Performance Evaluation and Sensitivity Analysis of a Novel Rectenna System for Deep Implanted Devices

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\textbf{Abstract—}We examine the performance of an implantable antenna combined with a rectifier circuit (Rectenna) in terms of polarization stability, effect of surrounding tissue electrical properties and implantation depth. A single-layer Planar Inverted F-Antenna (PIFA) that exhibits dual-resonance for data telemetry (MedRadio band, 402 MHz) and power transfer (ISM band, 915 MHz) is employed. Antenna polarization is investigated through axial ratio computations. Further, we consider nine tissue-dielectric scenarios comprising ±5\% and ±10\% variations in the initial tissue permittivity and conductivity. Subsequently, the antenna implantation depth is also altered. Indeed, proposed implantable antenna is robust with regards to reliability of wireless link, resonance response and radiation performance. Finally, an improved, previously presented, rectifier system is presented. As shown, its efficiency reaches almost 40\% (20\% increase) for an optimum load $R_{\ell}=9.5$ kOhm at a reference power level $P_{\ell}=-16$ dBm.

\textbf{Index Terms—} Implantable antenna, industrial, scientific and medical (ISM) band, Medical Device Radiocommunications Service (MedRadio), sensitivity, telemetry, wireless powering.

\section{I. INTRODUCTION}

Wirelessly-linked implantable medical devices (IMDs) can support in vivo monitoring, measurement and stimulation of physiological signs (e.g., blood pressure). The basic element of an implanted biosystem is the embedded antenna that allows the reliable transmission of vital data to external monitoring equipment. Implantable antenna design and performance for data telemetry have been significantly investigated within the Medical Device Radiocommunications (MedRadio) Services band (401-406 MHz) \cite{1}-\cite{3} and the Industrial, Scientific, and Medical (ISM) bands (433.1-434.8 MHz, 868-868.6 MHz, 902.8-928 MHz, and 2.4-2.5 GHz) \cite{4}.

Now, research is focusing on the investigation of wireless power transfer to implanted devices. Safety issues have been studied in \cite{5} while in \cite{6}, an implantable antenna has been designed for data telemetry (402 MHz), power transmission (433 MHz), and wake-up signal operation (2.45 GHz). 2.45 GHz is also utilized for wireless powering from some researchers \cite{7}. In \cite{8}, the authors introduce a novel single-layer PIFA that exhibits dual-frequency behavior for data telemetry (402 MHz) and power transfer (915 MHz). Implant powering is achieved through a rectifier.

In this paper, we study the performance of the implantable rectenna in \cite{8}, in terms of polarization stability and resilience to dielectric environment and implantation depth. As shown, on contrary with other designs, proposed antenna is pretty robust to environmental changes and good candidate for supporting implanted sensors. It is a low profile antenna with a rather simple structure, unlike other designs \cite{6}. It covers two frequency bands, not only for power transfer \cite{7} but for data telemetry as well. In addition, we further improve the rectifier system designed in \cite{8}.

Antenna performance is assessed under both data telemetry and power transfer operation scenarios. The antenna is implanted within a three-layered arm model. Polarization is examined through axial ratio computations into the main radiation planes. To evaluate antenna behavior in various dielectric environments we consider nine tissue-dielectric scenarios. The implantation depth impact on antenna resonance and radiation response is also addressed.

Paper is organized as follows. In Section II, we present the implantable antenna model and the numerical analysis of polarization, tissue-dielectric properties and implantation depth. In Section III, a refined rectifier in terms of efficiency is proposed. Conclusions follow in Section IV.

\section{II. ANTENNA DESIGN AND NUMERICAL ANALYSIS}

A parametric model of the implantable PIFA is shown in Fig. 1 \cite{8}. The antenna is printed on a Rogers RO 3210 substrate ($\varepsilon_r=10.2$, $\tan\delta=0.003$, $\delta=0.625$ mm) and is covered with an identical superstrate. The patch surface and the ground plane have planar dimensions of 13.8 mm x 15.8 mm and 14 mm x 16 mm, respectively. A slit ($w_1=0.9$ mm, $l_1=9.9$ mm) and an L-shaped slot ($w_2=1.3$ mm, $w_3=0.2$ mm, $l_2=12.9$ mm, $l_3=2$ mm) are removed from the patch for size reduction and dual-frequency operation at 402 MHz and 915 MHz, respectively. A shorting pin (radius 0.3 mm) further shrinks dimensions. High Frequency Structure Simulator (HFSS) is used for antenna design and analysis \cite{9}.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Geometry of the implantable PIFA operating at 402 MHz and 915 MHz, respectively \cite{8}.}
\end{figure}
The PIFA is implanted into a three-layered arm model consisting of skin (thickness 2.5 mm), muscle (thickness 25 mm), and bone (Fig. 2). The antenna is placed within the muscle tissue at a depth d=10 mm beneath the skin-air interface. The dielectric constants of the tissue model are evaluated at 402 MHz and 915 MHz, respectively [10]-[12].

A. Implantable antenna polarization

We focus on antenna polarization since potential polarization mismatch between the implanted PIFA and an external antenna could greatly affect wireless link reliability. Specifically, a wireless communication link could be built between the developed PIFA and an external half-wavelength dipole for data telemetry (402 MHz) and power transmission (915 MHz). The reliability of the biolink strongly depends on antenna radiation performance (gain, radiation pattern, and specific absorption rate), power transmission restrictions and path losses, as has been analyzed in [8], [13].

Under the assumption that the external antenna presents a linear polarization, the implanted PIFA polarization in the main areas in which the gain pattern lies (azimuthal and elevation planes) is investigated through axial ratio computations. In Fig. 2 (b), the numerical PIFA gain radiation patterns at 402 MHz and 915 MHz are illustrated. In Figs. 3 and 4, the axial ratio levels are recorded at both radiation planes for the MedRadio and ISM band, respectively. Notice that antenna planar surface lies on the xz plane. We see that the value of axial ratio is generally over 10dB for both frequency regions indicating an approximately linear polarization. This allows a satisfactory biolink response under possible antenna displacements.

B. Effect of tissue dielectric properties

The effect of tissue dielectric properties variation on the resonance and radiation performance of the proposed PIFA model is numerically evaluated at 402 MHz and 915 MHz, respectively. We consider nine tissue-scenarios comprising ±5% and ±10% variations in the initial permittivity ($\varepsilon_r$) and conductivity ($\sigma$) values to address differences between human bodies. Reflection coefficient ($|S11|$) results at the MedRadio and ISM frequency are recorded in Tables I and II, respectively. Provided that the implantable antenna is well-matched when $|S11|$ is less than -10 dB, its resonance performance is proved to be nearly insensitive for all tissue changes under study at both frequencies of operation.

Numerical maximum far-field gain values under all tissue scenarios at 402 MHz and 915 MHz are, also, listed in Table I and Table II, respectively. We see that a ±10% variation in the electrical properties creates small changes in the exhibited antenna gain. Furthermore, an increase in permittivity or decrease in conductivity can enhance implantable antenna gain. An implantable antenna should present adequate resonance and gain performance under different tissue-loading conditions. In our case as shown, the PIFA is rather robust.
C. Effect of antenna implantation depth

Antenna location can greatly affect resonance due to the complex surrounding tissue environment as seen in [14]. Here, we quantify antenna sensitivity in terms of resonance frequency detuning and gain variation as function of the implantation depth d. To that purpose, the antenna is implanted into different positions along y-axis [Fig. 2 (a)]. Reflection coefficient values at 402 MHz (|S11|@402 MHz) for various depths are shown in Fig. 5 (a). Assuming that sufficient performance is achieved when |S11| is less than -10 dB, we see that the developed antenna works appropriately even in muscle-skin interface (y=4 mm). Furthermore, antenna gain is reasonably changed relative to the initial antenna position (y=10 mm). We obtain satisfactory results at 915 MHz, as well [Fig. 5 (b)]. Maximum gain deviations reach 4.1% at d=14 mm and -12.8% at d=4 mm in MedRadio and ISM bands respectively.

An implantable antenna as the proposed PIFA, intended for stable data and power operation, should exhibit adequate resonance and gain response under various implantation depths regardless of the small volume.

III. Rectifier System

The rectifier converts RF energy collected by the implanted PIFA into useful DC power. It consists of an input filter, a rectifying circuit, an output filter and a load. The performance metric is the RF-to-DC conversion efficiency (n) defined as:

\[ n(\%) = \frac{P_{\text{DC}}}{P_r} \times 100\% = \frac{V_{\text{DC}}^2}{R_L P_r} \times 100\% \]  
(1)

where \( P_{\text{DC}} \) is the output DC power, \( P_r \) is the implanted antenna received power, \( V_{\text{DC}} \) is the output DC voltage, and \( R_L \) is the load resistance. In this study, the aim is to further optimize the efficiency of the implantable rectifier developed in [8] around the “reference power level” of \( P_r=-16 \text{ dBm} \). The schematic of the improved rectifier designed with the Advanced Design System (ADS) is depicted in Fig. 6. The input filter consists of a chip capacitor (\( C_M \)) and inductor (\( L_M \)), while, the rectifying circuit is a Schottky voltage doubler. A shunt chip capacitor \( C_r \) serves as the output filter. The newly-inserted series inductor \( L_b \) is the key-element to further suppress harmonics in the rectifying circuit and reinforce, thus, efficiency. It is necessary, though, to make minor changes in the value of the inductor \( L_M \) from 56 nH [8] to 51 nH.

The conversion efficiency and output DC voltage of the proposed rectifier as a function of PIFA input power are presented in Fig. 7. In contrast to the results in [8], the improved rectifier achieves an enhanced efficiency of 39.6% for an optimum load \( R_L=9.5 \text{ kOhm} \) at \( P_r=-16 \text{ dBm} \) compared to the previously obtained efficiency of 33.1%. However, a minor reduction of 7.6% in the output voltage is recorded.

<table>
<thead>
<tr>
<th>TABLE I. ANTENNA PERFORMANCE THROUGH THE VARIATION OF TISSUE ELECTRICAL PROPERTIES AT 402 MHz</th>
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<tr>
<td>Parameters ( \varepsilon_r (=57.12) )</td>
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<tr>
<td>( f_{\text{res}} ) (MHz)</td>
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<tr>
<td>( S_{11}@402 ) (dB)</td>
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<td>gain (dB)</td>
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<th>TABLE II. ANTENNA PERFORMANCE THROUGH THE VARIATION OF TISSUE ELECTRICAL PROPERTIES AT 915 MHz</th>
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<tr>
<td>Parameters ( \varepsilon_r (=54.9) )</td>
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<tr>
<td>( f_{\text{res}} ) (MHz)</td>
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<td>( S_{11}@915 ) (dB)</td>
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<td>gain (dB)</td>
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Fig. 5. Reflection coefficient and gain of the developed implantable PIFA with respect to implantation depth at (a) MedRadio and (b) ISM bands, respectively.

Fig. 6. Schematic of the improved rectifier system at 915 MHz.
IV. CONCLUSIONS

In this work, the performance of an implantable rectenna [8] with respect to polarization, tissue dielectric properties and implantation depth was examined. The rectenna, comprised of a Planar Inverter F-Antenna (PIFA) and a matched rectifier, was embedded into the muscle tissue of a canonical arm model. The antenna had double resonance supporting telemetry operation at 402MHz (MedRadio band) and 915MHz (ISM band). Antenna polarization was initially examined through axial ratio computations. The proposed PIFA exhibited stable polarization into the main radiation planes contributing to the reliability of a wireless biolink. Subsequently, the effect of tissue dielectric properties and implantation depth on the resonance and radiation response of the implanted PIFA was also evaluated. Various tissue-dielectric scenarios and implantation sites were implemented to prove the robustness of the developed antenna. Finally, we showed that the insertion of a series inductor within the rectifying circuit can greatly enhance the efficiency of a rectifier system.

In the future, we intend to fabricate the proposed rectenna system and to perform measurements in order to verify the validity of the simulated results and the practical effectiveness of the rectenna.

REFERENCES


