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Compact Optimized Antenna Solution for Radiation Coupling Improvement in the Subcutaneous Fat Layer

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***Abstract*—Fat intra-body communication (Fat-IBC) aims at confining microwave propagation to the subcutaneous adipose tissue layer for the creation of a safe high-speed, high-bandwidth data transmission link through the body. This technique can be exploited to connect implantable medical devices and to implement a two-way transmission of recorded neural data and sensory stimulation signals between brain and robotic limbs. In this paper, a compact printed antenna solution for non-invasive tests of the Fat-IBC on non-human primates (NHPs) is proposed. This antenna is a printed monopole with a triangular radiating element embedded into a rigid brick, properly optimized to favor the radiation coupling in a 5mm-thick fat layer and minimize the signal propagation through the air. A promising wave coupling in the adipose tissue is achieved and a compact realizable layout is finalized for future prototyping and testing.**

***Index Terms*—Antenna optimisation, compact antennas, fat channel, fat intra-body communication (Fat-IBC), tissue properties.**

I. INTRODUCTION

Fat intra-body communication (Fat-IBC) is an innovative technique which aims at exploiting the subcutaneous adipose tissue layer as a communication channel between implantable medical devices [1]–[3]. Microwaves undergo attenuation when penetrating in the human body, due to the high dielectric losses in the skin and muscle layers. However, the fat tissue is characterized by a very low electrical conductivity (see Table I) and this has suggested the idea to exploit this layer as a sort of "natural" waveguide for receiving and transmitting electromagnetic signals (see Fig. 1). The feasibility of this technique has been discussed and demonstrated using computer simulations and experiments [4], [5], and in-vivo measurements [6].

The EU H2020 FET Open project (965044) B-CRATOS - "Wireless Brain-Connect inteRfAce TO machineS" - aims at using the Fat-IBC technique for the creation of a bidirectional wireless connection system between brain and a prosthetic arm (see Fig. 1). Combining expertise in diverse fields spanning Electrical Engineering, Biomedical Engineering, Artificial Intelligence, and Medicine, the final ambitious goal of this project is to create a "closed loop" between the brain and

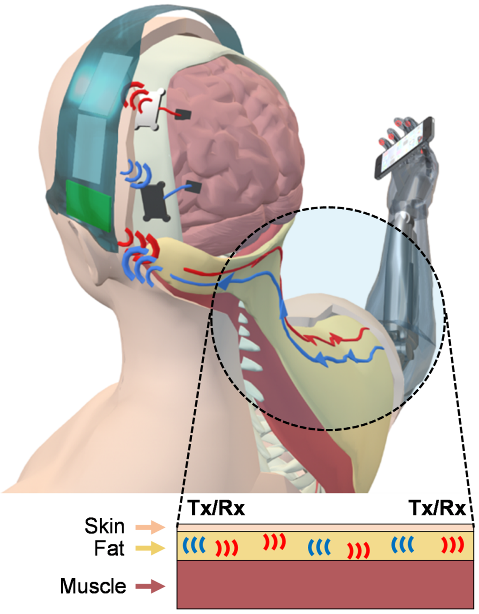

Fig. 1. Fat-IBC for the creation of a bidirectional wireless connection system between the brain and a prosthetic arm (B-CRATOS project).

TABLE I
VOLUME DENSITY AND DIELECTRIC PROPERTIES AT 2.44 GHz [1], [7]

Material	ρ (kg/m^3)	ε_r (-)	σ (S/m)
Skin	1109	38.570	1.58
Fat (Not Infiltrated)	911	5.328	0.11
Muscle	1090	53.290	1.82
RT/duroid 6010.2LM	3100	10.7	0.0033

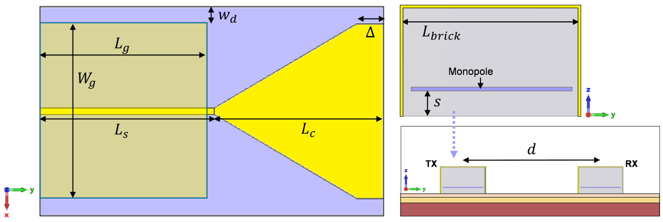

Fig. 2. Sketch of the proposed printed monopole antenna with a triangular-shaped radiating element, embedded into a rigid brick. *Left*: monopole antenna geometry; *right top*: side view of the brick antenna system with the metal coverage; *right bottom*: side view of the considered communication link.

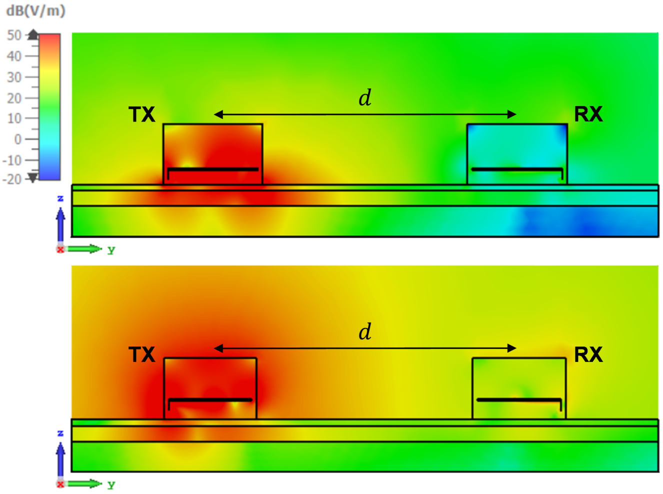

Fig. 3. Electric field magnitude for the optimized printed monopole antenna embedded into the coupling brick in the presence (*upper row*) and in the absence (*lower row*) of the metal coverage.

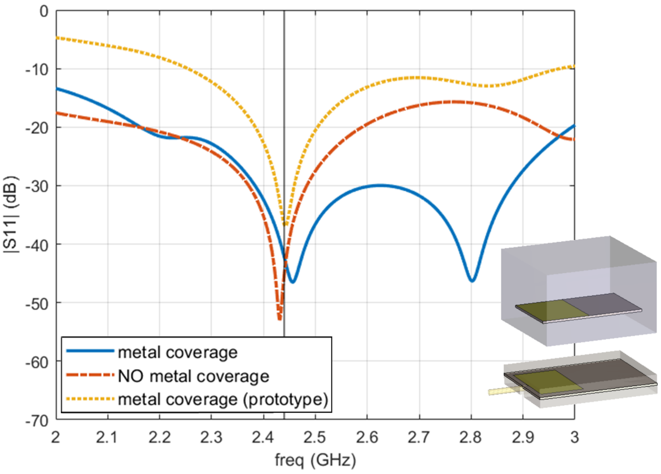

Fig. 4. Modulus of the S11 parameter as a function of frequency for different optimized configurations. The inset shows the optimized initial (*top*) and realizable (*bottom*) layouts.

the prosthesis, getting both a readout of the brain activity to control the prosthetic hand and providing tactile feedback from the hand to the brain.

In a first stage of this project, non-human primates (NHPs) and an external robotic hand will be used. NHPs will be trained to control a robotic limb and to interpret sensory feedback in a movement task. The Fat-IBC will be tested in an non-invasive way, i.e., using external epidermal antennas to couple the signals in the NHP subcutaneous fat layer.

In this paper, a printed monopole antenna with a triangular-shaped radiating element embedded into a rigid brick is optimized to properly convey the electromagnetic radiation through a 5mm-thick subcutaneous fat layer, using a full-wave commercial electromagnetic solver [8]. A metal coverage around the antenna is used to minimize the radiation coupling through the air and confine as much as possible the signal transmission into the fat tissue. The performance of the antenna in terms of the transmission coefficient will be compared to the one of another solution optimized by means of a genetic algorithm [9], and evaluated for different distances of a transmitting-receiving (TX-RX) link.

II. PRINTED MONOPOLE ANTENNA SOLUTION

The proposed solution is a monopole antenna with a triangular-shaped radiating element and a trimmed back-placed ground plane, printed on a substrate of Rogers RT/duroid 6010.2LM (see Table I), with fixed thickness $h_{sub} = 0.635$ mm. To improve the radiation coupling into the body, the radiating element is printed on the substrate side facing towards the tissue layers (while the ground is placed on the upper side of the substrate), and the antenna is embedded into a rigid brick, made of a material with relative permittivity $\varepsilon_{brick} = 10$. The five sides of the brick exposed to the air have been covered with a metal layer, to reduce the radiation coupling through the air.

The decision to consider the monopole antenna has been dictated by two reasons: first, a good behavior of this solution can be found in the literature [10], [11], in terms of radiation coupling through the human body; second, the presence of the triangular-shaped radiating element allows to easily obtain a not narrowband behavior around the central frequency of interest ($f = 2.44$ GHz). The whole antenna system was then positioned on a multilayer structure of skin, fat, and muscle tissues, with thicknesses 2 mm, 5 mm and 10 mm, respectively (see Fig. 2), and dielectric properties reported in Table I. The optimization has been performed using the parameters reported in Fig. 2 (except the link distance d), to minimize the reflection coefficient ($|S_{11}|$) at the central frequency $f = 2.44$ GHz and maximize the transmission coefficient ($|S_{21}|$) of the link reported in Fig. 2, where the second (RX) antenna is obtained by simply mirroring the transmitting (TX) one with respect to the xz plane. The distance s between the monopole antenna and the skin (see Fig. 2) is included in the optimization, being a crucial parameter for optimizing the radiation coupling in the underlying layers.

III. RESULTS

The results reported in Fig. 3 show the amplitude of the electric field for the antenna system optimized in the presence

TABLE II

TRANSMISSION COEFFICIENT OF THE PROTOTYPE STRUCTURE (WITH METAL COVERAGE) AT $f = 2.44$ GHZ FOR DIFFERENT LENGTHS d OF THE TX-RX LINK

d (mm)	50	100	150	200	250
$\|S_{21}\|$ **(dB)**	-24	-50	-63	-67	-70

(*upper row*) and in the absence (*lower row*) of the metal coverage. The two optimizations have been performed separately for the two cases. The overall dimensions of the brick are: $33 \times 30 \times 20$ mm^3 in the presence of the metal coverage, and $30 \times 30 \times 20$ mm^3 in the absence. As can be observed, the presence of the metal coverage reduces the radiation coupling through the air, thus allowing to isolate as much as possible the contribution of the Fat-IBC.

The corresponding reflection coefficients are reported in Fig. 4, showing a significantly wide bandwidth around the central frequency $f = 2.44$ GHz. Fig. 4 also reports the reflection coefficient obtained with a more realistic antenna layout, designed for future prototyping and testing. This layout is characterized by a brick with overall dimensions $35 \times 30 \times 5.635$ mm^3, obtained by melting the Rogers RT/duroid 6010.2LM antenna substrate with a lower and upper 2.5mm-thick layers made of the same material. The monopole antenna is fed with a microstrip line connected to an external coaxial cable (see the inset of Fig. 4).

The double resonance observed in Fig. 4 for the blue solid curve should be due to the configuration of the corresponding antenna system, which resembles the structure of an open-ended rectangular waveguide. Since a too broadband antenna may be not convenient for communications, as it means more unwanted signals getting in apart from the ISM 2.44 GHz (resulting in more complex/expensive communication electronics), the behavior of the prototype version (yellow dotted line in Fig. 4) seems to be the most promising one.

Table II reports the simulated transmission coefficient for the realizable structure, evaluated for different lengths d of the TX-RX link. An analogous computation performed for the optimized structure without the metal coverage provides a transmission coefficient in the range -22 dB $\div$ -36 dB for d varying from 50 mm to 250 mm. The higher value of the transmission coefficient at greater distances is due to an increased radiation coupling through the air, which is an effect that we want to limit to confine as much as possible the propagation through the fat layer.

To provide a comparison with another printed compact antenna solution, we considered an antenna optimized using a genetic algorithm (GA) approach (as reported in [9]), for a fat layer with thickness 5 mm, and covered with a metal layer. For a link distance $d = 100$ mm, a reflection coefficient of -14 dB and a transmission coefficient of -65 dB are achieved, showing a worse performance with respect to the brick monopole solution (see Table II). It has in fact been found that the signal loss for this kind of antennas optimized with the GA [9] increases significantly when the thickness of the fat layer is reduced from 10 mm to 5 mm.

IV. CONCLUSION

In this paper, a compact printed antenna solution for Fat-IBC transmission in a subcutaneous fat layer with thickness 5 mm has been investigated and optimized for future prototyping and testing.

Although an antenna solution without the metal coverage would certainly improve the transmission - due to the radiation coupling through the air - a layout with a metal coverage has been investigated to exploit the fat layer as the main communication channel and demonstrate the feasibility of the Fat-IBC approach in a non-invasive stage of the project. This has led to the identification of a compact realizable design showing a promising (not too broadband) behavior around the central frequency and a good radiation coupling through the subcutaneous fat layer. According to the achieved results, the average signal loss introduced by the selected antenna structure is low enough to make the device suitable for data links.

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