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A Dual-Band Miniaturized Circular Antenna for Deep in Body Biomedical Wireless Applications

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Abstract— In this paper, a novel miniaturized implantable circular PIFA antenna is presented. It supports both wireless information communication and wireless energy transmission at the Medical Device Radiocommunication band (MedRadio 402-405MHz) and the Industrial, Scientific and Medical bands (ISM 902.8-928 MHz). Antenna is circular to avoid sharp edges while miniaturization is achieved by adding two circular slots to the patch. Main scenario includes embedding into the muscle layer of a cylindrical three-layer model of a human arm for which several parameters are analyzed (resonance, radiation pattern and Special Absorption rate (SAR)). Power transmission efficiency and interaction distance limits to ensure connection are also evaluated.

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

I. INTRODUCTION

Recently, with the population's ageing acceleration, health care has gained more and more focus in the society. Implantable medical devices (IMD) have attracted much attention and have been popularly studied thanks to their huge potential to be light, small and utilized in various pragmatic applications. However, the question of designing an efficient system that supports both power and data transmission for IMDs remains crucial for researchers.

Radiation, as one of the mainly used methods for wireless charging, is more robust to location change and has a smaller size of the reception device than the induction and the midfield transmission method. For biomedical uses, several frequency bands are authorized: Medical Device Radiocommunication (MedRadio) Service band (401-406 MHz), and the Industrial, Scientific, and Medical (ISM) bands (433.1-434.8 MHz, 868-868.6 MHz, 902.8-928MHz and 2.4-2.5 GHz) [1-3]. Since the team of L.C. Chirwa [4] has published a study about the performances of an implanted source in human intestine under different frequencies in 2003, many research teams have carried out successively their own designs or analyses [5-7]. Some designs of antenna possess multiple resonant frequencies but have bigger sizes [8]; others are smaller in size but resonate at higher frequency which will certainly lead to higher losses in deeper implantation [9]; moreover, many researches are

performed in the skin layer, which adds difficulties to medical surgery and is less realistic [10-11].

In order to improve in the previous features, a miniaturized circular PIFA is proposed in this paper. Firstly, it has two different resonant frequencies at 403MHz and 915MHz which correspond to power and data transmission separately. Furthermore, the antenna is designed to be deep implanted into the muscle tissue and relatively not sensitive to the change of implantation depth and thus robust to changes of environment.

In section II, the detailed antenna structure is firstly presented with specific parameters. Some numerical results (such as: reflection coefficient, impedance, radiation pattern, special absorption rate (SAR)) are subsequently analyzed in section III. Then in section IV, the in-body/off-body interaction with an external dipole is analyzed.

II. ANTENNA DESIGN

A precise parametric model of the designed PIFA antenna is shown in fig.1. This antenna is made up of a ground plane, a patch, a substrate between them, a superstrate over the patch and a coaxial feeding. The substrate and superstrate are made from the same material: Rogers RO 3210 ($\epsilon_r=10.2$, $\tan\delta=0.003$). Both the patch and the ground plane are circular, connected with a ground wire (located at point W, diameter 0.3mm) which helps to decrease the antenna size. Two circular slots are also cut from the patch in order to have two operating frequencies at 402 MHz and 915 MHz. The coaxial cable (located at point F) is standardized to 50 Ω in impedance. All the parameters marked in Fig.1. are presented in Table I.

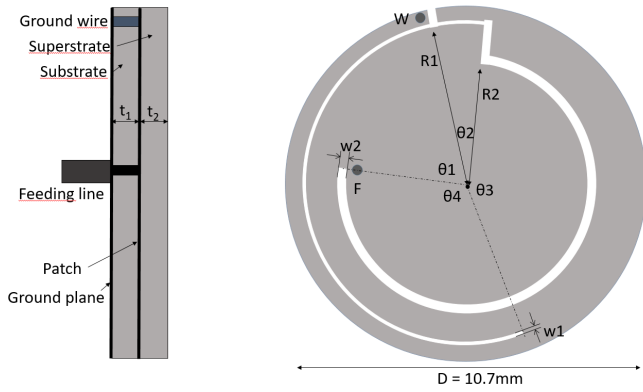


Fig. 1. Geometry of the designed circular PIFA antenna

TABLE I. ANTENNA PARAMETERS

Parameter Name	Value (mm)	Parameter Name	Value (deg)
R1	4.9	$\theta 1$	70
R2	3.76	$\theta 2$	18
w1	0.15	$\theta 3$	163
w2	0.32	$\theta 4$	109
t1	0.625		
t2	0.57		
D	10.7		

The PIFA has a circular shape to avoid sharp edges. Table II presents the comparison results between the circular PIFAs that are designed in previous publications and the one designed in this paper, which is smaller, embedded deeper and resonating at lower frequencies to reduce losses. The antenna is also analyzed in a more detailed model of the tissue as compared with previous works.

TABLE II. COMPARISON WITH PREVIOUS DESIGNS

Reference	Antenna Radius (mm)	Antenna Thickness (mm)	Resonant Frequency (GHz)	Examined Depth (mm)	Model used
[7]	8,5	1,535	2,4	2-3 mm	Muscle + Phantom
[9]	6	1,8	0,4;0,9	10 mm	Skin cube
[11]	7,5	1,91	0,4;2,4	10 mm	Skin cube
[12]	2,5	0,75	2,4	25 mm	Skin cube
This paper	5,35	1,095	0,4;0,9	10-16 mm	Three-layer model

The entire antenna is embedded in the human tissue model shown in Fig.2. As in [13], a three-layer cylindrical human arm model is used in this paper. The radius of each layer is: bone (25mm), muscle (25mm - 47.5mm) and skin (47.5mm - 50mm). The implantation depth is calculated as the distance between the center of the radiating patch and the external surface of the skin layer. The length of the “arm” is set to the minimum value to ensure proper consideration of a “realistic” case and avoid heavy calculations.

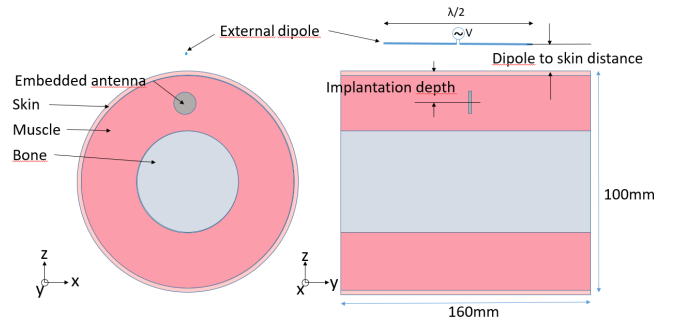


Fig. 2. Geometry of the three-layer arm model

TABLE III. DIELECTRIC CONSTANTS OF HUMAN TISSUE

Frequency		Bone	Muscle	Skin
403MHz	ϵ_r	13.22	57.15	46.81
	σ (S/m)	0.09	0.79	0.69
915MHz	ϵ_r	12.45	54.98	41.35
	σ (S/m)	0.15	0.93	0.85

III. ANTENNA CHARACTERISTICS

A. Reflection coefficients

Reflection coefficient is a key factor to characterize the resonant frequency of an antenna. Figure 3(a) and Figure 3(b) characterize the reflection coefficient (S_{11}) of the proposed antenna when implanted into the three-layer arm model at the depth from 10mm to 16mm at 403MHz and 915MHz. The human tissue dielectric constants (relative permittivity ϵ_r and electrical conductivity σ) at corresponding frequencies are shown in Table III.

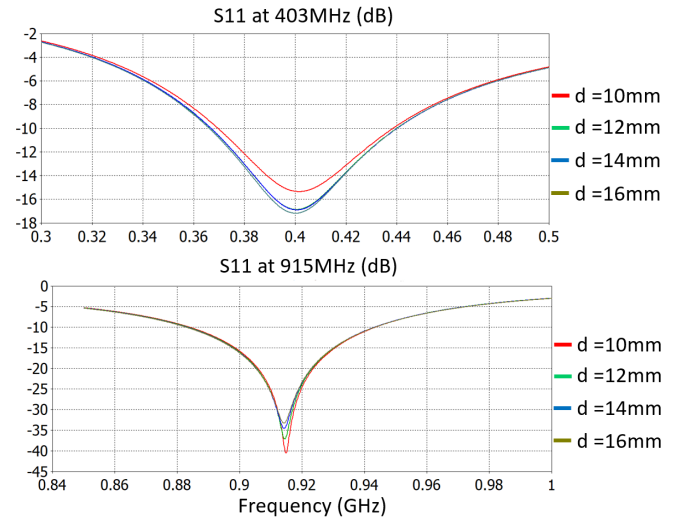


Fig. 3. Reflection coefficient of the antenna ([a] at 400MHz and [b] at 915MHz)

As seen in the S_{11} figure, the designed PIFA is not sensitive to the implantation depth. The -10dB bandwidth at 403MHz and 915MHz are 80MHz and 60MHz, which covers the entire corresponding authorized band.

B. Radiation pattern & efficiency

The radiation pattern is calculated in the center of the frequency band: 403MHz and 915MHz. The 2-D and 3-D radiation patterns are presented in Figure 4.

The antenna is implanted in 10mm depth here. At MedRadio band (403MHz), the maximum gain in far field is around -33.5dB and towards Z axis. The value is low due to antenna's tiny size and deep implantation of 10mm in muscle. At ISM band (915MHz), the gain is -33.65dB. It is worth pointing out that the antenna has better maximum gain at deeper location: at 16mm depth, its gain increases to -31.6dB at 403MHz and -33.1dB at 915MHz since the radiation pattern has a narrower main lobe.

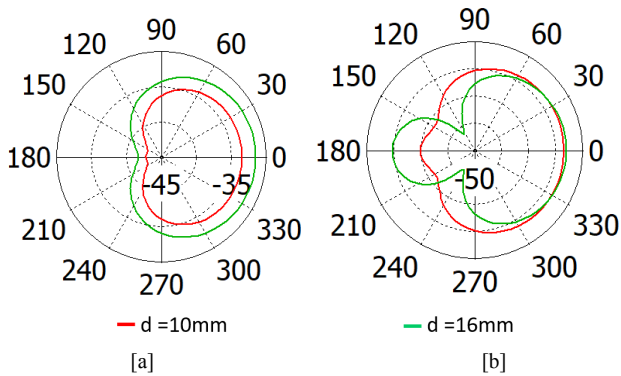


Fig.4. 2D radiation pattern of the antenna at 10 and 16mm implantation depth ([a] at 400MHz and [b] at 915MHz)

C. SAR

Special Absorption Rate (SAR) is a vital parameter that indicates the safety level of an embedded antenna, it represents the average amount of electromagnetic power that can be absorbed by human body. The two IEEE standards about SAR limits [13] [14] point out that the value of SAR of every 1g or 10g of human tissue cannot be higher than 1.6W/kg and 2W/kg respectively. In Table IV, it is given the maximum input power for the PIFA antenna that satisfies each SAR limits at 403MHz and 915MHz for implantation depths of 10 or 16mm.

TABLE IV. MAXIMUM INPUT POWER FOR PIFA ANTENNA

Max input power (mW)	1g-average		10g-average	
	10mm	16mm	10mm	16mm
403MHz	15.38	14.99	72.22	71.17
915MHz	14.08	14.01	86.33	91.19

IV. IN-BODY/OFF-BODY INTERACTION

The PIFA antenna is designed to receive energy and emit signal for information exchange at the same time, so it is necessary to evaluate its capacity and efficiency with a more realistic situation in order to examine its performances and also to choose the best energy transmitting frequency band.

In this section, a half-wavelength (in air) dipole is used as an external device for both energy and information transfer at the operating frequencies as shown in Figure 2.

The external device is located face-to-face with the main lobe of the PIFA at its operating frequency.

A. As a reception device from transmission dipole

The value of power received is a significant parameter to evaluate the performance of the implantable parameter as a reception device. In Table V, the power received by the PIFA from the dipole as well as the implantation depth and the dipole to skin distance in each case is provided. It should be noted that for each frequency band, there exist different radiated power limits: -16dBm (25μW) at MedRadio band (401-406MHz) [16] and 30dBm (1W) at ISM band (902-928MHz) [17].

TABLE V. RESULTS AS RECEPTION DEVICE

PIFA Dept h (mm)	External Dipole- Arm Surface Distance (mm)	Max Authorized Emission Power (dBm)	Max Power Received (dBm)	SAR		
				1g- Avera ge (W/kg)	10g- Avera ge (W/kg)	
403 MHz	10	105	-16	-54.5	1*10 ⁻⁴	3*10 ⁻⁵
	10	375	-16	-66.2	2*10 ⁻⁶	1*10 ⁻⁶
	16	375	-16	-64.5	2*10 ⁻⁶	1*10 ⁻⁶
915 MHz	10	105	30	-18.5	0.32	0.22
	10	375	30	-28.76	0.024	0.017
	16	375	30	-31.35	0.025	0.018

With the maximum authorized input power, antenna is able to receive 4000 times more energy (nearly 1000 times when embedded deeper) in the ISM band than in the MedRadio band. Therefore, in our case, the ISM band (902-928MHz) is chosen as the energy transmission band. The SAR value in both cases are much lower than the limits.

B. As an emission device to reception dipole

It is also necessary to analyze the power redelivered to the external dipole to ensure the possibility to receive signal from the PIFA when it is embedded. In [18], a RF-DC conversion circuit is proposed with an efficiency of 33.1%. If 5% of total converted DC power is assumed to be used for emitting signal, for each distance between the energy delivery dipole and the skin surface, there is always a corresponding maximum distance between the reception dipole and the skin surface in order to ensure the connection (energy received by the reception dipole \geq -90dBm [19] which is the minimum power that can be received by mobile phones without information loss) for every different implantation depth. The results are presented in TABLE VI. For example, if a dipole at 915MHz is fed with 30dBm and is 375mm from the tissue surface while the implanted

antenna is at 16mm depth, then under the above restrictions an external dipole (at MedRadio band) should be placed at a maximum distance of 155mm.

TABLE VI. RESULTS AS EMISSION DEVICE

Implantation depth (mm)	Distance between energy delivery dipole and arm surface at 915MHz (mm)	Maximum distance between reception dipole and arm surface at 400MHz (mm)
10	105	450
	375	185
	700	105
16	105	425
	375	155
	625	105

CONCLUSION

In this paper, a miniaturized circular PIFA antenna is designed to support both energy and information transmission. The antenna is embedded into a three-layer cylindrical model of arm and its performance is evaluated. It has dual resonant frequency which covers MedRadio (401-406MHz) and ISM bands (902-928MHz), with gain of -31.6dB at 403MHz and -33.1dB at 915MHz. The in-body/off-body link is also analyzed. It assesses firstly the amount of power that could be received from an external dipole at maximum authorized input power and leads to the choice of the energy transmission band. Then the amount of power that could be redelivered to the external device is also calculated, and the distance limits to ensure reliable connection are shown in the paper.

For the future work, the antenna will be fabricated and tested in a realistic environment and measurement results will be presented at the conference.

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