Development of Wideband Miniaturized Antennas Based on Fringe Field Capacitance Effects for Implantable MedRadio Band Biotelemetry

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Abstract

A compact meander planar inverted-F antenna (PIFA) with a broad bandwidth, miniature size, and low profile is proposed for implantable biotelemetry in the Medical Device Radiocommunications Service (MedRadio) band (401–406 MHz). The tuning mechanism of fringe field capacitance effects in human tissues on broadband impedance matching and size reduction is also investigated. Compared to existing miniature antennas, the proposed antenna has a 37% smaller volume and provides a 166% wider bandwidth by cutting partial substrate. For the antenna simulation and design, the proposed antenna was embedded into a simple box model (with box size of 55 × 55 × 20 mm³ and pork loin used as equivalent human tissue) and a male human body model (with Ansoft’s accuracy of 4 mm). Experiments were also conducted. Although the proposed antenna occupies a volume of only 77 mm³ (7.8 × 7.8 × 1.27 mm³), the received power was as high as -47 dBm at 401 MHz. A communication link with distance of 1 m between the proposed implantable transmitting antenna and the exterior receiving monopole (one-quarter wavelength) antenna was set up.

Keywords: Medical Device Radiocommunications Service (MedRadio), Meander planar inverted-F antenna (PIFA), Implantable biotelemetry, Fringe field capacitance, Conjugate impedance matching

1. Introduction

The number of Microsystems designed to be implanted into the human body for the early diagnosis of diseases and the monitoring of various physiological parameters has increased in recent years. Implantable antennas are applied to establish wireless communication links between implantable medical devices and exterior instruments for biotelemetry applications. Therefore, an increasing number of studies on implantable antennas have been reported [1-9] for biotelemetry applications in the Medical Device Radiocommunications Service (MedRadio) band (401–406 MHz) [10]. In addition, implantable antennas usually encounter the problem of frequency shift due to complicated human body tissue structures. Therefore, the design of implantable antennas with a broad bandwidth, miniature size, low profile, and good radiation performance is a critical issue. To reduce antenna size, most implantable antennas reported in the literature adopt the planar inverted-F antenna (PIFA) with a superstrate structure. These antennas include the two-layer stacked spiral PIFA [1,2], the three-layer stacked spiral PIFA [3,5-7], and the two-layer stacked π-shape PIFA [4,8]. A coplanar waveguide (CPW)-fed implantable antenna without a superstrate structure has been proposed [9]. However, some existing antennas have a large size [1-4,8], narrow band [1-6], or high profile [1-3,5-8].

To meet the requirements of a broad bandwidth, miniature size, and low profile, a meander PIFA loaded with an inverted L-strip capacitive structure [11] was implemented on a planar substrate. The tuning mechanism of fringe field capacitance effects was achieved by partially removing the substrate surrounding patch [12] to improve the antenna bandwidth and gain and to reduce size via conjugate impedance matching. In addition, input impedance that varies with the probe feed

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position [13] has been utilized to obtain a matched design. In the present study, the proposed antenna is positioned in a simple box model, which is a simplification of the human torso, to reduce simulation time. The emulated human torso tissues, which need to take into account the body’s permittivity and conductivity, were approximated using average human muscle tissue. To evaluate the functionalities of the proposed antenna, the antenna was also simulated in a male human body model (with Ansoft’s accuracy of 4 mm) [14]. Pork loin has a dielectric constant that is similar to that of human muscle and was thus adopted to emulate human tissue in experiments. Moreover, conformance to the latest IEEE standards of specific absorption rate (SAR) (1-g [15] and 10-g [16]) was assessed. The proposed antenna structure was simulated in the MedRadio band.

2. Materials and methods

Nano-sized collagen I particles with diameters of 20-30 nm, produced using a high-voltage electrostatic field system as described in detail elsewhere [17,19]. All chemicals used in this study were of reagent grade.

2.1 Human tissue dielectric characteristics and simulation models

An implantable antenna for biotelemetry is greatly affected by human body tissues, which act as the surrounding medium. General antenna design theory assumes a non-conducting surrounding with a relative permittivity of 1 in vacuum or air. However, an antenna embedded inside a human body and surrounded by the body torso tissue is in a lossy medium with high permittivity. In addition, the dielectric characteristics of human body tissues are highly frequency-dependent [17-19].

The proposed antenna was placed inside a one-layer simple box model at a depth of 4 mm. The simple box model, shown in Fig. 1(a), was filled with emulated human torso tissue to evaluate the properties of the equivalent material and to model the overall behavior of the human body dielectric structure. According to Office of Engineering and Technology (OET) Bulletin 65 supplement C [20] of the Federal Communications Commission (FCC), thus the human body torso tissue can be approximated using average muscle tissue. Therefore, the surrounding medium of the proposed antenna can be approximately determined as one homogeneous layer with a relative permittivity of 58.8 and a conductivity of 0.84 S/m in the MedRadio band. By the way. Some commercial body tissue simulation liquids [21] also follow the FCC regulations [20].

The proposed antenna was then placed into the left chest at a depth of 4 mm inside an Ansoft human body model [14] (see Fig. 1(b)) to verify the simplified box model. The Ansoft human body model has millimeter-level accuracy, more than 300 parts, and frequency-dependent material parameters.

2.2 Selection of emulated human tissue

In general, implantable antennas are simulated and measured in containers filled with emulated human tissue fluid, which is made from deionized water, sugar, salt, and cellulose (or TX-151) [1-3.5-7]. However, the fabrication procedures of emulated human tissue are quite complex and it is difficult to accurately match the permittivity and conductivity of human tissue. Thus, this study adopted pork loin as the test tissue, as its dielectric properties are similar to those of human muscle and it is easily acquired.

Figure 2(a) shows the relative permittivity and conductivity of minced pork loin placed in a 120 × 120 × 50 mm³ container measured using a dielectric probe kit (Agilent 85070E) and a network analyzer (Agilent 8753E). The relative permittivity and conductivity of the frequency points. A comparison of the relative permittivity and minced pork loin were measured from 0.1 to 3.1 GHz at 301 conductivity of the pork loin and

![Figure 1](image1.png)  
Figure 1. (a) Simple box model filled with emulated tissue and (b) Ansoft human model for proposed antenna.

![Figure 2](image2.png)  
Figure 2. (a) Dielectric properties of minced pork loin measured by Agilent 85070E probe kit, and (b) comparison of pork loin (measured values) and human muscle (theoretical values) in terms of relative permittivity and conductivity.
muscle [17–19] is shown in Fig. 2(b). The pork loin has a relative permittivity of 59.2 and a conductivity of 0.86 S/m in the MedRadio band, which are similar to those of human muscle, making the pork loin suitable for emulating human tissue. Note that the test tissue for verifying the proposed antenna was at room temperature (around 26 °C) [8].

2.3 Dimensions of proposed antenna

Using the Ansoft high-frequency structure simulator (HFSS), a wideband miniaturized implantable meander PIFA was designed for biotelemetry applications (401 MHz). As shown in Fig. 3, the proposed antenna has two-layer stack structures. The substrate and superstrate are both Rogers 3210, with a thickness of 0.635 mm, loss tangent of 0.0027, dielectric constant of 10.2, and copper cladding of 1/2 oz. The meander part is composed of a serpentine line section and an inverted L-strip section. In addition, the serpentine line comprises nine 7 × 0.5 mm² rectangular strips and eight 0.3 × 0.3 mm² shorter strips. The spacing between rectangular strips is 0.3 mm. The serpentine line section of the proposed antenna can be considered as an inductive short-terminated transmission line, and the inverted L-strip section (marked with continual oblique line in Fig. 3) can be considered as a capacitive loading [11]. The 50-Ω feed point and the short pin are also plotted in Fig. 3. The feed point feed f is indicated as a small black round shape at strip f in Fig. 3. Moreover, for good impedance matching, the positions of the feed point at other strips were evaluated. The other five positions of the feed point (denoted as feed a, feed b, feed c, feed d, and feed e, and indicated as small gray round shapes) at strip a, strip b, strip c, strip d, and strip e, respectively, are shown in Fig. 3. They are used for the simulation and evaluation of the implantable antenna design.

![Figure 3. Geometry of proposed antenna.](image)

2.4 Parametric study of proposed antenna

Initially, the proposed antenna, with a width (W) of 8.4 mm and a length (L) of 6.6 mm, exhibited inductive behavior in tissue. From the imaginary part of the impedance shown in Fig. 4(b), when the size of the proposed antenna was reduced from 8.4 × 8.4 mm² to 7.8 × 7.8 mm² by partially removing the substrate surrounding the patch [12], the inductive impedance gradually shifted to a capacitive one. From the real part of the impedance shown in Fig. 4(a), when the size was reduced to 7.8 × 7.8 mm², impedance broadband matching to 50 Ω could be achieved easily by tuning mechanism of fringe field capacitance effects, which is a conjugate impedance matching method that can enhance antenna bandwidth and reduce size. On the other hand, the tuning mechanism of fringe field capacitance effects was achieved by the method of removing the partial substrate and superstrate.

As mentioned previously, the input impedance of the proposed antenna varies with the probe feed position [13]. In Fig. 3, each position of the feed point (feed a, feed b, feed c, feed d, feed e, and feed f) at individual strips (strip a, strip b, strip c, strip d, strip e, and strip f) was used to evaluate and achieve impedance matching. The above-mentioned two tuning techniques were utilized to obtain a matched design. When the probe feed position was shifted from strip a to strip f progressively, the impedance of the real part matched 50 Ω, as shown in Fig. 4(c), and that of the imaginary part decreased from inductive impedance to capacitive impedance, as shown.
in Fig. 4(d). The input impedance reached around 50 + j0 Ω in the MedRadio band when feed f was set as the feed point and parameter F was 1 mm at strip f. As shown in Fig. 4(e), with the optimal parameters (feed point feed f with parameter W = 7.8 mm and parameter F = 1 mm at strip f), the deepest simulated $S_{11}$ (-25 dB) was achieved.

The antenna resonance frequency can be shifted significantly by adjusting the magnitude of parameter L, as shown in Fig. 4(f). Therefore, the magnitude of parameter L can be varied to achieve impedance matching and tuning of the resonance frequency shift in human tissues. In Fig. 4(f), the antenna resonance frequency shifted to a lower band when the magnitude of parameter L was increased, which lengthens the antenna’s current path. The geometry parameters of the proposed antenna obtained from simulations are listed in Table 1.

Table 1. Geometry parameter values of proposed antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$W$ (mm)</th>
<th>$L$ (mm)</th>
<th>$F$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>7.8</td>
<td>6.6</td>
<td>1</td>
</tr>
</tbody>
</table>

2.5 Experiment setup

The simulation and measurement environments of the proposed implantable antenna are shown in the insets of Fig. 5, respectively. The measured $S_{11}$ values were obtained using a network analyzer and the received power was measured using a radio-frequency (RF) signal generator (SMC 100A) and a spectrum analyzer (HP N9340B). As shown in the inset of Fig. 5(b), for the real environmental communication link, the distance between the proposed implantable transmitting antenna and the one-quarter wavelength exterior receiving monopole antenna was 1 m. In addition, the real receiving environment was installed near some Wi-Fi access points, which are strong sources of RF (2.4 GHz) interference.

3. Results and discussion

3.1 Analysis of proposed antenna characteristics

The proposed antenna with the parameters listed in Table 1 was fabricated and tested. Figure 6 shows photographs of the proposed design. Figure 5(a) compares the $S_{11}$ values obtained from the Ansoft human model, simple box model, and measurements. It reveals good measured impedance matching in the MedRadio band (401-406 MHz), with a measured $S_{11}$ of -20 dB and a broad -10-dB bandwidth of 203 MHz (322-525 MHz). In addition, the results show that the simulation with the simple box model matches that with the Ansoft human model. The former model can thus be used to simplify the simulation process. The simulated $S_{11}$, resonance frequency, bandwidth, and resonance frequency deviation values of the proposed antenna embedded in the skin, muscle, heart, pork loin, and Ansoft human model are listed in Table 2. For all human tissues, the $S_{11}$ value satisfied the requirement of -10 dB and remained consistent. The radiated power and radiation efficiency obtained in the simple box model and Ansoft human model are shown in Table 3.

Figure 5. (a) Simulated (simple box model and Ansoft human model) and measured $S_{11}$ values for proposed antenna, and (b) measured maximum received power at 1 m away from proposed implanted antennas (delivered power is 1 mW).

Figure 6. Photographs of proposed miniaturized antenna.

Table 2. Simulated $S_{11}$ values of proposed antennas implanted into biological tissues in MedRadio band.

<table>
<thead>
<tr>
<th>Tissues</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$ (S/m)</th>
<th>$S_{11}$ (dB)</th>
<th>Resonant $f_0$ (MHz)</th>
<th>Bandwidth (MHz)</th>
<th>Deviation $f_0$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork loin</td>
<td>59.2</td>
<td>0.86</td>
<td>-23</td>
<td>401</td>
<td>320-502 (182)</td>
<td>0</td>
</tr>
<tr>
<td>Heart</td>
<td>66.1</td>
<td>0.96</td>
<td>-22</td>
<td>380</td>
<td>305-481 (176)</td>
<td>5</td>
</tr>
<tr>
<td>Muscle</td>
<td>58.8</td>
<td>0.84</td>
<td>-24</td>
<td>406</td>
<td>328-500 (172)</td>
<td>2</td>
</tr>
<tr>
<td>Skin</td>
<td>46.7</td>
<td>0.69</td>
<td>-20</td>
<td>427</td>
<td>349-525 (176)</td>
<td>6</td>
</tr>
<tr>
<td>Ansoft model</td>
<td>N/A</td>
<td>N/A</td>
<td>-17</td>
<td>389</td>
<td>323-473 (150)</td>
<td>3</td>
</tr>
</tbody>
</table>

Relative permittivity: $\varepsilon_r$, Conductivity: $\sigma$. 
Table 3. Comparison of radiated power and radiation efficiency (delivered power = 1 W) between simple box model and Ansoft human model in the MedRadio band.

<table>
<thead>
<tr>
<th>Model type</th>
<th>Radiated power (W)</th>
<th>Radiation efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple box model</td>
<td>0.0148</td>
<td>0.0151 (1.51 %)</td>
</tr>
<tr>
<td>Ansoft human body model</td>
<td>0.0107</td>
<td>0.0109 (1.09 %)</td>
</tr>
</tbody>
</table>

In the real receiving environment (see Fig. 5(b)), the communication link distance was 1 m and 1 mW was delivered to the proposed antenna. The experimentally measured received power was around -47 dBm in the MedRadio band. In a previous study, for a communication link [1] with a distance between the implanted antenna and an exterior dipole antenna of less than 30 cm and a delivered power of 8.8 mW, the radiation efficiency was 0.25% [1], which is four times lower than that obtained for the proposed antenna (1.09%). Consequently, it can be concluded that the link budget of the proposed antenna is enough to support implanted biotelemetry applications.

Figure 7 shows the simulated three-dimensional far-field radiation patterns and the simulated average SAR (1-g and 10-g) distribution of the proposed antenna for the simple box model and Ansoft human model, respectively. In the upper part of Fig. 7(a), since the proposed antenna in the simple box model is electrically very small and symmetrically surrounded by a homogeneous medium, the radiation pattern is nearly omni-directional and, monopole-like. In the Ansoft human model, the implantation site is asymmetrical and inhomogeneous. The radiation pattern shown in the upper part of Fig. 7(b) is twisted and more nulls. Furthermore, the IEEE C95.1-1999 standard restricts the SAR average over any 1 g of tissue in the shape of a cube (1-g average SAR) to less than 1.6 W/kg [15], and the IEEE C95.1-2005 standard restricts the SAR average over any 10 g of tissue in the shape of a cube (10-g average SAR) to less than 2 W/kg [16]. In this paper, conformance with these IEEE standards ([15,16]) was assessed. The simulated 1-g and 10-g average SAR distributions of the proposed antenna implanted into the simple box model and Ansoft human model are shown in the lower part of Figs. 7(a) and 7(b), respectively, with the delivered power assumed to be 1 W. The maximum 1-g and 10-g average SAR values computed in this study are summarized in Table 4. For the maximum allowable net input power levels, the results satisfy the IEEE restrictions for SAR. Note that the IEEE C95.1-1999 standard is much stricter than the IEEE C95.1-2005 standard. For satisfying the stricter regulations, a net input power of 3.0 mW (which is exhibited in Ansoft human model) is considered for the proposed antenna.

To determine the delivered power of the proposed antenna in human body tissue, the limitation for the maximum effective radiated power (ERP) (25 μW in free space [22]) and the radiation efficiency of the proposed antenna in the Ansoft human model given in Table 3 were utilized. ERP is the product of the power delivered by the antennas and the radiation efficiency of antennas. The maximum ERP is limited to avoid damage to neighboring radio services and human bodies. However, with the radiation efficiency (1.09 %) of the proposed antenna in the Ansoft human model, the antenna generates a radiated power of 32.7 μW, which is larger than the limitation of ERP (25 μW). For conformance with the regulations of ERP, a delivered power of 2.2 mW was adopted for the proposed antenna to generate radiated power of less than 25 μW. Finally, a comparison of existing antennas [1-8] with the results listed in Table 5 reveals that the volume of the proposed antenna is only 63% that in [7], the profile is 67% those in [3-8], and the bandwidth is 166% wider than that in [7]. Therefore, the proposed antenna is suitable for implantable biotelemetry in the MedRadio band.

Table 4. Maximum SAR (delivered power = 1 W) and maximum allowable net input power in the MedRadio band.

<table>
<thead>
<tr>
<th>Model type</th>
<th>Max. SAR (W/kg)</th>
<th>Max. net input power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-g average</td>
<td>10-g average</td>
</tr>
<tr>
<td>Simple box model</td>
<td>521</td>
<td>54</td>
</tr>
<tr>
<td>Ansoft human body model</td>
<td>525</td>
<td>56</td>
</tr>
</tbody>
</table>

3.2 Capability of matching to RFIC directly without RF matching network in MedRadio band

According to the results in the previous section, 50-Ω impedance matching of antennas can be easily achieved by tuning mechanism of fringe field capacitance effects and adjusting the probe feed. However, if a radio-frequency integrated circuit (RFIC) is not matched to an impedance of 50 Ω, the impedance of the proposed antenna can be easily adjusted to match the specifications without a balun [23]. For
Table 5. Comparison of proposed antenna to reported implantable antennas.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Volume (mm$^3$)</th>
<th>BW (MHz)</th>
<th>Gain (dB)</th>
<th>Radiation efficiency</th>
<th>Simulated model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. [1]</td>
<td>24 × 32 × 4</td>
<td>35</td>
<td>N/A</td>
<td>0.25%</td>
<td>Upper part of human torso</td>
</tr>
<tr>
<td>Ref. [2]</td>
<td>29.4 × 19.6 × 6</td>
<td>35</td>
<td>-35</td>
<td>N/A</td>
<td>Human shoulder without head</td>
</tr>
<tr>
<td>Ref. [3]</td>
<td>11 × 7.5 × 1.905</td>
<td>50</td>
<td>-26.2</td>
<td>0.31%</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Ref. [4]</td>
<td>22.5 × 22.5 × 1.27</td>
<td>80</td>
<td>-25</td>
<td>N/A</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Ref. [5]</td>
<td>11 × 4.8 × 1.905</td>
<td>84</td>
<td>-14.2</td>
<td>1.3%</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Ref. [6]</td>
<td>10 × 10 × 1.905</td>
<td>50</td>
<td>-26</td>
<td>0.61%</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Ref. [7]</td>
<td>8 × 8 × 1.905</td>
<td>122</td>
<td>-37.9</td>
<td>0.55%</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Ref. [8]</td>
<td>18.5 × 22.5 × 1.9</td>
<td>120</td>
<td>-27.3</td>
<td>N/A</td>
<td>Small cube of human skin</td>
</tr>
<tr>
<td>Proposed Antenna</td>
<td>7.8 × 7.8 × 1.27</td>
<td>203</td>
<td>-14.8</td>
<td>1.09%</td>
<td>Whole human body model</td>
</tr>
</tbody>
</table>

example, RFIC CC1101 (low-power sub-1-GHz RF transceiver, Texas Instruments) [24] has an impedance of 116 + j41 Ω at around 400 MHz from the RF-port towards the antennas. The RFIC can be matched directly by tuning mechanism of fringe field capacitance effects and adjusting the probe feed of the antennas in the MedRadio band. To do this, the antenna size can be slightly reduced from 8.2 × 8.2 mm$^2$ to 8 × 8 mm$^2$ to obtain a capacitive reactance. The real and imaginary parts of the impedance are shown in Figs. 8(a) and 8(b), respectively. When the size of the antenna is 8.1 × 8.1 mm$^2$, the real and imaginary parts of the impedance are around 120 Ω and around + j41 Ω, respectively. The feed point also influences the antenna’s impedance, as shown in Figs. 8(c) and 8(d). To verify this, the feed point was set at feed c and the feed position (parameter C) at strip c was adjusted. When parameter C was set at 5.9 mm, the real part of the impedance was 116 Ω and the imaginary part has minor effects. Therefore, the optimal parameters (feed c with parameter C = 5.9 mm at strip c and parameter W = 8.1 mm) are obtained for directly matching to TI CC1101 at an impedance of 116 + j41 Ω for an RF matching network in the MedRadio band.

4. Conclusion

Conjugate impedance matching and feed position methods were used to develop a miniature, low-profile, broadband, high-gain, and high-efficiency implantable PIFA. To apply the proposed antenna in various human tissues, impedance matching and resonance frequency tuning can be easily achieved by adjusting the magnitude of parameter L. Furthermore, for satisfying ERP and SAR (average 1-g and 10-g) limitations, the maximum delivered power of the proposed antenna must be limited to 2.2 mW. For practical applications, a reliable communication link over a distance of 1 m was evaluated. The measured receiving power was about -47 dBm, which is enough to support the link budget for implanted biotelemetry. Compared to previous reports, the proposed antenna exhibits a much wider bandwidth, higher gain, and very good efficiency. Simulation results show that the proposed antenna can be matched to an RFIC directly without using an RF matching network in the MedRadio band. Therefore, the proposed antenna is suitable for implantable biotelemetry in the MedRadio band.

![Figure 8. Parametric study on simulated impedance of (a) real part and (b) imaginary part for various substrate sizes (parameter W), and parametric study on simulated impedance of (c) real part and (d) imaginary part for various magnitudes of parameter C.](image)

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