Design and Optimization of Miniaturized Dual-band Implantable Antenna for MICS and ISM Bands

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Abstract— This work discusses the design method towards the implementation of a compact, stacked, implantable antenna for biotelemetry applications. The proposed antenna consists of three stacked layers, printed on high permittivity grounded substrate. The bottom layer of the antenna above the ground plane, contains a meandered structure with a symmetrically placed T-shaped slot. The middle layer consists of two U-shaped radiators and an M-shaped metallic segment is further added on the top layer to further enhance the radiation efficiency of the antenna. These three stacked layers, form a symmetrical closed loop structure resonating on its fundamental resonant mode, at 403 MHz, for the Medical Implant Communication Service (MICS) band. A shifted higher order mode of the same closed loop structure, along with the negative currents on ground plane enables wide band operation, at 2.45 GHz, for the industrial, scientific, and medical (ISM) band. To resolve the constraints associated with implanting an antenna in human body that usually results in detuning and impedance mismatch, the antennas most important radiating sections were thoroughly investigated. A fully parametrized solution is proposed that makes the antenna a good candidate for a device, implanted at several different areas of the human body with potentially different electrical properties with consequently different detuning effect. For further investigation, the particle swarm algorithm was implemented to optimize the antennas performance while operating inside a compact, $23 \times 23 \times 5\,\mathrm{mm}^3$ block of human skin, equivalent phantom. The simulated performance of the proposed prototype antenna, indicates that it can be used for either in-vitro or in-vivo operations.

1. INTRODUCTION

Biotelemetry enables full duplex wireless communication between implantable antennas with on-body receiver antennas. Designing a wearable on-body antenna is comparatively easier because of its placement in an environment where body is normally in one direction and air in the other. This, allows the designers to control the radiation pattern of the antenna towards the human body by introducing a reflector or a cavity. On the other hand, designing an implantable antenna is a more challenging task due to a number of factors. First and far most challenge is the detuning factor and impedance mismatching that occurs when the antenna is placed inside human body. This is due to high water content and high conductive human tissues. Moreover detuning and mismatching are normally unpredictable and vary from tissue to tissue because different tissues have different electrical properties. The second major problem that arises while designing implantable antenna is its size. Since, MICS band at 403 MHz is assigned for implantable devices for on-body devices communication, the antenna effective aperture area at this frequency is rather large. However, the requirement is that the antenna integrated with the implantable device, along with power unit, should be as small as possible since the device is expected to be implanted inside the human body. A significant amount of work has already been done where different antenna design topologies have been proposed by researchers. To test the performance of an antenna in in-vivo environment, simulations are generally carried out inside simple layered phantoms [1, 2] or in realistic body phantoms [3, 4]. Electrical properties of these phantoms are either modeled using Cole-Cole model [2, 5] or multi-pole Debye model [6]. Some researchers [3, 5, 7] also measured the electrical properties of human tissues (skin, fat, muscle) using dielectric probe kit or impedance analyzer and then used these properties in simulations to test the performance of their proposed solution. To achieve compactness, researchers have tried different methods and several types of antennas, including spiral [2, 8, 9], meandered patch [4, 5, 7–9], folded square IFA [10], 2D and 3D spherical [8, 11] and multilayered [12] configurations. All these methods reduce the antenna size by increasing the length of the current flow path on the same plane (meandered and spiral) or in all three dimensions (3D spiral, 3D ring and stacked). In addition, a shortening pin between ground and patch may also effectively reduce the required physical dimensions of an implantable antenna [13] and has been widely used. It has been observed that antennas designed for a specific tissue are not expected to perform equally well in any substantially different tissue surrounding. In this work, we propose a solution which not only covers MICS and ISM bands for implantable applications, but additionally it can be customized to a random tissue environment. The behavior of the antenna is thoroughly studied and a range of geometric parameters are presented for best antenna performance.

2. PROPOSED LAYERED IMPLANTABLE ANTENNA

Figure 1 shows the geometry of the proposed layered implantable antenna. The overall dimensions of the antenna are $15 \times 18 \times 1.97\,\mathrm{mm}^3$, and the antenna consists of three copper coated substrate layers. In this study, Roger's RO3210 as substrate was used since its electrical properties resemble with those of biocompatible substrate ceramic alumina ($\epsilon_r = 9.4$ and $\tan\delta = 0.006$). RO3210 was preferred because it can be easily available and is compatible with conventional fabrication techniques making in-house prototype fabrication possible. The proposed antenna consists of the ground layer and three stacked patch layers as shown in Figure 1. The bottom layer of the antenna, fed at the upper right corner, comprises a patch with identical slits having length and width pl_1, pl_3, pw_1 and pw_3 respectively. These slots along with the T shaped slot in the middle of the patch introduce a meandered structure used for size reduction. To further decrease the size of the antenna, a short pin is introduced on the bottom layer as shown in Figure 1. The middle layer of the antenna comprises of two U-shaped coupling resonators with a capacitive coupling gap. The right U-shaped resonator is fed at the upper right corner with extended coaxial feed whereas the left U-shaped resonator is fed by via1 connecting the bottom layer and the middle layer at the upper left corner, exactly opposite to the feed point. To further increase the resonance capacity of the antenna, an M-shaped, third layer is introduced on the top layer of the substrate. Via2 and via3 connect the middle with the top layer at lower right and lower left corners respectively. The M-shaped top layer consists of a radiating patch with two identical slits, having dimensions rl_1, rl_2, rw_1 and rw_2 respectively.

The effective current path in this antenna comprises of a meandered patch on the bottom layer, the left U-shaped patch of the middle layer, the M-shaped patch of the top layer and the right U-shaped patch of the middle layer. This current path makes an approximately $\lambda/4$ closed loop structure, resonating at the fundamental resonant mode at 403 MHz covering the MICS band. Furthermore, a higher order harmonic of the same resonant closed loop structure, was adjusted to operate at 2.45 GHz ISM band, resulting in a dual band operation using the same structure. To further enhance the radiation efficiency of the proposed antenna at ISM band, the effective length of the meandered patch on the bottom layer, that depends upon its coupling with the ground plane was further optimized. The next step was to study the behavior of the antenna in different tissue surroundings, which is equivalent to implanting the antenna at different body parts, and to identify various antenna tuning parameters simultaneously, for MICS and ISM bands. This study resulted in a fully parametrized antenna model with a minimum and maximum defined range of geometrical parameters that may adjust the effective wavelength of the $\lambda/4$ closed loop resonator, and the

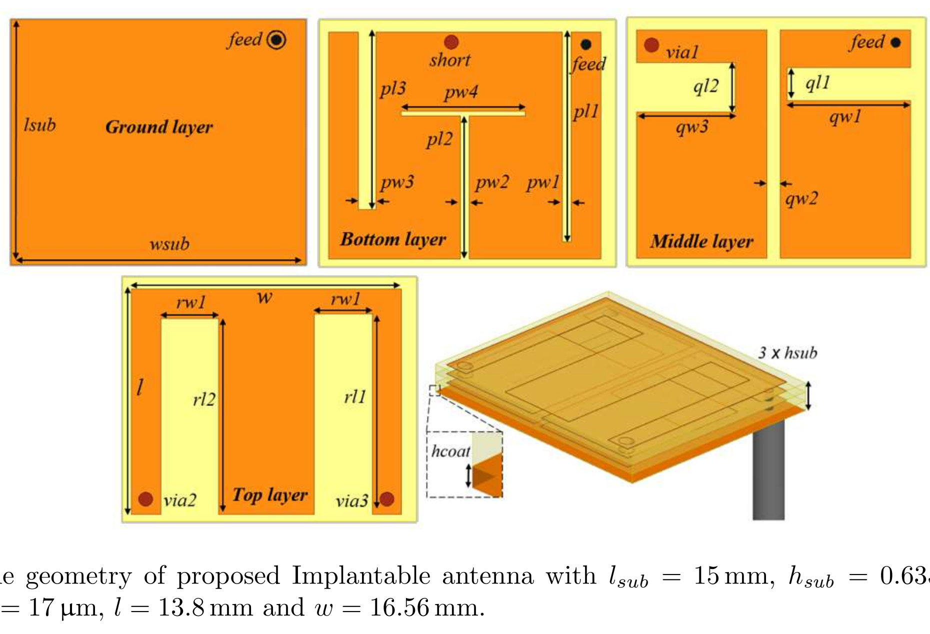

Figure 1: The geometry of proposed Implantable antenna with $l_{sub} = 15\,\mathrm{mm}$, $h_{sub} = 0.635\,\mathrm{mm}$, $w_{sub} = 18\,\mathrm{mm}$, $h_{coat} = 17\,\mu\mathrm{m}$, $l = 13.8\,\mathrm{mm}$ and $w = 16.56\,\mathrm{mm}$.

meandered patch of the bottom layer. One case is presented in this paper where the antenna is placed in $23 \times 23 \times 5\,\mathrm{mm}^3$ block of human skin phantom. Note that measured electrical properties of skin tissue reported in [5], were used for this test. As predicted, significant detuning was observed both at MICS and ISM bands as shown in Figure 2.

Results shown in Figure 2(a), indicate that, when the antenna was placed in skin phantom, a resonant frequency shift of around 50 MHz towards lower frequencies, was observed for the MICS band. Significant degradation in impedance matching can also be observed in Figure 2(a). The frequency downshift was raised up to 130 MHz at the ISM band as can be seen in Figure 2(b). In order to tune the antenna dimensions on both targeted frequency bands simultaneously, particle swarm algorithm in combination with FDTD simulation was used. The resulting set of optimized values of the antenna parameters are listed in the fourth column of Table 1, where the third column shows the seed values for the particle swarm optimizer. The watch function to optimize the antenna in given tissue environment is set to be:

$$f = \max\left(|S_{11}\,(\mathrm{dB})_{403\,\mathrm{MHz}}|, |S_{11}\,(\mathrm{dB})_{2.45\,\mathrm{GHz}}|\right) \tag{1}$$

It took 20 iterations for the particle swarm algorithm to converge and tune both minima at the desired frequency bands. Impedance bandwidth of 9 MHz (from 398 MHz to 407 MHz) covering the MICS band and 72 MHz (from 2438 MHz to 2510 MHz) covering the ISM band, were achieved as a result of optimization. Note that return loss minima can be further tuned at the desired frequencies

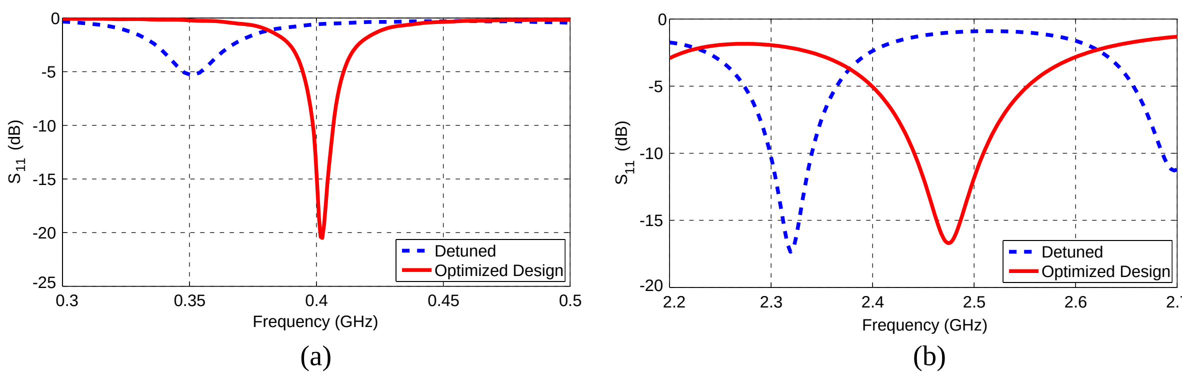

Figure 2: Detuning of antenna when placed in $23 \times 23 \times 5\,\mathrm{mm}^3$ human skin phantom [5] and optimization using particle swarm algorithm at (a) MICS band and (b) ISM band.

Table 1: Antenna optimization parameters.

Symbol	**minimum value (mm)**	**maximum value (mm)**	**seed value (mm)**	**optimized parameter in skin phantom**
pl_1	08.60	13.60	10.60	12.75
pl_2	01.00	13.00	01.00	08.70
pl_3	08.60	13.60	10.60	10.80
pw_1	00.50	02.00	01.00	00.54
pw_2	00.50	00.70	01.00	00.50
pw_3	00.50	02.00	01.00	01.17
pw_4	04.00	08.00	06.00	07.56
ql_1	03.00	09.00	06.00	03.00
ql_2	03.00	09.00	06.00	06.00
qw_1	05.00	07.50	06.00	07.46
qw_2	00.20	00.90	00.30	00.81
qw_3	05.00	07.50	06.00	05.90
rl_1	11.00	13.00	12.00	12.30
rl_2	11.00	13.00	12.00	12.00
rw_1	03.00	06.00	04.50	03.50
rw_2	03.00	06.00	04.50	03.50

at a cost of increased iterations of the optimization algorithm. Columns 2 and 3 of Table 1 list the range of controlling geometric parameters. The particle swarm algorithm requires both a rang as well as a seed value of a geometrical parameter optimization to be initiated. Values listed in Table 1 can be used for this purpose. The expected result should be an optimized set of values for which the customized antenna operates simultaneously at both MICS and ISM bands and this should be feasible for any given random tissue surrounding environment.

3. CONCLUSION

This paper describes a miniaturized implantable antenna with a meandered and stacked structure. By varying the length and width of each parameter listed in Table 1, the antenna is excited at two resonant frequencies, at MICS and ISM bands. It was demonstrated that the proposed antenna can be tuned using the particle swarm algorithm, to operate adequately when placed inside several different human tissue models. The next phase of this work includes the antenna fabrication and in-vitro or in-vivo antenna testing, and additionally the integration of the antenna to the suitable microchip to build a complete implantable system.

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