Design of a Novel Miniature Implantable Rectenna for In-Body Medical Devices Power Support

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Abstract—A human tissue-implantable rectenna that comprises a compact-size planar inverted F-antenna (PIFA) and a rectifier system is presented. The developed PIFA is intended for wireless data telemetry and power transmission operation within the Medical Device Radiocommunications Service band (MedRadio, 402-405 MHz) and the industrial, scientific and medical band (ISM, 902.8-928 MHz), respectively. PIFA miniaturization and dual-frequency operation is accomplished through the slit insertion and L-shaped slot loading upon patch surface. The implanted antenna design analysis is carried out inside the muscle tissue of a cylindrical three-layered phantom representing the human arm. The resonance, radiation, and Specific Absorption Rate (SAR) performance of the implanted PIFA is assessed. Subsequently, a rectifier system is designed based on power link budget calculations and safety considerations; the RF-to-DC conversion efficiency is, then, evaluated.

Index Terms—Implantable antenna, industrial, scientific and medical (ISM) band, Medical Device Radiocommunications Service (MedRadio), planar inverted-F antenna, rectifier, telemetry, wireless powering.

1. INTRODUCTION

Implantable Medical Devices (IMDs) support various diagnostic and therapeutic functions including sensing, stimulation, and drug delivery. On the basis of reinforcing operation effectiveness, miniature antennas are integrated into IMDS to communicate with external health monitoring equipment and wirelessly transmit vital signs (e.g., cardiac beat, blood pressure, glucose, and body temperature). Indeed, radio frequency (RF) antenna-based medical telemetry has drawn the scientific attention in recent years with regard to implantable antenna design and performance response [1]-[3].

The state-of-the-art of research in implantable antennas indicates that planar inverted-F antennas (PIFA) or patch antennas operating in the 401-406 MHz Medical Device Radiocommunications Service (MedRadio) frequency band have been investigated for wireless biotelemetry purposes [4]-[8]. Planar dipole [9] and monopole [10], [11] antenna structures designed to resonate at MedRadio have, also, been suggested for in-body communication. Moreover, in [12], a wire dipole antenna has been developed (0.951-0.956 GHz) for in-body wireless communication.

Many research groups have conducted great work on implantable antennas for RF biomedical data telemetry. However, there is important research deficiency on the investigation of RF wireless power transfer to implanted bio-devices. In [13], a chip antenna along with an energy harvesting circuit made of an inductor and a chip capacitor was developed for RF power transmission. Safety issues and Federal Communications Commission (FCC) restrictions of RF powering were studied in [14]. The development of implantable rectenna consisting of an implantable antenna and a rectifier system has, also, been presented for wireless RF implant powering. The implantable rectenna receives and converts RF energy collected by the implanted antenna into useful power for the biologically-embedded medical systems. In [15], an implantable antenna was designed for wireless data telemetry (MedRadio, 402 MHz), power transmission (ISM, 433 MHz), and wake-up signal operation (ISM, 2.45 GHz). A conversion efficiency of 86% was achieved when the antenna input power was 11 dBm and the load was 5 kOhm at 433 MHz. A compact single-band implantable PIFA with a rectifier has, also, been suggested for wireless powering (ISM, 2.45 GHz) in [16]. A parasitic patch over the human body was designed for increased antenna gain. A conversion efficiency of 42% was, then, obtained at -10 dBm input power and for 3.25 kOhm load.

The objective of this study is to present a novel small-sized rectenna implanted into the muscle tissue of a three-layered arm model which could be integrated into an IMD. A single-layer PIFA is adopted as the radiating element aiming at antenna structure simplicity and low-profile. The implanted PIFA exhibits dual-frequency behavior for wireless data telemetry (402 MHz) [17] and power transmission (915 MHz) [18], respectively. A rectifier system is, also, developed taken into account power link calculations and patient safety considerations. A satisfactory conversion efficiency of 33.1% is achieved at received antenna power of -16 dBm and for 9.5 kOhm load at 915 MHz.

This paper is organized as follows. Section II presents the antenna design and the equivalent tissue-simulating model. In section III, the simulation results including antenna resonance and radiation performance, as well as specific absorption rate (SAR) are featured. A power communication link and the
proposed rectifier system for the implantable rectenna are exhibited in Section IV. Conclusions follow in Section V.

II. ANTENNA DESIGN

The geometry of the proposed implantable PIFA is shown in Fig. 1. The radiating patch is printed on a high-dielectric substrate (Rogers RO 3210, \(\varepsilon_r=10.2, \tan\delta=0.003\)) of 0.625 mm thickness \((t)\) and is covered with an identical superstrate layer. 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 of width \((w_1)\) 0.9 mm and length \((l_1)\) 9.9 mm is removed from the rectangular patch for antenna size reduction at MedRadio band. An L-shaped slot is, also, cut from patch surface for achieving additional antenna operation at 915 MHz. The loaded slot has a non-uniform width of 1.3 mm \((w_2)\) and 0.2 mm \((w_3)\), respectively, and total length 14.9 mm \((l_2=12.9 \text{ mm}, l_3=2 \text{ mm})\). A shorting pin (radius 0.3 mm) is introduced to increase the effective antenna size and further enhance antenna miniaturization. Ansys High Frequency Structure Simulator (HFSS) is used for antenna design process and extraction of numerical results [19].

Fig. 1. Geometry of the proposed implantable PIFA operating at 402 MHz and 915 MHz, respectively.

Considering antenna implantation into human arm muscle, we employ a three-layered tissue model consisting of skin (thickness 2.5 mm), muscle (thickness 25 mm), and bone (Fig. 2) [20]. The antenna is placed at a depth \(d=10 \text{ mm}\) beneath the skin-air interface, with the center of the ground plane consisting the origin of the coordinate system. The dielectric constants of the tissue-emulating model are evaluated at 402 MHz and 915 MHz for data telemetry and power transmission, respectively and are listed in Table I [21].

### Table I. Electrical Properties of the Tissues Used in This Study

<table>
<thead>
<tr>
<th>Tissue</th>
<th>(\varepsilon_r)</th>
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<tr>
<td>Skin</td>
<td>46.7</td>
<td>0.69</td>
<td>41.33</td>
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</tr>
<tr>
<td>Muscle</td>
<td>51.1</td>
<td>0.79</td>
<td>54.99</td>
<td>0.95</td>
</tr>
<tr>
<td>Bone</td>
<td>13.1</td>
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<td>12.44</td>
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Fig. 2. Numerical three-layered tissue model enclosing the proposed PIFA.

### III. NUMERICAL RESULTS

A. Antenna Resonance Performance

Fig. 3 illustrates the simulated reflection coefficient \(|S_{11}|\) frequency response of the designed implantable PIFA when embedded into the muscle tissue of the cylindrical phantom (Fig. 2). The antenna presents a resonance frequency at 402 MHz for wireless data telemetry operation, as shown in Fig. 3 (a). The 10-dB impedance bandwidth is 33 MHz covering the MedRadio frequency band. The implantable PIFA exhibits, also, resonance at 915 MHz for wireless power transmission operation, as depicted in Fig. 3 (b). The obtained bandwidth is 49.6 MHz covering the desired ISM band.

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Fig. 3. Reflection coefficient characteristics of the proposed implantable PIFA within (a) the MedRadio (402 MHz), and (b) the ISM (915 MHz) bands, respectively.

B. Antenna Radiation Performance

The simulated far-field gain pattern when the proposed antenna is implanted into the arm muscle tissue is presented in Fig. 4. The maximum gain is calculated to be -35.6 dB for the MedRadio band [Fig. 4 (a)], and -23.4 dB for the ISM band [Fig. 4 (b)], respectively. In both frequency bands, the radiation pattern is nearly omnidirectional since it is affected by the surrounding tissue medium.
C. Specific Absorption Rate (SAR)

SAR analysis is conducted in order to assess the electromagnetic power absorbed by the muscle tissue at 402 MHz. When the proposed antenna is assumed to deliver 1 W, the simulated maximum 1-g and 10-g average SAR values are 426.5 W/kg and 96.8 W/kg, respectively (Table II). IEEE standards limit, though, the maximum 1-g and 10-g average SAR to a value of less than 1.6 W/kg and 2 W/kg, respectively, for general public exposure \cite{22}, \cite{23}. To abide by the SAR restrictions, the input power of the implanted PIFA should be confined to the values presented in Table II (second column).

**TABLE II. SIMULATED PEAK SAR (INPUT POWER 1 W) AND MAXIMUM INPUT POWER FOR SAR LIMITS COMPLIANCE IN THE MUSCLE TISSUE**

<table>
<thead>
<tr>
<th>402 MHz</th>
<th>Peak SAR [W/kg]</th>
<th>Maximum input power [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-g average</td>
<td>325.6</td>
<td>4.9</td>
</tr>
<tr>
<td>10-g average</td>
<td>88.9</td>
<td>22.5</td>
</tr>
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IV. DESIGN OF THE RECTIFIER SYSTEM

A. Wireless Power Link Calculation

Prior to the design of the rectifier, a wireless power link is built between the developed PIFA (receiver, $R_x$) implanted into the canonical arm model and an external dipole antenna (transmitter, $T_x$) at 915 MHz. It should be noted that the specific ISM band is selected for the antenna wireless power operation based on the parametric study in \cite{24}. The numerical power link set-up is shown in Fig. 5 (a). The objective is to evaluate receiver’s sensitivity to collect RF signals for wireless power transmission as a function of distance ($D$). Key factors such as i) the implanted antenna gain, ii) the transmitting power ($P_t$) regulated by SAR and effective isotropic radiated power (EIRP) restrictions, and iii) the path losses considerably determine the power ($P_r$) received by the implanted PIFA \cite{24}.

The transmitting power of the external dipole ($P_t$) is set to 1 W (30 dBm) based on the FCC restrictions regarding the maximum output power in the ISM bands. The maximum EIRP is, also, confined to 36 dBm \cite{18}, \cite{25}. Based upon these transmitting power restrictions, the maximum 1-g and 10-g average SAR values within the tissue phantom [Fig. 5 (a)] are calculated and are equal to 0.42 W/kg and 0.28 W/kg, respectively for $D=10$ cm. The simulated transmission coefficient [$S_{21}$] between the implantable antenna (port 1) and the external antenna (port 2) is applied in order to calculate the received power ($P_r$) through the relationship:

\[
|S_{21}| = \frac{P_r}{P_t}
\]  

As illustrated in the obtained numerical data [Fig. 5 (b)], the implanted antenna received power ($P_r$) recorded at a determined $T_x$-$R_x$ distance $D=40$ cm is -16 dBm and is implemented as the “reference power level” within the rectifier system analysis.

B. Rectifier System Design

The rectifier system has the capability to convert RF energy collected by the implanted antenna into direct current (DC) power for the integrated electronics (e.g., sensor) within the IMD. The rectifier consists of an input filter, a rectifying circuit, an output filter, and a load. The main performance metric of the rectifier analysis is the RF-to-DC conversion efficiency ($n$) defined as:

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

where $P_{DC}$ is the output DC power, $P_r$ is the implanted antenna received power, $V_{DC}$ is the output DC voltage, and $R_L$ is the load resistance. The rectifier is designed with the Advanced Design System (ADS) software. The aim is to optimize the efficiency of the energy harvesting system throughout a power range around the “reference power level” of $P_r=-16$ dBm.
The schematic of the designed rectifier is depicted in Fig. 6. The input filter consists of a chip capacitor (C1) and a chip inductor (L1,2) in a series-parallel manner (L-network configuration). The rectifying circuit topology is a two-stage voltage doubler with the Schottky diode as the non-linear rectifying component. Subsequently, a shunt-mounted chip capacitor C2 is applied as the output filter to effectively short any leaking RF energy and pass the useful DC power to the load. Optimum capacitor and load values are acquired through parametric study in order to find the best compromise between the output voltage and the conversion efficiency.

The simulated conversion efficiency and output DC voltage of the developed wireless power system is presented in Fig. 7. A conversion efficiency of 33.1% and an output DC voltage of 0.34 V is achieved at the received power Pr=-16 dBm for an optimum load Rl=9.5 kOhm.

Fig. 7. Simulated conversion efficiency and output DC voltage of the designed rectifier system.

V. CONCLUSIONS

This work presents an implantable rectenna design for wireless data telemetry and power transmission operation. Firstly, a novel simple PIFA with miniature dimensions is designed when embedded into the muscle tissue of a canonical arm model and its performance is evaluated. The proposed antenna exhibits dual-frequency resonance at 402 MHz (MedRadio) and 915 MHz (ISM) bands for data and power transmission, respectively. The simulated 10-dB impedance bandwidths cover both frequency bands. The maximum gain is -35.6 dB at 402 MHz and -23.5 dB at 915 MHz. Furthermore, an SAR analysis is conducted in order to assess the electromagnetic power absorbed by the muscle tissue at 402 MHz calculating the maximum allowable power incident on the antenna. Subsequently, a wireless power link is established between the developed PIFA (receiver) and an external dipole (transmitter) at ISM band in order to evaluate receiver’s sensitivity as function of distance. Finally, a rectifier system is designed. A conversion efficiency of 33.1% and an output DC voltage of 0.34 V is achieved at a received antenna power of Pr=-16 dBm for a load of Rl=9.5 kOhm.

In future work, further design analysis will be conducted with regard to antenna’s dual-frequency operation. Efficient techniques to enhance implantable antenna gain and, therefore, the received power will, also, be explored. Subsequently, the fabrication and the experimental validation of the proposed implantable rectenna will be carried out.

REFERENCES


[22] IEEE standard for safety levels with respect to human exposure to radiofrequency electromagnetic fields, 3 kHz to 300 GHz, IEEE Standard C95.1, 1999.

[23] IEEE standard for safety levels with respect to human exposure to radiofrequency electromagnetic fields, 3 kHz to 300 GHz, IEEE Standard C95.1, 2005.
