A Digitally Assisted Repeater Antenna for Implant Communications

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***Abstract*—The wireless link between an implant and an off-body gateway may be difficult to secure due to the fact that electromagnetic waves quickly attenuate as they propagate through human tissues. Depending on the depth of the implant within the body, the signal strength may be quite weak by the time the waves reach the skin. In order to address this problem, a digitally assisted repeater antenna has been designed to be located outside of the patient's body, which can detect the signals radiated by the implant and relay those signals to the off-body gateway. The radiation pattern of the antenna is switched between two modes depending on the link it is forming: in-body link or off-body link. With an overall size of 30 x 30 x 3.15 mm, the antenna operates in the 2.4 GHz ISM band. The repeater is aimed to be used to secure wireless communications with a smart orthopaedic hip implant. Therefore, for a typical depth of such an implant of 4 cm, the repeater has been shown to enable a decrease of more than 40 dB in the transmit power level while the distance between the implant and the off-body gateway is kept constant.**

***Index Terms*—implant communications, reconfigurable antennas.**

I. Introduction

Smart implants are increasingly recognised for use in surgical procedures on patients. Typically, a smart implant, which in our case is an orthopaedic hip implant, includes sensors for sensing the environment surrounding the implant and a transmitter for wirelessly transmitting data reporting on the environment to an off-body gateway.

MedRadio spectrum frequency allows operation in the 401-406 MHz range. In addition, in 2012, FCC incorporated Medical Body Area Networks MBAN into MedRadio which covers 2360-2400 MHz band [1]. Therefore the majority of work on implantable antennas has been done in these two frequency bands: 401-406 MHz and 2.4 GHz. Following the guidelines given in [2], which discusses the relation between the the optimum operating frequency and the depth of the implant, the repeater here is designed in 2.4 GHz ISM band. Note that for the hip implant case, the depth is estimated to be 3 to 4 cm.

The link between the implant and the outside world depends heavily on the distance between the person and the off-body gateway. [3] and [4] proposed on-body receiver antennas and proved that the repeater not only improves the telemetry range, but also is useful to decrease the transmit power of the implant and hence preserving patient safety against radiated EM field and increasing the battery lifetime. Note that this phenomenon have not been extensively studied in the literature. Tow of the rare examples are [5] and [6], which propose multiple

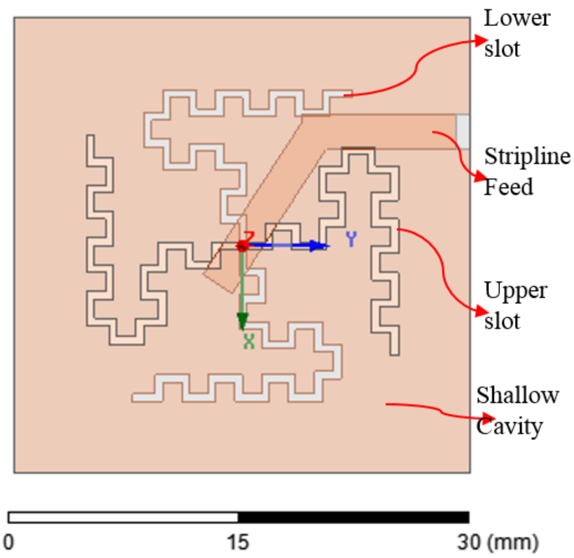


Fig. 1: Antenna diagram, slots miniaturized inspired by second order Koch-fractal configuration

band operation and their repeaters were intended for shallow implants. On the other hand [7] has done through system level analysis with a single mode antenna operating at the 2.4 GHz ISM band for communicating with deeper implants. They compared different transmission mechanisms such as "amplify and relay", and "on-body transceiver". "Amplify and relay" scenario was shown to perform as good as using an on-body transceiver furthermore being lower-cost, energy-efficient, and smaller in size. Here, a repeater antenna which connects a deep implant operating at the 2.4 GHz ISM band to an off-body gateway using an "Amplify and relay" mechanism is proposed. The digitally assisted repeater antenna has multiple radiation modes both operating at the same frequency which has not been proposed before to the author's knowledge.

The high magnetic near-fields are less susceptible to dissipation in the human body since human tissues have no magnetic losses ($\mu_r = 0$) [8]. Therefore magnetic antennas, including the slot antenna investigated in this study, are more suitable for facing the human skin in order to form the communication link with an implant.

Cavity backed slot antennas with reconfigurable input impedances and resonant frequencies were studied before. [9] discussed input impedance diversity by means of multiple feeds and a single slot backed by a cavity. [10] presented

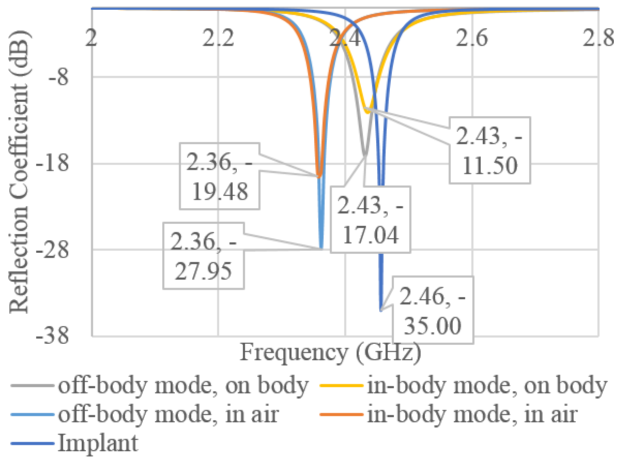
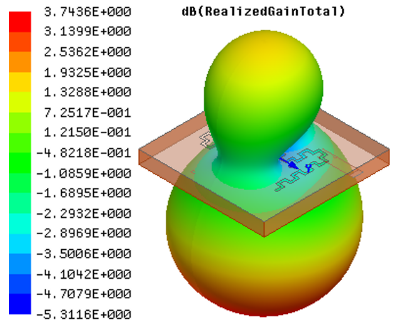
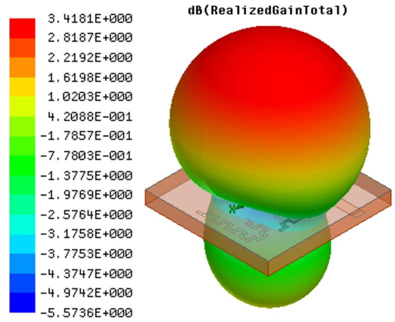


Fig. 2: The | s11| of the repeater antenna for each activation: in-body mode and off-body mode when the antenna is located in air and on a tissue block with 4 cm separation between the skin and the antenna, and of the implant antenna of the test scenario.



(a) The in-body mode is activated



(b) The off-body mode is activated

Fig. 3: The radiation pattern of the antenna when the antenna is located in vacuum.

frequency tuning in a cavity backed antenna while [11] is an example to a cavity backed slot antenna with polarization diversity. However radiation pattern diversity with a single feed in a shallow cavity backed slot antenna has not been discussed before. This paper proposes re-configurability in terms of radiation pattern with the application to implant communications. It is achieved with multiple slots on the same shallow cavity with a common feed point and the steering is realized with switches short circuiting the slots alternately.

Section II describes the antenna design steps. The results are presented in Section III and the paper concludes in Section IV.

II. Antenna Design

Two slots are carved into the opposite faces of a single rectangular shallow cavity and both slots are fed with the same stripline which meanders in between the slots as seen in Figure 1. The slots are activated in an alternating way by means of two switches located in the centre of each slot. When a switch is turned on, the slot on the opposite side is activated. This is a novel and a simple way of achieving radiation pattern diversity in a cavity backed slot antenna. Having a shorted slot on the opposite wall of the cavity does not affect the activated slot since the shorted slot operates at a higher frequency and its polarization is orthogonal to the active slot.

As a starting point, the cavity and the slots are considered to be isolated, the substrate is chosen to be air and the slots are assumed to be straight. The location of the slot and the cavity resonances can be theoretically predicted. The interaction between them is ignored at this stage. If the slot is a thin slot of which length is much greater than its width, then the lowest slot resonance, TE_{10} will be primarily defined by the slot length. The length of the slots are 75 mm for this particular example and hence TE_{10} mode occur at 2 GHz. The slot width should be kept as small as possible for practical reasons since switches are going to be located on them. Here 0.5 mm width is which are less than 0.01 λ . Note that increasing the width improves the 10 dB bandwidth of the input response.

The cavity mode with the lowest resonant frequency is TE_{101} according to Eqn 1 where a and d are the length and width of the cavity (which are equal in this case) and b is the cavity height. The thickness of the cavity is 3.15 mm which is less than 0.03 λ where λ is the wavelength of the first resonant frequency. Assuming that the backing cavity is fully enclosed, TE_{101} mode resonant frequency of the modelled backing cavity is calculated to appear around 2.8 GHz. In practice, the actual cavity resonances will shift due to the introduction of the slots, and the slot resonance will also be affected by the cavity. Therefore fine tuning should be performed using simulations.

In order to cater for the application, the digitally assisted repeater antenna is designed on Rogers RT Duroid 5889 and the slots are miniaturized by meandering inspired by second order Koch-fractal configuration as seen in Figure 1. Note that the miniaturized structure is 56% smaller than the original structure.

$$f_{nml} = \frac{c}{\sqrt{\epsilon_r}} \sqrt{\left(\frac{l}{2d}\right)^2 + \left(\frac{m}{2b}\right)^2 + \left(\frac{n}{2a}\right)^2} \qquad (1)$$

The stripline width is calculated such that its characteristic impedance is 50 Ω. It can be matched to any impedance depending on the system's output impedance. It encounters both slots at the same point then is open circuited at a distance where both slots are matched to the system while the other one is shorted with a switch. Since the position of the feed line is fixed, the impedance can only be tuned with the length of the feed line.

The switches can be realized with RF-mems technology. The ON state is simulated here by replacing the switch location with a conductive plane of width 150 um and length 400 um [12]. The switch is positioned on a conductive bridge and its width is set to 700 um where the length depends on the width of the slot. The OFF state is simulated by an open circuit of 400 um between the bridge legs. The simulated performance results are not affected by the insertion of the additional switch model.

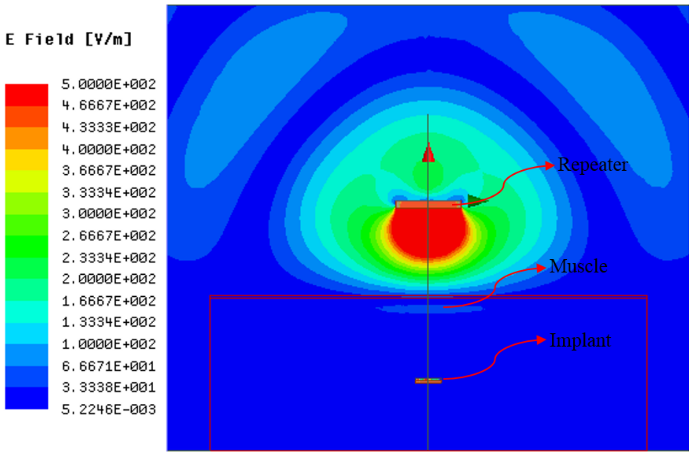
III. Results and Discussion

The antenna is designed and analysed through Ansys Electronics Desktop. The frequency response of each slot while the other one is shorted with a switch is plotted in Figure 2. The generated radiation patterns are plotted in 3D in Figure 3. Note that these radiation patterns are generated while the antenna is located in vacuum. Surely, the response will change once the antenna is located near lossy body tissue. Further analysis have been performed in order to demonstrate the performance of the antenna as a repeater as presented next.

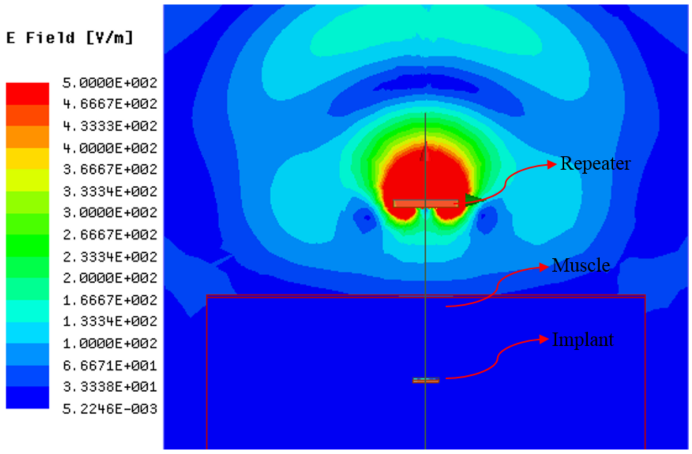
In a realistic scenario, the repeater is expected to be located near the human body to collect data from the implant. Locating the antenna near the lossy tissues deteriorates the performance of the antenna, especially during the in-body mode of operation. Therefore the antenna's reflection coefficient is monitored while the separation between the skin and the antenna is changed. As seen in Fig 2 40 mm has been found to be an acceptable separation with minimal detuning.

In order to demonstrate the great impact of the repeater at a system level, a transmission scenario is simulated where a 4 cm deep implantable antenna [2] operating at 2.4 GHz is excited and the repeater is located 4 cm away from the skin. The repeater communicates with an off-body gateway which is located away from the skin. In order to maintain a reliable link between the implant and the off-body gateway, the implant's transmit power should be more than 40 dB greater for the direct link scenario. In other words, while decreasing the transmit power of the implant by 40 dB, the reconfigurable repeater can achieve a reliable link of same length between the implant and the off-body gateway, without amplification. If amplified, it will further extend the link between the repeater and the off-body gateway. The E-field distribution in the vertical plane within the aforementioned scenario can be seen in Fig 4. This demonstrates how the energy is focused towards the desired direction.

Note that, a repeater without reconfigurable radiation pattern is still a better option than the direct link so that the transmit power level of the implant is minimized. In such a



(a) The in-body mode is activated



(b) The off-body mode is activated

Fig. 4: The E-field distribution in the vertical plane when the antenna is located on a 20 x 20 x 7 cm muscle block at 2.45 GHz.

scenario, an antenna with a constant radiation pattern with the main beam towards the off-body gateway will enable a reduction of the implant transmit power by 22 dB.

Figure 4 shows the E field distribution for in-body and off-body modes for the test scenario. Finally, it should be noted that in the future the separation between the repeater antenna and the body can be further decreased by means of an external insulation layer on top of the skin so that the repeater can be integrated into clothing. This technique was previously proposed in [8]. It was shown that at MedRadio band, the effect of external insulation layer, although not as important as an internal insulation layer, has a positive impact. It is a similar concept as using a bolus layer for superficial hyperthermia [13] or using matching liquid for microwave imaging.

IV. Conclusion

Here a digitally assisted antenna which directs it radiation pattern towards the body or away from the body depending on the link it forms by means of a couple of switches is proposed. The antenna is miniaturized inspired by Koch-fractal configuration and shown to operate at 2.36 GHz. The antenna's application to implant communications is then investigated. The antenna is located on a muscle block with 4 cm separation between the antenna and the skin. It has been shown that the antenna operates in the 2.45 GHz ISM band with the off body mode having 90% efficiency and the in-body mode having 72%. The antenna has been demonstrated to greatly improve the system performance by enabling a decrease of 40 dBs in the transmit power level of the implant.

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