Design of a Compact Implantable Rectenna for Wireless Pacing Applications

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***Abstract*—In this work, a novel design of an implantable dipole rectenna with good efficiency is presented for wireless pacing applications. The proposed rectenna consisted of an elliptical-shaped printed dipole antenna, which used additional C-shaped structures to increase the inductance and achieve a resonance of 1.2 GHz. A separately designed full wave rectifier was tested and then integrated with the dipole antenna using matching circuitry. The manufactured prototype rectenna was tested in an ovine model *in vivo*, while the radio frequency energy was transmitted externally using a horn antenna held at a distance of 25 cm above the thorax. We have demonstrated that a small implantable rectenna could capture and harvest enough safe recommended RF energy to power a microprocessor at 3 V for wireless pacing applications. This novel method of wireless powering has the potential to eliminate the leads or replace the batteries required for the conventional pacemakers.**

I. Introduction

Lately, wireless power transfer using radio frequency (RF) for implantable medical devices (IMDs) has gained a lot of interest and attention of the researchers, mainly due to the bigger size of the batteries and also due to the complications caused by the leads in devices such as pacemakers. The use of RF as an energy source can eliminate the batteries and leads and can power the pacemaker wirelessly. Miniaturized antenna, efficient rectifier and matching circuitry are the important elements for such a system, which have to be designed for a human body with variations in the dielectric properties. Achieving compactness and efficiency simultaneously presents an interesting design challenge, and the current state-of-the-art has much room for improvement.

Rectennas for applications in air have received good attention but there is limited work reported for implantable applications. An implantable rectenna consisting of a planar inverted-F antenna having an efficiency of 45% has been reported for wireless power transfer in [1]. In [2], an implantable rectenna for wireless battery charging has been proposed. Asif *et al.* has proposed a metamaterial based rectenna for wireless pacemaker applications [3].

In this paper, we propose a low profile and compact implantable printed dipole rectenna for wireless pacing applications. More specifically, a novel elliptical-shaped dipole antenna with C-shaped structures has been introduced, which increased the inductance of the antenna and achieved a resonance of 1.2 GHz. Following the simulations and optimizations in HFSS, a manufactured prototype antenna was tested *in vitro*. A separately designed rectifier circuit was manufactured and tested for efficiency and then a matching circuit was used for integration with the proposed antenna. The complete manufactured rectenna system was then insulated and tested in an ovine model in an *in vivo* experiment. The harvested output voltage was supplied to a microprocessor to mimic a real pacemaker and results were measured. The *in vivo* experiment results demonstrated the wireless power transfer at safe power density levels.

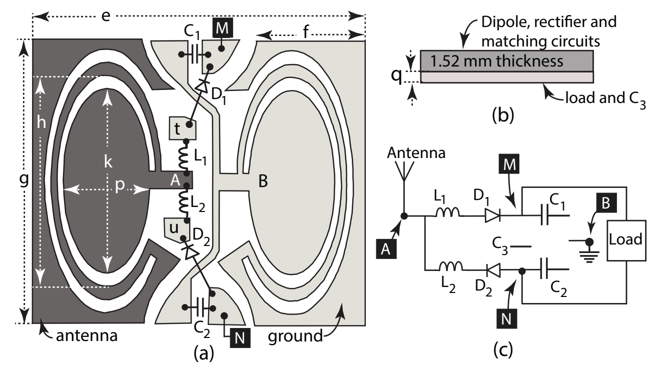

Fig. 1. (a) Geometry of the proposed implantable dipole rectenna(V_{out}) is measured at M and N). Details of the dimensions are (in mm): $e = 12$, $g = 10$, $f = 3.6$, $h = 7.4$, $k = 6.4$, $p = 3.0$, $q = 1.52$. (b) Side view of the proposed design. (c) Schematic diagram of the full wave rectifier ($D_1 = D_2 =$ HSMS2850 Schottky diode, $C_1 = C_2 = 120$ pF, $L_1 = L_2 = 12$ nH, $C_3 = 4$ μF).

II. Implantable Rectenna Design

Fig. 1 (a) and (b) shows the layout of the proposed dipole antenna with detailed dimensions. Two symmetrical elliptical-shaped elements with C-shaped designs are used, which increased the electrical path and introduced additional inductance to achieve a resonance of 1.2 GHz. To design an implantable antenna for a complex human body environment, the dielectric properties of the muscle were used from Gabriel's database [4] in HFSS simulations. At the frequency of 1.2 GHz, the electrical properties used in the simulations were, permittivity $(\varepsilon_r) = 53.4$, conductivity $(\sigma) = 1.0554$ S/m, and (mass density) $\rho = 1040\,\text{kg/m}^3$. The antenna was designed on Rogers TMM10i substrate with a permittivity of (ε_r) 9.8,

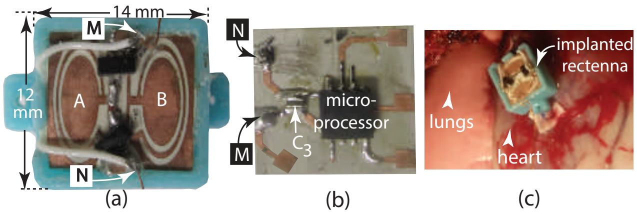

Fig. 2. Pictures of (a) complete prototype showing 3D enclosure and output voltage measuring points at M and N, (b) microprocessor (PIC12LF1840) and charging capacitor C_3, and (c) implanted rectenna secured on the left ventricle of an ovine model.

and loss tangent ($\tan\delta$) of 0.002. This substrate with higher dielectric value was chosen to achieve miniaturization.

The rectification was achieved using the circuit shown in Fig. 1(b), which is a modified version of the circuit proposed in [3]. This circuit combines two half wave rectifiers in a novel way to achieve full wave rectification, which was optimized in Advanced Design System. A 12 nH inductor was used as a filter and a matching element between the rectifier circuit and the antenna, which was selected in the experimental characterization at a range of input power levels at 1.2 GHz. To minimize the errors, the rectifier and matching circuit components were integrated into the antenna design in HFSS using lumped RLC boundaries. Some traces of one arm of the dipole were extended to accommodate these components and the design was finally optimized. Pictures of the complete prototype rectenna are shown in Figs. 2 (a) and (b).

III. Design Results and Measurement

The rectifier circuit was separately manufactured and tested for efficiency measurements. A microprocessor, with a pacing signal routine, was used as a load, as shown in the inset of Fig. 3 (a). Efficiency and output voltage of the rectifier circuit at various input power levels is measured at 1.2 GHz and shown in Fig. 3. Also, the final insulated implanted antenna (only) was tested in a porcine tissue using a balun. All the measurements were performed in an anechoic chamber using a vector network analyzer (E5071C) and shown in Figs. 3 (b) and (c), showing the matching performance and the radiation patterns. The small deflections in the results are attributed to the fabrication errors and also due to the variations of the dielectric properties used in the simulations. The simulated and measured realized gain was 0.64 dBi and -1.3 dBi, respectively. This was due to the small size of the antenna and also due to the losses in the body.

To test the performance of the prototype rectenna for wireless pacing application, an *in vivo* experiment was performed. The insulated rectenna was implanted and secured on the left ventricle of the ovine model, as shown Fig. 2 (c). A horn (HRN 0118) antenna (held 25 cm above the ovine model) was used to transmit the RF energy, while the harvested output voltage up to 3 volts (max) was measured using the instrumentation wires connected to the output of the implanted rectenna. In this experiment, the transmit frequency was 1.2 GHz, horn antenna

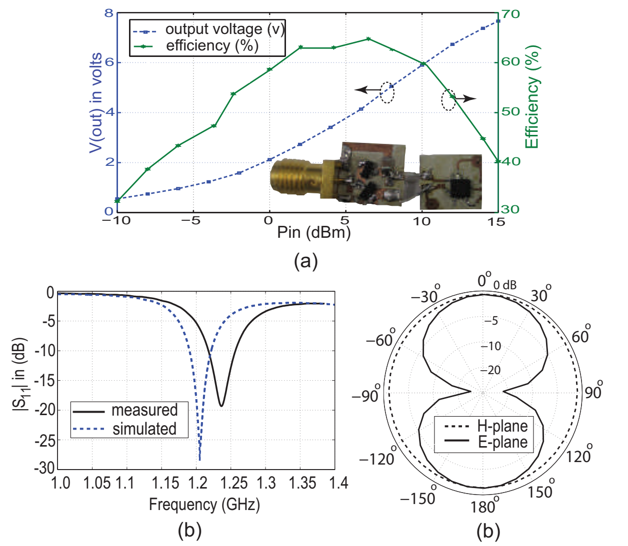

Fig. 3. (a) Measured performance of the rectenna at various input levels and fixed frequency of 1.2 GHz. (b) Matching performance of the dipole antenna measured in a porcine tissue. (c) Measured radiation patterns in E- and H-planes.

gain was 6.5 dBi, while 10 dBm of power was transmitted from the horn at a distance of 25 cm from the thorax. Using the equations given in [5], the computed power density was computed to be *8.2* $\mu W/cm^2$.

IV. Conclusion

This work has proposed a novel elliptical-shaped dipole rectenna for wireless pacing applications. The printed dipole antenna was designed at 1.2 GHz and its simulated results agreed well with the measured results. The measured efficiency of the full wave rectifier showed an efficiency of 65% (approx). The completed manufactured prototype rectenna coupled with a microprocessor was tested *in vivo* in an ovine model, while it was exposed to a continuous source of radio frequency at 1.2 GHz. The implanted prototype rectenna harvested a maximum of 3 volts (DC) at the heart of the ovine model, which generated a good pacing signal at safe recommended RF energy. The application of this wireless powering technique is not limited to pacemakers only and can be used to power other implantable medical devices.

References

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