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Implantable rectenna system for biomedical wireless applications

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Abstract— In this paper, a complete RF to DC wireless power transmission implantable rectenna system is presented. For simplicity, an external half-wave dipole at Industrial, Scientific and Medical bands (ISM 902.8-928 MHz) is selected as an energy emitter from outside human body. An embedded circular dipole antenna receives the energy and then converts it to DC power by a rectifying circuit. The structure of the system is discussed in details. Finally, the rectifying efficiency and the global system's efficiency are examined for different external antenna to human body distances, different embedded depth and various levels of circuit's input power.

Keywords—Wireless power transmission system, Rectenna, Rectifying efficiency, Industrial, Scientific and Medical (ISM) bands

I. INTRODUCTION

Wireless energy transmission has gained significantly attention in biomedical domain during those recent years. An implantable medical devices (IMD) could have various type of uses like condition monitoring, drug delivery, information exchange, etc. [1] In comparison with near-field inductive charging, far-field radiative charging can be used with a higher implantable depth and is much more robust to the change of antenna locations, directions and surrounding environment.

A Radio Frequency (RF) medical energy transmission system normally consists of 2 parts: An antenna for capturing energy and a circuit for converting alternate current (AC) power to direct current (DC) power. There are many scientific publications on the antenna design [2][3]. Moreover, the rectenna system has also been studied by many research teams in the world [4]: H. W. Cheng et. al. has studied in [5] a rectenna system that operates at 400MHz with a circuit input power of 10dBm and rectifying efficiency of 76%; B. J. DeLong et. al. has proposed a rectenna structure that operates at 2.4GHz in free space, but the efficiency at -20dBm is only around 7% [6]; C. Liu et. al. has worked on an rectenna system which is implanted in body but only have an efficiency of 20% with an input

power of -20dBm and implantation depth of 4mm [7]. In conclusion, due to its high operating frequencies and low input power level, the design of a deep-implanted and efficient energy transmitting rectenna is still a challenge for researchers.

In this paper, a deep-implanted rectenna system with a low power input below -20dBm is examined. The power transmission structure is presented, important characteristics of the embedded antenna are detailed and a global co-simulation involving both the antenna part and the rectifying circuit is performed. The system is analyzed in a 3D realistic simulation environment: the entire rectenna system is embedded in a three-layer (skin, muscle et bone) cylindrical human arm model. Numerical results are also presented.

II. RECTIFYING SYSTEM DESIGN

This section presents the structure of the entire power rectifying system.

A. Power conversion system structure

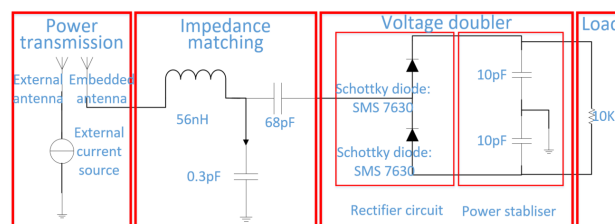


Fig. 1. Rectenna system structure

Figure 1 shows a detailed design of the rectifying system including all the components and their values. This system has four sections in total. The first one is the power transmission part proposed in [8], an external dipole transmits microwave power to a circular dual-band dipole antenna which is embedded in-body and resonates at 402MHz and 915MHz. The dipole antenna operates at the power transmission frequency band: 902.8-928MHz. The

second section is the impedance matching circuit, minimizing the mismatch loss and reducing the reflection. The third section is a standard voltage doubler using the SMS 7630 Schottky diode fabricated by the Skyworks company and two capacitors of 10pF as voltage stabilizer. The final section is a 10KΩ load that simulates the energy consuming part in real case.

B. Power Transmission model

Power transmission scenario is shown in figure 2. A three-layer cylindrical human arm model (radius are: Bone 0-25mm; Muscle 25-47.5mm; Skin 47.5-50mm) is used as simulation environment. In order to save the calculation time, the length of the arm model is set to the minimum value such as does not affect the results. An external half wavelength dipole radiates energy from outside the arm to the deep-implanted in muscle (more than 10mm from skin) circular dipole. S21 and other necessary power transmitting values are all presented in [8]. This system operates at 915MHz (ISM / Industrial, Scientific, and Medical band). As discussed in [8], the maximum power received by the embedded antenna (the circular dipole) when the external antenna is over 200mm away from body is lower than -20dBm since the maximum authorized radiated power by the external antenna at this frequency band is 30dBm [9]. Also in this case, the Special Absorption Rate (SAR) values are 0.28 W/kg and 0.19 W/kg for every 1g average and 10 g average of the human tissue, which satisfy the 2 IEEE standards about SAR limits [10] [11], and ensures the safety level of the embedded antenna (circular dipole).

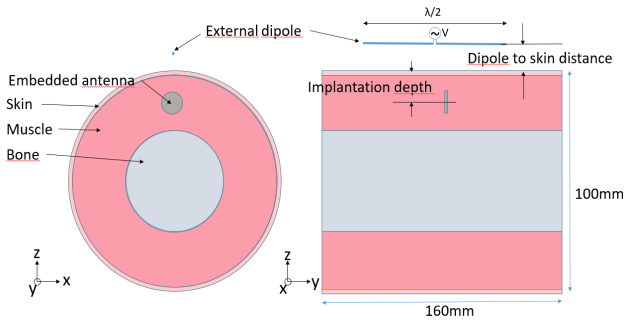


Fig. 2. Power transmission link design

C. Power Transmitting Antenna Design

The embedded antenna is a circular antenna. The detailed design is shown in figure 3.

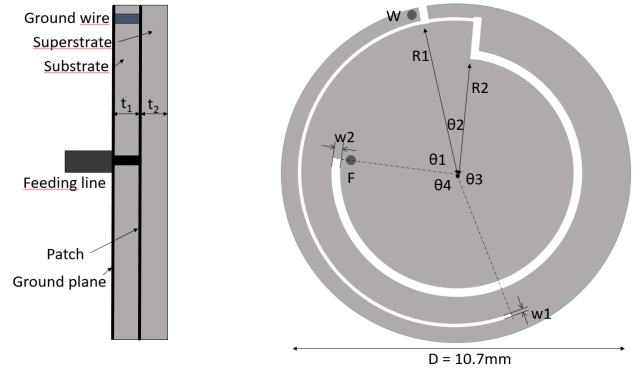


Fig. 3. Detailed design of the reception antenna

The antenna is made up of a radiating slot patch with a ground plane. The patch and the ground plane are grounded by a ground wire of radius = 0.15mm that is located at point W (see Fig.3). Two circular slots are cut away from the patch. The patch is printed on a layer of substrate made of Rogers RO 3210 ($\epsilon_r=10.2$, $\tan\delta=0.003$) which has a thickness of $t_1=0.64$ mm. The antenna is fed by a coaxial cable at point F and the patch is covered by a circular superstrate that of the same material and size as the substrate. All detailed parameters are presented in Table. I.

TABLE I. ANTENNA PARAMETERS

Parameter Name	Value (mm)	Parameter Name	Value (deg)
R1	4.9	θ_1	70
R2	3.76	θ_2	18
w1	0.15	θ_3	163
w2	0.32	θ_4	109
t1	0.64		
t2	0.64		
D	10.7		

The reflection coefficient of the antenna at 915MHz and for different implantation depths is shown in figure 4. As seen, it is practically unaffected by the related position inside the arm model.

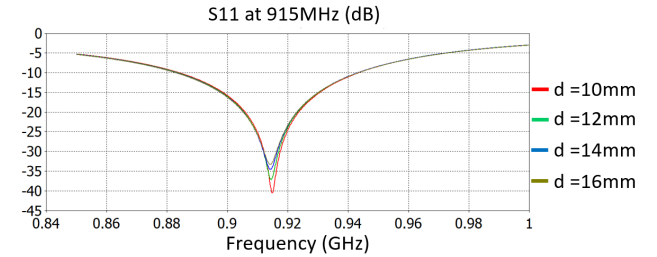


Fig. 4. S11 of the circular dipole antenna at 915MHz band

D. Rectifying Circuit Design

Once the power transmission model is established, the choice of the non-linear component for the rectifying circuit is of vital importance. The chosen diode must be adapted to high frequency and have low power consumption since the input is low. As mentioned in [12], the Schottky diode SMS 7630 fabricated by Skyworks company has good low-power performance and thus is chosen to be used with an input below -20dBm.

Furthermore, an impedance matching circuit is optimized between the embedded antenna (circular dipole) and the rest of circuit in order to reduce the reflection loss and the power consumption of the components.

E. Numerical Results

The global simulation is performed by CST [13] that supports at the same time electromagnetic modeling and circuit simulations. All the circuits are off-the-shelf components and are based on spice models. The rectifying efficiency is calculated by the ratio between the power consumed by the load and the power received by the embedded antenna (circular dipole). Global system efficiency is defined as the ratio between power consumed by the load and the power emitted by the external dipole. Table II shows the relationship between the global system efficiency, rectifying efficiency, the distance between the two antennas and the embedded depth of the circular dipole.

TABLE II. RECTIFYING EFFICIENCY OF THE CIRCUIT

Embedded depth (mm)	Dipole to skin distance (mm)	Power consumed by load (dBm)	Rectifying efficiency (%)	Global system efficiency (%)
10	175	-26.71	24.00	0.213
10	250	-30.31	17.74	0.093
10	550	-42.04	6.37	0.006
16	175	-30.35	18.47	0.092
16	250	-35.01	11.91	0.032
16	550	-48.01	2.76	0.001

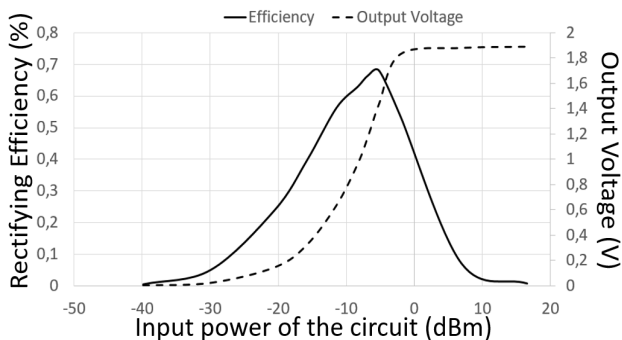


Fig.5. Efficiency and output voltage results for the rectifying circuit

From the results shown in Table II, when the dipole emits 30dBm power, the rectifying efficiency of the circuit can reach 24% when the received power by the embedded antenna (circular dipole) is -20dBm and load is 10KΩ. However, the efficiency is also relatively low when the in-body antenna is implanted deeper in the body or the external antenna is far from the body with all the loss at each component. Figure 5 shows the circuit's rectifying efficiency as a function of the circuit's input power. With the existence of the non-linear component, there is a phase

delay between the current and the voltage. Thus, input power is calculated by:

$$P_{active} = U_{rms} * I_{rms} * \cos \varphi_c \quad (1)$$

where U_{rms} and I_{rms} are the root mean square (rms) values of the voltage and the current right after the receiver antenna (circular dipole) respectively and φ_c is their phase difference. According to Figure 3, the efficiency of the rectifying circuit can reach up to 67.9% when the input power of the circuit is -5.1dBm.

CONCLUSION

A wireless RF to DC implantable power rectifying system for biomedical applications is presented in this paper. System operates at 915 MHz ISM band. With the limitation of radiated power (30dBm), a series of numerical experiments is carried out in order to calculate efficiency for various implantation depths of the embedded antenna (circular dipole) and various distances between the external dipole and the human arm. For embedded depth of 10mm and skin to external dipole distance equal to 175mm, the input power of the circuit is estimated to -20dBm and a rectifying efficiency of 24% is obtained for a 10KΩ load. Moreover, for the above scenario, the DC power rectified by this system is capable of feeding simultaneously two sensors that mentioned in [14] which requires only 1.1μW each. It is noted that the rectifying efficiency can theoretically reach 67.9% for the presented circuit as shown in Figure 5.

In future work, the rectifier circuit will be fabricated and experimentally validated. Some measurement results will be presented at the conference.

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