Implantable antennas: The Challenge of Efficiency

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***Abstract*—A discussion on the main challenges designing efficient antennas for bio-implantable communication devices is presented, along with some of the main issues encountered in their characterization. Such devices are used in conjunction with health monitoring or health care systems. Implantable antennas are, by nature, electrically small, and difficulties linked to electrically small antenna design apply. But implants are also located in a lossy host body, which induces a major change of paradigm with classic Electrically Small Antnnas (ESA), as the main design challenge for implantable antennas will be to reach an acceptable efficiency, and not a broad enough bandwidth. In this paper, we present first the main challenges to be met in designing implantable antennas, followed by suggestions for an efficient design procedure. Finally, the specific difficulties in characterizing implantable antennas are emphasized.**

Index Terms*— Implantable antennas, body phantoms, antenna efficiency, antennas in lossy matter, cable effects, in vitro and in vivo antenna characterization.

I. INTRODUCTION

The purpose of using antennas in a Bio-Implant can be either for telecommunication or therapy. In the former case, information is transmitted into or out of the host body (telemetry), in the second the antennas are used to provide energy, as in hyperthermia for instance. In this work, essentially antennas for telemetry will be considered.

The first use of antennas inside a living body dates as far back as five decades [1] and many designs have been proposed since. Early work on implantable antennas concerned mostly antennas for therapeutic or sensing applications[2][3][4]. In both cases, the antennas work in their near field and propagation over a certain distance is not an issue.

In telemetry applications, the system should transmit data over a certain distance[5][6], and features like radiation efficiency and bandwidth are essential to provide transmission over a large enough range with a high enough data rate. Early publications on this type of antennas started in the late nineties, but the physical size of the antennas presented were still large for real in body implantation [7], and the data rate was low[8][9]. Moreover, they relied on inductive coupling at low frequency with an external coil [10]. The main disadvantage of such designs is the very short communication range, which makes the reading process cumbersome for the patient. This has lead to the increased use first of ISM band at 2.45 GHz and then to the definition of the Medical Radio (or MedRadio) band which is defined between 401 and 406 MHz for medical telemetry [10]. Since these early contributions, many papers on implantable antennas for different telemetry applications have been published (for an overview, consult [11][12]). For instance, a PIFA for intracranial pressure sensor is proposed in [13] while a loop and foldable whip antenna are presented in [14][15] for intraocular telemetry and blood glucose monitoring, respectively. A pseudo-normal-mode helical antenna is disclosed in [16] whereas flexible solutions are recently considered, such as the conformal dipole in [17].

Previous designs mainly target the Industrial, Scientific and Medical (ISM) 2.45\;GHz frequency range, the Medical Device Radiocommunication Service band (MedRadio, 401-406\;MHz) has been recently allocated for implant communication [18] and is more and more used.

Ideally, implants have to be in the range of 1 to 10 mm in diameter for a length of 5 to 35 mm, in order to facilitate the surgical procedure, while in the MedRadio band the free space wavelength is around 74 cm, and in the ISM band it is around 12 cm. This implies that implantable antennas must be heavily miniaturized, leading to the design of ESAs with dimensions of some fractions of the free space wavelength (typically $\lambda_0/30$ and $\lambda_0/5$ for the MedRadio and ISM bands, respectively).

It is well known [19][20][21] that decreasing the electrical size of an antenna will lead to a decrease of its electromagnetic performances, and many studies focus on how to obtain a good compromise between size and performances (see for instance[22]). All these studies consider however lossless (or low loss) miniature antennas radiating into free space. In the case of implantable antennas, we have an important change of paradigm as the antenna is directly surrounded by biological tissues. The main quality criterion in the design of such antennas is not the bandwidth or the radiation efficiency of the antenna anymore, but the amount of power the antenna is able to transmit out of the host body. The efficient design of such antennas will thus have to take into account the host body, and will have to develop specific strategies in order to achieve this goal. In section II we will give some general consideration on transmission into a lossy medium, and the particular case of a living (human or animal) host body for an implant will be considered. In section III, a possible efficient design procedure will be proposed and illustrated on a practical example. Finally, some conclusions will be presented in section IV.

II. ANTENNAS IN LOSSY MEDIA

Implantable antennas are usually electrically small antennas (ESAs): If we consider the MedRadio band used in telemetry application (401-406 MHz), the wavelength is around 75 cm while the longest dimension of the implanted antenna is usually

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smaller than 4 cm. We have thus an electrically small antenna problem and the first impulse in a design procedure would be to apply the usual ESA design techniques. However, doing this, we neglect the fact that in the implantable antenna case the radiation takes place in a lossy environment, and the designs obtained are usually sub-optimal when this important fact is not taken into account. Indeed, the

A. *effect of a lossy surrond on antenna characteristics*

In order to assess the impact of the lossy surrounding medium on the antenna characteristics, let us consider a simplified antenna designed in the MedRadio band, based on the antenna presented in [23]. The antenna is depicted in Figure 1a, while the simplified body phantom in which it will be placed is shown in Figure 1b [24].

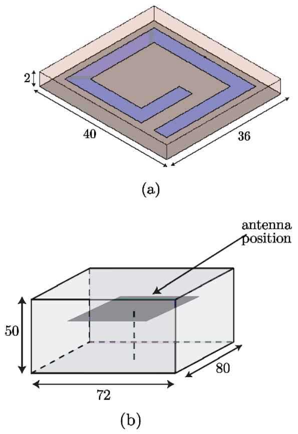

Figure 1. Simplified spiral antenna (a) and body model (b)

1) *Effect of the bandwidth*

On Figure 2, we see the input reflection coefficient of this antenna when placed in free space and when surrounded by a lossless body phantom, while on Figure 3 we see the same reflection coefficient when placed in a lossy body phantom.

From this example, it is easy to see that as expected, the change in relative permittivity of the medium surrounding the antenna will lower the resonant frequency but have only a small impact on the bandwidth, while the losses in this medium will greatly enlarge the latter. But at his point, the significance of this bandwidth should be questioned, as it is more related to power lost in the surrounding medium than useful bandwidth related to power radiated out of the body phantom.

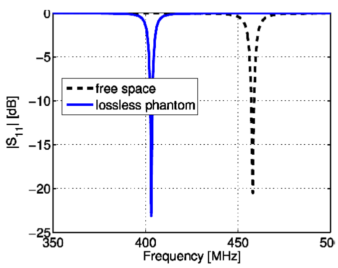

Figure 2. Antenna radiating into a lossless medium

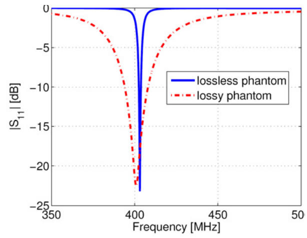

Figure 3. Antenna radiating into a lossy medium

2) *Effect on radiation pattern*

Moore [25] pointed out already in the early sixties that the conventional definition for the radiation pattern fails in the case of an antenna radiating into a lossy medium, as " the diagram of antenna in a conducting medium is strongly dependent upon the origin of coordinates" [25], and was nicely demonstrated on the diagram of a hypothetical linear antenna carrying a uniform current. To illustrate this effect, let us again consider the antenna of Figure 1a, this time inserted into two lossy phantoms differing by their lateral extensions (72mm x 80mm x 50 mm and 216mm x 240 mm and 50 mm). We see on Figure 4 that the far field patterns of these antennas are very different [24].

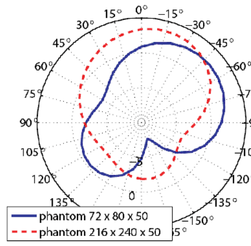

Figure 4. Radiation pattern of a spiral antenna placed into two different phantoms.

And it has to be noted that for implantable antennas, things become even more complex than described by Moore for antennas radiating into a uniform lossy medium due to the complexity and inhomogeneity of biological tissues.

3) *Effect of efficiency*

For an antenna radiating into free space, the radiated power depends on the far field components only as the near field is mainly reactive thus not affecting the radiated or the absorbed power. In the case of an antenna radiating into lossy matter, the near field strongly couples with the surrounding medium close to the antenna and thus increases the losses. Thus, the total radiated power depends on the radial distance r. This point was made as early as the early sixties [25][26][27][28] and led to a variety of definition of the radiation efficiency of an antenna radiating into an infinite of semi-infinite lossy medium.

In the case of implantable antennas, the situation is slightly simpler as the complex lossy medium surrounding the antenna is of finite dimensions, an as we can consider that the receiver is placed outside this medium in a far field region (field decay in $1/r$). In this case, we can use the classic definition

$$e_{rad} = \frac{P_{rad}}{P_{source}} \qquad (1)$$

where P_{rad} is evaluated in free space at far field distance.

It is also clear that, due to the strong coupling of the near field components to the encapsulation of the antenna will have an important effect on the radiation efficiency. This encapsulation has two main purposes: provide a biocompatible housing of an implant, and, for the antenna, isolate it from the lossy surrounding. It is now clear that the shape and dimension of this capsule can have an important effect on the radiating characteristics of an implanted antenna. This was already pointed out by Wheeler in 1961 [26] in the case of VLF antennas used for submarines.

B. *Examples of the effect of encapsulation on the radiation efficiency.*

In order to get some insight on the effects of the lossy body on the antenna's performances, and the potential mitigating effect of the bio-compatible encapsulation of the implant let us considered the simplified model proposed in [29] and depicted in Figure 5. In this model, the different layers of biological tissues are arranged as concentric spherical shells, at the centre of which an elementary source is located. The first layer is air, containing the source, the second the bio-compatible insulation and the following one or several layers representing the host body: muscle, skin fat, etc.

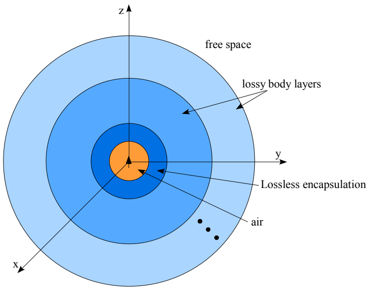

Figure 5. Simplified body model

The electromagnetic fields generated by the elementary (electric, magnetic or Huygens) source located at the centre of the model are computed using a spherical wave expansion and a mode matching technique [29]. The overall attenuation due to the different layers is computed from these fields. Let us consider a scenario where the radius of the central air shell is 5 mm and the radius of the lossless encapsulation shell is variable. The host body is made of three layers: muscle, fat and skin, where the radius of the muscle shell is 82 mm (ε_r=57.1-j35.51), the radius of the fat shell 86 mm (ε_r=5.58-j1.83) and the radius of the skin shell 90mm (ε_r=46.7-j30.72).

Both Zirconia (ε_r=29-j0.0507) and PEEK (ε_r=3.2-j0.0076), were used for the encapsulation shell. Table I gives the attenuation through each layer compared to the case with no encapsulation cell, for an electric dipole used as an elementary source.

We see that Zirconia gives better results than PEEK due to its lower loss but also to its higher dielectric constant, which allows for a concentration of the near field in the low loss surrounding of the antenna. The second point, which is rather intuitive, is that a thicker encapsulation will lower the overall losses. But it is also interesting to notice, especially in the case of PEEK, that this effect comes to certain saturation after a thickness of 2 mm as the losses are nearly the same for a thickness of 3 mm. Moreover, we need for practical reasons to consider that PEEK is a material far easier to handle and manufacture than Zirconia, thus more suitable for the building of real implants. Similar studies have been done for magnetic and Huygens sources [29], showing that the magnetic sources have less losses in the body than electric source, the performance of the Huygens source lying between those two.

TABLE I. POWER LOSS IN DB DUE TO DIFFERENT BODY LAYERS FOR AN EXCITATION THROUGH AN ELECTRIC DIPOLE: L1 IN THE ENCAPSULATION LAYER, L2 IN THE BODY AND L3 TOTAL LOSS

Insu-lation	**Thickness**								
	1mm			**2mm**			**3mm**		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
Zirc.	0.1	44	44.1	0.5	38.9	39.4	1.1	35.3	36.4
Peek	3.7		47.7	7.5		46.4	10.8		46.1
None	L2=L3=53.0								

We can conclude from this that the low loss encapsulation can help mitigating the loss by concentrating the near field in a low loss region.

III. DESIGN GUIDELINES AND EXAMPLE

Implantable antennas are electrically small antenna radiating into a lossy medium, which has a relevant impact on the design of an efficient implantable antenna: it changes the antenna characteristics and makes the overall design procedure much more complex. In order to keep the design procedure easy to overlook and to understand the effect of each parameter, we propose to proceed step by step as explained below:

1. Choose an initial antenna type to be used (loop antenna, PIFA type antenna or dipole family). This choice will depend on the bandwidth required, the communication electronics used (requiring balanced or unbalanced feeding lines) and the volume available. Analyze the near field of the proposed antenna to see if it is suitable and to obtain initial information about the volume and shape of encapsulation

2. Perform an initial design considering a homogeneous lossless medium surrounding the antenna (but keep the conductive and dielectric losses of the materials used to build the antenna). This has the advantage of speeding up the simulation time required in a way to allow for an optimization. But it has also the advantage of giving information about the "radiation bandwidth" of the antenna as opposed to the "loss bandwidth"

achieved once the antenna is placed into lossy surroundings.

3. Miniaturize the design using classic miniaturization techniques[22], but keeping a tight control on the near field.
4. Add the losses in the homogeneous body model and add the encapsulation layer. Re-tune the antenna.
5. Add a more realistic body phantom as the medium surrounding the antenna. Re-tune the antenna.

A dual band antenna for an implantable modular sensor was designed following the rules stated above. The implant is made of a cylinder of 10 mm of diameter and 32 mm height, and contains the bio-compatible encapsulation, the electronic circuitry, the batteries, the sensor and the antenna. The communication electronics is based on a commercially available circuit [30], which uses the MedRadio band (401-406 MHz) for the data transfer and the ISM (2.45 GHz) for a wake up signal. The overall implant is shown in Figure 6 and the antenna in Figure 7. It is a dual band single excitation point antenna covering both specified bands. The ground plane has a shape and location helping to direct the beam out of the host body and thus optimize the overall radiated power.

The simulated and measured reflection coefficients for the MedRadio band is given in Figure 8, the results are similar for the ISM band and we see that the antenna is well matched.

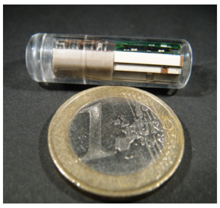

Figure 6. Implant with antenna and circuitry

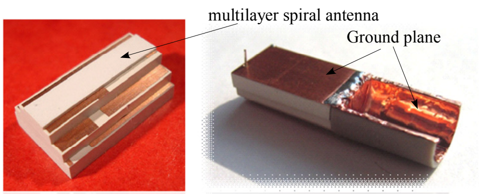

Figure 7. Dual band antenna

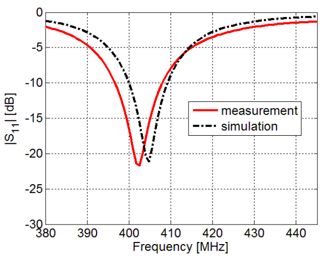

Figure 8. input reflection coefficient (MedRadio Band)

The simulated gain of this antenna is of -17.5 in the ISM band and -29.4 in the MedRadio band.

This module was implanted in conjunction with a temperature sensor into a pig (Figure 9), in order to monitor the temperature evolution after a graft using autologous stem cells. Two modules were implanted, one directly under the skin and one in depth, under 30 mm of muscle tissue. The aim of the experiment was to allow telemetry without disturbing the medical experiment. A reading distance of 10 m was thus required.

Figure 9. Implantation of the intramuscular module

The system set up in the farm where the pig was located after the operation is depicted in Figure 10. A base station is located in the barn above the stable, and a reference module was placed in the stable on a shelf above the animal to monitor the ambient temperature in the stable. Temperature measurements were performed every 5 minutes over a period of 15 days by the three modules and wirelessly reported to the base station. The results are reported on Figure 11. We see that the intramuscular implant always records a higher temperature than the subcutaneous implant, as expected. The sleep/wake rhythm of the pig is also clearly visible. The reliability of the data transfer was excellent over the entire period. More details about this experiment can be found in[31].

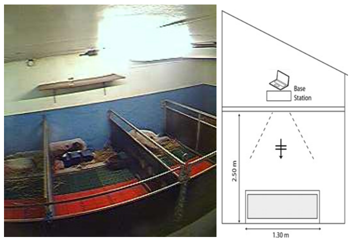

Figure 10. System setup

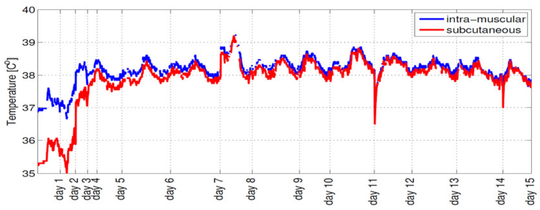

Figure 11. Temperature results

IV. CONCLUSIONS

Antennas for implants are electrically small antennas. However, the fact that they do radiate into a lossy medium greatly influences their radiation characteristics. In order to perform an efficient design of such an antenna, the influence of the lossy medium surrounding the antenna on both near and far field terms have to be understood. Once this is done, all the knowledge developed in the past for the design of electrically small antennas becomes very relevant in the design procedure and can be built upon to propose new guidelines taking into account the understanding of the loss mechanisms involved.

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