have been proposed. For instance, the conventional miniaturization techniques are used of high-permittivity
substrate [19], shorting pin [20], and the meander line as radiating patch [21]–[24]. Besides, the method to significantly reduce the antenna size has been achieved by increasing the current path with embedded meandered slot and slots in the ground plane [25]. Moreover, the synthesized metamaterial particle split-ring resonator (SRR) [26] and a combination of complimentary SRR and C-shaped slot [2] have been effectively utilized for antenna size reducing method. Other techniques of miniaturizing implantable antenna have been proposed in [27]–[33]. Although the aforementioned researches have relatively high on the size of reduction, the design complexities and the low peak gain of the antennas are not suitable for its combination with most of the IMDs.

In this work, we present an ultra-miniaturized implantable antenna in the frequency band of 2.4 GHz (industrial, scientific and medical band (ISM)). In order to do this, the meander line method, the embedding of a 1.2 Ω resistor in the edge of antenna, and the high dielectric substrate/superstrate are employed. Besides to further extend the impedance, four rectangle slots are etched in the ground plane. The proposed implantable antenna has an ultra-compact size with the total dimension of 2.5 mm × 2.5 mm × 1.28 mm³, and a high gain value of −18.4 dBi, which is the smallest size and almost higher gain compared to the most relevant researches in literature. To validate the numerical simulation results, the designed antenna is fabricated and tested with minced pork and the skin-mimicking gel (to imitate the human tissue model). In addition, for ensuring the safety for patient the SAR is investigated and the simulated results reveal that the SAR value compliant with IEEE standard for various implanted scenarios (head, arm, and leg model) in CST software. The effects of the coaxial cable on the proposed antenna performance are also discussed. In all cases of measurements and simulation results exhibits a good agreement.

II. ANTENNA DESIGN AND OPTIMIZATION

A. ANTENNA DESIGN PROCESS

1) SIMULATION MODEL
Firstly, a single layer of homogeneous skin phantom (HSP) with the dimension of 25 mm × 25 mm × 25 mm is generated for simulation as shown in Fig. 1(a). The antenna is embedded in the center of the HSP, and the HSP is surrounded by a radiation boundary box with dimensions of 100 mm × 100 mm × 100 mm. The dielectric permittivity (εr) and the conductivity (σ) of the HSP at 2.4 GHz are assigned as 38.1 and 1.44 (S/m), respectively. The simulations are implemented with the finite-element method (FEM) based full-wave electromagnetic simulation tool in CST Studio Suite software. Besides to investigate the practical scenarios, the proposed antenna is embedded in the heterogeneous of head, arm, and leg model, as exhibited in Fig. 1(b).

2) LAYOUT OF THE PROPOSED ANTENNA
Fig. 2 demonstrates the detailed geometric of the proposed antenna structure. The overall dimension is 2.5 mm × 2.5 mm × 1.28 mm³ (8 mm³). Fig 2 (a) shows the radiating patch with a meander line structure. Fig 2(b) shows the ground plane with two pairs of a rectangle cut slot exist on it.
A low resistance chip resistor with $R = 1.2 \, \Omega$ is added at the start point of the meander line on the top and connected to the ground plane through substrate. Also, the flexible 50 $\Omega$ coaxial located at the point of $f_x$ and $f_y$ is adopted to excite the antenna. Besides the comprehensive details of the antenna are presented in Fig. 2(c) and (d) with the isometric and the side view, respectively.

Aforementioned, with the regard to bio-compatibility and proof of the miniaturization concept, the high permittivity is employed. Several previous works such as [34]–[36] have popularly used the high permittivity Rogers 3210 ($\varepsilon_r = 10.2$ and $\sigma = 0.0035$) or Rogers RT/duroid 6010 ($\varepsilon_r = 10.2$ and $\sigma = 0.0035$) with the thin thickness of 0.25 mm, 0.5 mm, or 0.635 mm. In this work, the Taconic CER-10 having a high dielectric constant $\varepsilon_r = 10.2$ and loss tangent of $\sigma = 0.0035$ is utilized for both substrate and superstrate. In this work, due to the real length of the chip resistor R, the substrate thickness is set of $h = 0.64$ mm. Moreover, the superstrate with the similar properties to substrate is used to provide insulation and avoid short circuits caused by high permittivity tissues [27]. By optimization, an ultra-compact implantable antenna operating at 2.4 GHz for biomedical applications is achieved, and the detailed parameter can be found in Table 1.

3) DESIGNING STEPS
The design concept in this section is presented to design the proposed a biomedical implantable antenna with ultra-compact size operating at 2.4 GHz. Fig. 3 illustrates the designing steps of the proposed antenna, and Fig. 4 shows the comparison of reflection coefficient in difference design steps. The final structure is the evolution through three design and optimize models (Ant. I, Ant. II and Ant. III).

STEP 1 (Ant. I): Initially, the design starts from a conventional spiral-shaped printed on a 7 mm $\times$ 7 mm $\times$ 0.64 mm substrate. As indicated in Fig. 4, the spiral-shaped antenna exhibits the resonant at 2.58 GHz with a poor matching impedance. Herein, the employing of the spiral-shaped due to the property of being less sensitive to the dielectric variation of human body tissue [37].

STEP 2 (Ant. II): We can optimize the antenna with the spiral shape in step I to exactly obtain the resonant frequency at 2.4 GHz; however, at this time we need to increase the antenna dimension. This step presents to reduce the resonant frequency of the desired band and reduce overall dimension. The meander lines with different widths and lengths for radiating patch and a shorting pin are employed. At this time, the operating frequency shifts down to 2.44 GHz with $S_{11} = -15$ dB and the overall antenna size decrease to 5 mm $\times$ 5 mm $\times$ 0.64 mm.

STEP 3 (Ant. III): In this step, to obtain the ultra-compact size possible and the good matching at 2.4 GHz, the shorting pin in step 2 is replaced with a low resistance chip resistor $R = 1.2 \, \Omega$. As a result, the antenna dimension can be further scaled down to 2.5 mm $\times$ 2.5 mm $\times$ 0.64 mm, and the antenna resonant frequency operating exactly at 2.4 GHz. Compare to the initial antenna dimension, the optimized structure has a size reduction of 280%.

STEP 4 (Ant. IV): In the final step of the design process the proposed implantable antenna with ultra compact size and a desired bandwidth at 2.4 GHz is obtained by inserting two pairs of a rectangle cut slot to the ground plane. It can be noted from Fig. 4 that the designed implantable antenna operating at 2.4 GHz with the impedance bandwidth covers from 2.2 GHz to 2.63 GHz (18 % for $| S_{11} | \leq -10$ dB).

B. PARAMETRIC ANALYSIS
This section exhibits the comprehensive parametric studies with different important design parameters such as: the width and length of the meander line’s arms ($W_1$, $W_2$), the cut slot on ground plane ($c$, $L_3$); and the variation of the key parameter R (value of the resistor). Other parameters like $g$, $g_1$, $g_2$, $L_1$, $L_2$ are not investigated in this study, because they are variables depending on mentioned parameters. The parametric studies are established with the same HSP and configuration as in Fig. 1(a) to understand their effects on the antenna reflection coefficient ($S_{11}$). It should be emphasized that for
the purpose of designing ultra-compact biomedical implant antenna, the values of the parametric studies gradually change from the smallest possible to larger value.

1) EFFECT OF VARYING THE $W_1$ OF THE MEANDER LINE

Fig. 5 shows the impact to the simulated reflection coefficient of the variation on the parameter $W_1$. The value of $W_1$ is changed from 0.3 mm to 0.45 mm. As shown in Fig. 5, when $W_1$ increases, the operating frequency of the antenna slightly changes. It is worth noting that the wider impedance bandwidth and the better impedance matching can be achieved with the lower value of $W_1$; however, owning to the real width of the resistor $R$ the value of width $W_1 = 0.45$ is selected, that provides a perfect width respond for resistor soldering.

2) EFFECT OF VARYING THE WIDTH $W_2$ OF THE MEANDER LINE

This concept is investigated by studying the effect of varying $W_2$ (the width from 0.32 mm to 0.62 mm) to the proposed antenna reflection coefficient ($S_{11}$). It can be clearly seen from Fig. 6 that the width of $W_2$ plays a main role in strongly controlling the shifting of the resonant frequency. The smaller value of $W_2$ is, the lower antenna operating frequency can be achieved. However, by expanding $W_2$, the reflection coefficient of the antenna is not only shifted to 2.4 GHz, but also produced the better matching impedance. Therefore, with the value width of $W_2 = 0.62$ is chosen for the stable impedance matching and the closed to the desired resonant frequency.

3) EFFECT OF VARYING THE WIDTH $C$ AND LENGTH $L_3$ OF THE CUT SLOT ON THE GROUND PLANE

As mentioned earlier, four rectangle slots on the ground plane contribute to enhance bandwidth characteristics of the proposed antenna. In fact, by using antenna with a full ground plane can ensure the radiation direction from the body toward base station [27], however; with our proposed structure this issue can be solved. Thus, we implement a parametric analysis of the slot width ($C$ from 0.1 mm to 0.4 mm) and the slot length ($L_3$ form 0.4 mm to 1.0 mm) to the antenna reflection coefficient. From the simulation results, the resonant frequency of antenna slightly changes with $C$ value, as shown in Fig. 7(a). On the other hand, the parameter of $L_3$ plays a main role in the proposed antenna impedance matching,
as shown in Fig. 7(b). Finally, the stage of \( L_3 = 1.0 \) mm and \( C = 0.3 \) are adopted, which provides the widest impedance matching with a bandwidth of 18.75 % (2.2 GHz – 2.63 GHz) at 2.4 GHz.

4) EFFECT OF VARYING THE VALUE OF ADDING RESISTOR R
The value of resistor element \( R \) is the key parameter to achieve the suitable bandwidth that covers the desired antenna resonant frequency, maximizes the antenna performance, and greatly supports for reducing antenna dimension. Fig. 8 shows the comparison of the return loss with different values of resistor element. A shift of antenna operating frequency to lower band is pointed out by using higher value of \( R \). Once can notice from the figure that the variation of resistor element has a significant influence on the antenna working band, however, the increment value of \( R \) to obtain lower resonance frequency is not linear. As a result, when \( R = 10 \Omega \), a degradation in the impedance matching at higher frequency is observed. According to the results analysis, the antenna dimension can be more miniaturized but for the sake of fabrication we utilize the value of \( R = 1.2 \) \( \Omega \) for the proposed antenna.

5) EFFECT OF COAXIAL CABLE
Moreover, we conduct three simulations to evaluate the feeding coaxial cable effect that can impact antenna impedance matching. The investigation is conducted in three cases:

Case I: The antenna without coaxial cable, the discrete port is employed, as shown in Fig. 9(a).

Case II: A short 50 \( \Omega \) coaxial cable with the length is reduced to 9 m, as shown in Fig. 9(b).

Case III: The long coaxial cable with the length is longer than HSP box, as shown in Fig. 9(c).

Fig. 9(d) and (e) present the simulated reflection coefficients and the realized gains for three cases. In the same manner, although it has the variation, the impedance matching and realized gain of three cases of the simulation is acceptable.

The results reveal that small coupling exists of currents following on the biological tissue and the external conductor of the cable [12], [24].

C. ANTENNA FABRICATION
The proposed structure of the biomedical implantable antenna is fabricated using PCB (printed circuit board) technology. The prototype antenna with a miniaturized size of 2.5 mm \( \times \) 2.5 mm \( \times \) 1.28 mm\(^3\) is manufactured on a Taconic CER-10 having a dielectric constant \( \varepsilon_r = 10.2 \) and loss tangent of \( \sigma = 0.0035 \) substrate. Afterward, we carefully solder the resistor to antenna prototype in the laboratory. Next, an SMA coaxial cable is soldered with the fabricated antenna prototype for excitement, the combination with the superstrate on the top by glue. Fig. 10 demonstrates the final configuration of the manufactured antenna prototype.

III. MEASUREMENT RESULTS AND DISCUSSION
To validate the proposed structure, the characteristics of the prototype are experimentally measured. For measurement, the 8719D vector network analyzer with covering frequency of 50 MHz to 13.5 MHz is used. Fig. 11(a) depicts the setup for reflection coefficient and bandwidth characteristics measurement in the case of minced pork and Fig. 11(b) in the case of skin-mimicking gel, respectively. Both skin-mimicking gel and minced pork are used to emulate human tissue models. Herein, the skin-mimicking gel is the result of mixing substances together that are Diethylene glycol butyl ether (5.1 %), Triton X-100 (36.7 %) and Deionized water (58.2 %) [38]. Subsequently, the comparison of simulated and measured reflection coefficient of the 2.4 GHz ultra-miniature biomedical implantable antenna is present in Fig. 12. It is clearly realized that the measured result in minced pork provides the measured bandwidth.
of reflection coefficient $|S_{11}|$ below $-10$ dB range from 2.19 GHz to 2.59 GHz (16.6 %); and in skin-mimicking gel the measured bandwidth is observed to be from 2.26 GHz to 2.72 GHz (17.8 %). Compare with the simulated result, the measured $|S_{11}|$ result in minced pork shows a good agreement with simulation, whereas in scenario of skin-mimicking gel the $|S_{11}|$ slightly shifts to higher frequency. The slight difference in the skin-mimicking gel scenario can be caused by the dielectric properties of the measurements is not exactly coincide with the simulation [28], or by the air gap between the antenna and superstrate (there is always exists an air gap in glue layer, which could be avoided only with the use of a highly accurate manufacturing machine [39]).

Moreover, the gain and radiation pattern characteristics are measured in a microwave anechoic chamber. The prototype is placed in far-field on transmitting antenna and the positioned on the position can be rotated freely. To measure the radiation pattern as a function of angle, the prototype is rotated so that the transmitting antenna illuminates the prototype from different angles. The measurement shift angles are done at $10^\circ$, $15^\circ$, respectively. Fig. 13 shows the measurement process of gain and radiation pattern in the microwave anechoic chamber.

The antenna radiation characteristics will be affected when implanted in different scenarios. Fig. 14 presents radiation patterns of the simulated in heterogeneous environment of the human body (skin phantom, head model, arm model, and leg model) and measured in minced pork of proposed antenna at 2.4 GHz. It is prominent from the figure that for all the mentioned scenarios the attained radiation patterns exhibit relatively omnidirectional. In the simulation, the simulated peak gain values are obtained $-16.8$ dBi, $-20.8$ dBi, $-23.5$ dBi and $-25.1$ dBi. Whereas a $-18.3$ dBi peak gain is
observed in the minced pork measurement. Generally, in all cases of the simulations results and measurements exhibit a good agreement. The comparison gain of the proposed ultra-miniaturized antenna with respect to realized gain and peak gain is illustrated in Fig. 15. As is clear from Fig. 15, due to the feeding losses and properties of available dielectric material [27], [40], produces a slight variation on the value of realized gain. However, the result implies that the proposed antenna has fairly high gain for the entire bandwidth. Also, Fig. 15 shows the radiation efficiency of the proposed antenna. On account of the coupling of the antenna and the human tissue, the efficiency decreases significantly. In this work, the proposed antenna provides an acceptable radiation efficiency, which around 0.23 % at the resonant frequency. It is notable that based on the implantation depth, the efficiency of the implantable antenna is regularly found less than 1 %.

The current distributions of the antenna on the ground plane and the radiator are demonstrated in Fig. 16. It can be clearly seen that when the exited phase is 0° and 180° the maximum current concentrates around the feed and a small part of the meander line, whereas, when the excited phase to the antenna with the phase of 90° and 270°, the stronger current distribution is observed on the meander line. A similar mechanism can be found on the ground plane. It is noteworthy that, when the resistor R is embedded to the antenna, the capacitance will decrease and the resistor R turns into a component to produce a 1/4λ antenna (a quarter-wavelength monopole).

In general, when the antenna implanted inside a human body the surrounding tissues will affect by the radiating electromagnetic energy, which is dangerous to the patients wearing it. Therefore, to ensure the safety for patients, it is required to take into account the specific absorption rate (SAR). The SAR values must comply with IEEE C95.1-1999 (United States standard), limit the peak average SAR value for 1 g of tissue to 1.6 W/kg and 10 g of tissue to 2 W/kg, respectively [41]. We perform SAR numerical analysis at 2.4 GHz with head, leg, and arm in the human body model of CST software. The transmitter power to the proposed antenna is 1 W, Fig. 17 depicts the SAR distribution at the three mentioned implant locations, and Table 2 lists the detailed SAR values and corresponding maximum allowable input power. It can be observed from the analyses that the proposed implantable antenna produces relatively low SAR values in case of head, and arm, the maximum SAR of 363 W/kg with a maximum acceptable input power of 4.40 mW in the leg tissue (highly conductive nature). Although SAR value is not a concerning issue, the analysis SAR value of the proposed implantable antenna encounters the IEEE evaluation standard. Finally, the results of the proposed antenna are compared to previous reports related to implantable antennas for the ISM band, as exhibited in Table 3. It is clear that our proposed antenna has the smallest size and almost higher gain.

![FIGURE 15. The comparison of the peak gain, realized gain and the efficiency of the proposed antenna.](image1)

![FIGURE 16. Current distribution on radiation patch and ground plane.](image2)

![FIGURE 17. The simulation average SAR distribution over 1 g for (a) head model, (b) right leg model, (c) left arm model at 2.4 GHz.](image3)

| Human body tissue | 1-g Max Average SAR (W/kg) | 10-g Max Average SAR (W/kg) | Max Net Input Power (mW) | Max Net Input Power (W/kg) |
|-------------------|---------------------------|-----------------------------|-------------------------|---------------------------|
| Head              | 296                       | 38.6                        | 51.8                    | 4.40                      |
| Leg               | 363                       | 44.9                        | 55.1                    | 4.40                      |
| Arm               | 282                       | 36.3                        | 55.1                    | 5.66                      |
TABLE 3. Comparison of the proposed implantable antenna with previous studies.

| Reference | Frequency (GHz) | Dimension (mm$^3$) | Bandwidth (%) | Gain (dBi) | SAR (W/kg) | Implantation scenario | Implantation depth (mm) |
|-----------|----------------|--------------------|---------------|-----------|-----------|-----------------------|------------------------|
| 14        | 2.45           | $19 \times 19.4 \times 1.27$ (0.155$\lambda$ x 0.159$\lambda$ x 0.01$\lambda$) | 4.4           | -22.0     | 314       | N/A                   | Skin Layer             | 3                     |
| 23        | 2.4            | $7 \times 6.9 \times 1.52$ (0.056$\lambda$ x 0.055$\lambda$ x 0.012$\lambda$) | 3.34          | -16.7     | 336.84    | N/A                   | Skin Layer             | 2                     |
| 29        | 2.4            | $3 \times 4 \times 0.5$ (0.024$\lambda$ x 0.032$\lambda$ x 0.004$\lambda$) | 21.8          | -25.9     | 270.28    | 31.04                 | Deep Tissue            | 60                    |
| 30        | 2.4            | $9.8 \times 9.8 \times 1.27$ (0.078$\lambda$ x 0.078$\lambda$ x 0.01$\lambda$) | 21.5          | -33.0     | 486       | 90                    | Skin Layer             | 3                     |
| 33        | 2.4            | $\pi \times 3.5^2 \times 1.0$ (\(\pi \times (0.028\lambda)^2 \times 0.008\lambda\)) | 14.9          | -20.75    | 568.2     | 84.6                  | Brain Layer            | 10                    |
| 34        | 2.45           | $7 \times 6 \times 0.254$ (0.057$\lambda$ x 0.049$\lambda$ x 0.002$\lambda$) | 17.8          | -9.81     | 524.3     | 50.2                  | Skin Layer             | 4                     |
| 35        | 2.4            | $\pi \times 5^2 \times 1.27$ (\(\pi \times (0.04\lambda)^2 \times 0.01\lambda\)) | 9.8           | -26.4     | 712.1     | N/A                   | Skin Layer             | 4                     |
| This work | 2.4            | $2.5 \times 2.5 \times 1.28$ (0.02$\lambda$ x 0.02$\lambda$ x 0.01$\lambda$) | 16.6          | -18.3     | 363       | 44.5                  | Skin Layer             | 12.5                  |

IV. CONCLUSION

This paper presents a miniaturized implantable antenna operating at 2.4 GHz for medical implant applications. The high dielectric substrate/superstrate, the meander line patch and a chip resistor are employed to design the proposed antenna. The resistor connects the side meander line of the patch and ground plane, and to be influential factor in frequency tuning, impedance matching and size reduction. As a result, the antenna prototypes with an ultra-compact dimension of 2.5 mm $\times$ 2.5 mm $\times$ 1.28 mm$^3$ (8 mm$^3$) is validated by testing inside minced pork and skin-mimicking gel. The prototypes are experimentally measured. The experiment results exhibit an impedance bandwidth of 16.6 % and a relatively high gain of 18.3 dBi at 2.4 GHz ISM band. Furthermore, the proposed antenna satisfied the IEEE C95.1-1999 safety guidelines in the investigation implanted locations (head, arm, leg). With the superior properties of our proposed antenna compare to previous reports leading to numerous potential applications in biomedical implantable systems.

REFERENCES

[1] W.-C. Chen, C. W. L. Lee, A. Kiourti, and J. L. Volakís, “A multi-channel passive brain implant for wireless neuroprosthetic monitoring,” *IEEE J. Electromagn., RF, Microw. Med. Biol.*, vol. 2, no. 4, pp. 262–269, Dec. 2018.

[2] X. Y. Liu, Z. T. Wu, Y. Fan, and E. M. Tentzeris, “A miniaturized CSRR loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 577–580, 2017.

[3] E. Y. Chow, Y. H. Ouyang, B. Beier, W. J. Chappell, and P. P. Irazoqui, “Evaluation of cardiovascular stents as antennas for implantable wireless applications,” *IEEE Trans. Microw. Theory Techn.*., vol. 57, no. 10, pp. 2523–2532, Oct. 2009.

[4] K. Gosalia, G. Lazzi, and M. S. Humayun, “Investigation of a microwave data telemetry link for a retinal prosthesis,” *IEEE Trans. Microw. Theory Techn.*., vol. 52, no. 8, pp. 1925–1933, Aug. 2004.

[5] S. H. Lee, J. Lee, Y. J. Yoon, S. Park, C. Cheon, K. Kim, and S. Nam, “A wideband spiral antenna for ingestible capsule endoscope systems: Experimental results in a human phantom and a pig,” *IEEE Trans. Biomed. Eng.*, vol. 58, no. 6, pp. 1734–1741, Jun. 2011.

[6] H. Bahrami, S. A. Mirbozorgi, R. Ameli, L. A. Rasch, and B. Gosselin, “Flexible, polarization-diverse UWB antennas for implantable neural recording systems,” *IEEE Trans. Biomed. Circuits Syst.*, vol. 10, no. 1, pp. 38–48, Feb. 2016.

[7] D.-H. Kim, J. Viventi, J. J. Amsden, J. Xiao, L. Vigeland, Y.-S. Kim, J. A. Blanco, B. Panilatis, E. S. Frechette, D. Contreras, D. L. Kaplan, F. G. Omenetto, Y. Huang, K.-C. Hwang, M. R. Zakin, B. Litt, and J. A. Rogers, “Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics,” *Nature Mater.*, vol. 9, pp. 511–517, Apr. 2010.

[8] G. Kaur, A. Kaur, G. K. Toor, B. S. Dhaliwal, and S. S. Pattanaik, “Antennas for biomedical applications,” *Biomed. Eng. Lett.*, vol. 5, pp. 203–212, Sep. 2015.

[9] J. Kim and Y. Rahmat-Samii, “Implanted antennas inside a human body: Simulations, designs, and characterizations,” *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 8, pp. 1934–1943, Aug. 2004.

[10] C. Liu, Y.-X. Guo, and S. Xiao, “Compact dual-band antenna for implantable devices,” *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1508–1511, 2012.

[11] Z. Duan, Y.-X. Guo, and J. Xiao, “Differentially fed dual-band implantable antenna for biomedical applications,” *IEEE Antennas Propag.*, vol. 60, no. 12, pp. 5587–5595, Dec. 2012.

[12] F. Merli, L. Bolomey, J.-F. Zurcher, G. Corradini, E. Meurville, and A. K. Skrivervik, “Design, realization and measurements of a miniature antenna for implantable wireless communication systems,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3544–3555, Oct. 2011.

[13] A. Kiourti and K. S. Nikita, “Miniature scalp-implantable antennas for telemetry in the MICS and ISM bands: Design, safety considerations and link budget analysis,” *IEEE Trans. Antennas Propag.*, vol. 60, no. 8, pp. 3568–3575, Aug. 2012.

[14] L.-J. Xu, Y.-X. Guo, and W. Wu, “Dual-band implantable antenna with open-end slots on ground,” *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1564–1567, 2013.
A. Kiourti, J. R. Costa, C. A. Fernandes, A. G. Santiago, and W. Cui, R. Liu, L. Wang, M. Wang, H. Zheng, and E. Li, “Design of a dual-band implantable antenna and development of skin mimicking gels for continuous glucose monitoring,” IEEE Trans. Microw. Theory Techn., vol. 56, no. 4, pp. 1001–1008, Apr. 2008.

C. J. Sanchez-Fernandez, O. Quevedo-Teruel, J. Requena-Carrion, L. Delan-Sanchez, and E. Rajo-Iglesias, “Dual-band microstrip patch antenna based on short-circuited ring and spiral resonators for implantable medical devices,” IET, Microw. Antennas Propag., vol. 4, no. 8, pp. 1048–1055, 2010.

R. Warty, M. R. Tofighi, U. Kawoos, and A. Rosen, “Characterization of implantable antennas for intracranial pressure monitoring: Reflection by and transmission through a scalp phantom,” IEEE Trans. Microw. Theory Techn., vol. 56, no. 10, pp. 2366–2376, Oct. 2008.

F. Faisal and H. Yoo, “A miniaturized novel-shape dual-band antenna for implantable applications,” IEEE Trans. Antennas Propag., vol. 67, no. 2, pp. 774–783, Feb. 2019.

C. L. Yang, C. L. Tsai, and S. H. Chen, “Implantable high-gain dental antennas for minimally invasive biomedical devices,” IEEE Trans. Antennas Propag., vol. 61, no. 5, pp. 2380–2387, May 2013.

H. Li, Y. X. Guo, C. Liu, S. Xiao, and L. Li, “A miniature-implantable antenna for MedRadio-band biomedical telemetry,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1176–1179, 2015.

R. Das and H. Yoo, “Biotlemetry and wireless powering for leadless pacemaker systems,” IEEE Microw. Wireless Compon. Lett., vol. 25, no. 4, pp. 262–264, Apr. 2015.

J. Blaetter, Y.-S. Kang, and A. Kiourti, “In vivo testing of a miniaturized 2.4/4.8 GHz implantable antenna in postmortem human subject,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 12, pp. 2334–2338, Dec. 2018.

I. A. Shah, M. Zada, and H. Yoo, “Design and analysis of a compact-sized multiband spiral-shaped implantable antenna for scalp implantable and leadless pacemaker systems,” IEEE Trans. Antennas Propag., vol. 67, no. 6, pp. 4230–4234, Jun. 2019.

C. Liu, Y.-X. Guo, and S. Xiao, “Capacitively loaded circularly polarized implantable patch antenna for ISM band biomedical applications,” IEEE Trans. Antennas Propag., vol. 62, no. 5, pp. 2407–2417, May 2014.

C. Liu, Y.-X. Guo, and S. Xiao, “A hybrid patch/slot implantable antenna for biotelemetry devices,” IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 1646–1649, 2012.

J. D. Baena, J. Bonache, F. Martin, R. M. Sillero, F. Falcone, T. Lopezeti, M. A. G. Lasso, J. Garcia-Garcia, and I. Gil, “Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines,” IEEE Trans. Microw. Theory Techn., vol. 53, no. 4, pp. 1451–1461, Apr. 2005.

M. Zada, I. A. Shah, A. Basir, and H. Yoo, “Ultra-compact implantable antenna with enhanced performance for leadless cardiac pacemaker system,” IEEE Trans. Antennas Propag., vol. 69, no. 2, pp. 1152–1157, Feb. 2021.

Z. Xia, H. Li, Z. Lee, S. Xiao, W. Shao, X. Ding, and X. Yang, “A wideband circularly polarized implantable patch antenna for ISM band biomedical applications,” IEEE Trans. Antennas Propag., vol. 68, no. 3, pp. 2399–2404, Mar. 2020.

X. N. Ketavath, D. Gopi, and S. S. Rani, “In-vitro test of miniaturized CPW-fed implantable conformal patch antenna at ISM band for biomedical applications,” IEEE Access, vol. 7, pp. 43547–43554, 2019.

R. Liu, K. Zhang, Z. Li, W. Cui, W. Liang, M. Wang, C. Fan, H. Zheng, and E. Li, “A wideband circular polarization implantable antenna for health monitor microsystem,” IEEE Antennas Wireless Propag. Lett., vol. 20, no. 5, pp. 848–852, May 2021.

S. Hout and J.-Y. Chung, “Design and characterization of a miniaturized implantable antenna in a seven-layer brain phantom,” IEEE Access, vol. 7, pp. 162062–162069, 2019.

M. Zada, I. A. Shah, and H. Yoo, “Metamaterial-loaded compact high-gain dual-band circularly polarized implantable antenna system for multiple biomedical applications,” IEEE Trans. Antennas Propag., vol. 68, no. 2, pp. 1140–1144, Feb. 2020.

W. Cui, R. Liu, L. Wang, M. Wang, H. Zheng, and E. Li, “Design of wideband implantable antenna for wireless capsule endoscopy system,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 12, pp. 2706–2710, Dec. 2019.

A. Kiourti, J. R. Costa, C. A. Fernandes, A. G. Santiago, and K. S. Nikita, “Miniature implantable antennas for biomedical telemetry: From simulation to realization,” IEEE Trans. Biomed. Eng., vol. 59, no. 11, pp. 3140–3147, Nov. 2012.

C. M. Lee, T. C. Yo, C. H. Luo, C. H. Tu, and Y. Z. Jiang, “Compact broadband stacked implantable antenna for biotelemetry with medical devices,” Electron. Lett., vol. 43, no. 12, pp. 660–662, Jun. 2007.

W.-C. Liu, F.-M. Yeh, and M. Ghavami, “Miniaturized implantable broadband antenna for biotelemetry communication,” Microw. Opt. Technol. Lett., vol. 50, no. 9, pp. 2407–2409, Sep. 2008.

S. Kim and H. Shin, “An ultra-wideband conformal meandered loop antenna for wireless capsule endoscopy,” J. Electromagn. Eng. Sci., vol. 19, no. 2, pp. 101–106, Apr. 2019.

T. Yilmaz, T. Karacolak, and E. Topsakal, “Characterization and testing of a skin mimicking material for implantable antennas operating at ISM band (2.4 GHz-2.48 GHz),” IEEE Antennas Wireless Propag. Lett., vol. 7, pp. 418–420, 2008.

S. A. Shah and H. Yoo, “Scalp-implantable antenna systems for intracranial pressure monitoring,” IEEE Trans. Antennas Propag., vol. 66, no. 4, pp. 2170–2173, Apr. 2018.

M. Yousaf, I. B. Mabrouk, M. Zada, A. Akram, Y. Amin, M. Nedil, and H. Yoo, “An ultra-miniaturized antenna with ultra-wide bandwidth characteristics for medical implant systems,” IEEE Access, vol. 9, pp. 40086–40097, 2021.

IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, Standard C95.1-1999, Apr. 1999.

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