Design Strategies for Implantable Antennas

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***Abstract*— Considerations on the efficient design and the characterization of antennas for bio-implantable communication devices are presented. These devices are used in conjunction with health monitoring and/or health care systems. First, the main challenges to be met in designing such antennas are presented, subsequently followed by the proposition of a design procedure. Finally, the specific difficulties in characterizing implantable antennas are emphasized.**

I. INTRODUCTION

The need for implantable telecommunication devices dedicated to medical application has been growing fast over the past ten years. The main applications of such devices are either therapeutic (e.g., hyperthermia or balloon angioplasty) or diagnostic allowing data transmission between a base station and the implant. The latter can be either mono-directional (in endoscopy application for instance) or bi-directional (e.g., in sensing and drug delivering systems), and can comprise or not a wake up system. In the latter case, the system may use two frequency bands, one for wake up and one for transmission.

Most of the early work on implantable antennas concern antennas for therapeutic applications [1-3] (hyperthermia, balloon angioplasty, etc.) or for sensing applications. In both cases, the antennas works in its near field and propagation over a certain distance is not an issue. In telemetry applications on the other hand, the system should transmit data over a certain distances [4, 5]: in this case, features like the radiation efficiency and the bandwidth are essential in order to provide transmission over a large enough range with a high enough data rate. The first publications on this type of antennas started in the late nineties, but the physical size of the antennas presented were large if real in body implantation is considered [6], and the data rate was low [7, 8]. Since these contributions, many papers on implantable antennas for different telemetry applications have published (for an overview, consult [9]). In the frame of this paper, we are going to summarize some aspects specific to such antennas, and illustrate these points on the example of a deeply implanted bio-sensor [10-11].

Early work on implants for telemetry relied on inductive coupling at low frequency with an external coil [12]. 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 of the *Medical Radio Communication Band* (or *MedRadio*) band which is defined between 401 and 406 MHz for medical telemetry applications and the ISM band between 2.4 and 2.5 GHz [13].

In the *MedRadio* band the free space wavelength is around 74 cm, while in the ISM band it is around 12 cm. Typical implants on the other hand have to be much smaller, ideally in the range of 5-10 mm in diameter for a length of up to 30-35 mm in order to be easily implanted. The implication is that implantable antennas will be heavily miniaturized, leading to dimensions of some fractions of the free space wavelength. It is well known [14-16] 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 17]. 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 loss 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. The present contribution proposes such a specific strategy: Section II will be dedicated to the assessment of the role of the host body and of the antenna encapsulation. Section III will propose a design strategy, which will be demonstrated on a specific example in section IV. Finally, section V will illustrate some of the problems encountered while measuring implantable antennas.

II. BODY LOSSES AND ENCAPSULATION

As mentioned in the introduction, all studies on the fundamental limitation of electrically small antennas have been performed for antennas radiating into a lossless environment, usually the free space. 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 [18], let us considered the simplified model proposed in [18] and depicted in Fig. 1. It consists of an elementary source (electric, magnetic or Huygens), and concentric spherical layers representing the environment of the antenna. 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.

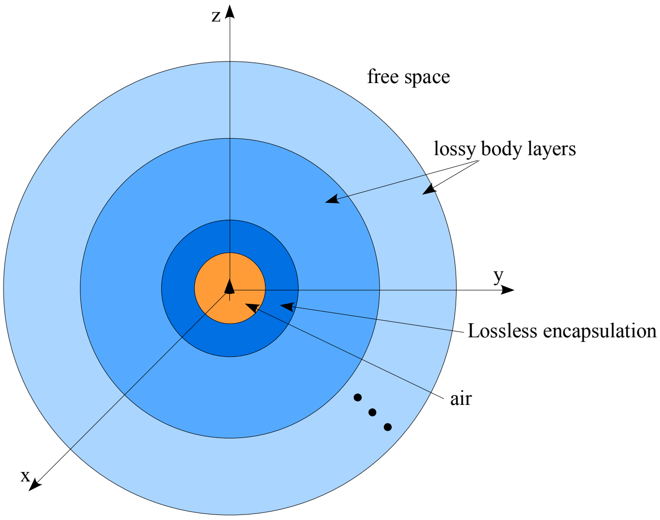

Fig. 1: Simplified body model

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 [18]. The overall attenuation due to the different layers is computed from these fields. Let us consider the following scenario:

- Radius of the central air shell: 1 mm
- Radius of the lossless encapsulation shell: variable
- The host body is made of three layers: muscle, fat and skin
- Radius of the muscle shell: 82 mm
- Properties of the muscle shell: ε_r=57.1-j35.51
- Radius of the fat shell: 86 mm
- Properties of the fat shell: ε_r=5.58-j1.83
- Radius of the skin shell: 90 mm
- Properties of the dry skin shell: ε_r=46.7-j30.72

Both Zirconia (ε_r=29-j0.0507) and Peek (ε_r=3.2-j0.0076), materials having both good bio-compatible properties 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 at 403.5 MHz.

TABLE I
POWER LOSS IN DB DUE TO DIFFERENT BODY LAYERS FOR AN ELECTRICAL EXCITATION: L1 IN THE ENCAPSULATION LAYER, L2 IN THE BODY AND L3 TOTAL LOSS (L1+L2)

Insu-lation	**Thickness**								
	1mm			**2mm**			**3mm**		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
Zirconia	0.1	44.0	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								

The first thing we notice is that Zirconia is on an electromagnetic point of view a better encapsulation material than Peek. This is quite obvious, as the loss angle of Zirconia is lower than the one of Peek, but also because of the high dielectric constant of Zirconia: due to the latter the near fields will concentrate in the encapsulation layer and thus contribute far less to the losses than in the Peek case were the dielectric constant is lower. The second point, which is rather intuitive, is that a thicker the 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 [18], showing that the magnetic sources have less losses in the body than the electric one, the performance of the Huygens source lying between those two.

In conclusion to these considerations and for the set up of design guidelines we can say that:

- The low loss encapsulation layer can help mitigating the power loss by concentrating the near fields in a low loss region.
- The thickness of the encapsulation is of relevance, as it should comprise the largest part of the antenna near field. Once this is achieved, the available volume should be used for the antenna.
- High permittivity materials are more suitable electromagnetically but tend to be hard to manufacture.
- Magnetic and Huygens sources have lower overall losses in the body than electrical sources.

III. DESIGN GUIDELINES

As mentioned in the introduction, antennas for implantable telemetry systems are electrically small antennas like most of antennas for wireless applications, but with the additional difficulty that the implant will be located in a complex lossy medium. In order to perform a successful design, it is meaning full to go step by step from the simple to the complex. The following steps are proposed:

- 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.
- 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 helps also to ensure that the bandwidth reach by the antenna is "real" bandwidth and not due only to losses in the body.
- Miniaturize the design using classic miniaturization techniques [17].

- Add the losses in the homogeneous body model and add the encapsulation layer. Re-tune the antenna.
- Add a more realistic body phantom as the medium surrounding the antenna. Re-tune the antenna.

The last steps may seem tedious, as the antenna needs to be retuned twice in this design cycle. The overall procedure is however time efficient, as the experience gained in steps 2 and 3 will greatly help shorten steps 4 and 5. Moreover, adding the insulation layer enhances the result stability. An example of a design made using this principle can be found in [19].

Looking at this design procedure, we see that using an efficient and accurate simulation tools is a key issue for the success of the design. Implanted devices are electromagnetically rather complex to analyze: indeed, they involve 3-D structures embedded in inhomogeneous highly lossy materials. As a consequence, the best suited numerical tools are based on a differential rather than an integral approach. Moreover, implanted antennas are usually narrowband, making a frequency domain approach more efficient than a time domain formulation. The electromagnetic solvers most commonly used in literature for the design of implanted antennas are thus based on the finite element method (FEM) or a hybrid method. Once the solver is determined, the appropriate models should be set up for the host of the implant (body phantom), the capsule and the antenna, where a key issue is the correct description of the antenna feed [18]. Of course, different levels of detail are usually required depending on the design phase. Moreover, all usual simulation procedures and special care required to analyze electrically small antennas should of course been taken in addition to the points mentioned above.

IV. DESIGN EXAMPLE

A dual band antenna for an implantable modular sensor was designed following the rules stated above [10-11]. The implant is 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 [20], which uses the *MedRadio* band for the data transfer and the ISM (2.45 GHz) for a wake up signal. The antenna is depicted in Figure 2, while the overall implant is shown in Figure 3. 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 radiated beam out of the host body and thus optimize the overall radiated power.

The simulated and measured reflection coefficients for both bands are given in Figures 4 and 5.

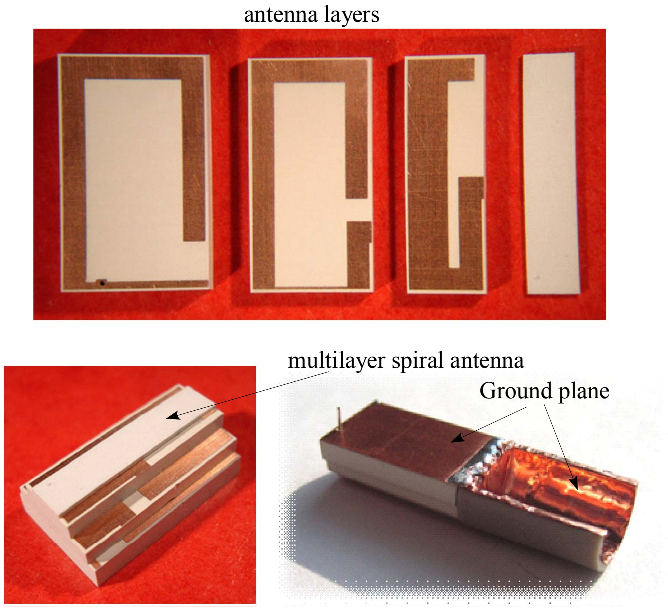

Figure 2: Dual band antenna

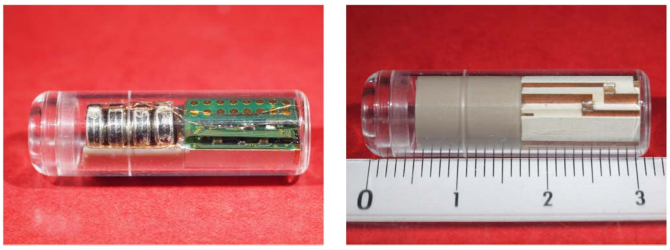

Figure 3: Implant with antenna and circuitry

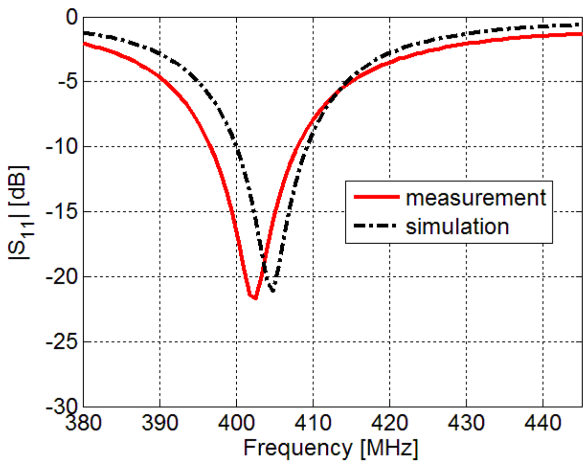

Figure 4: input reflection coefficient (MedRadio Band)

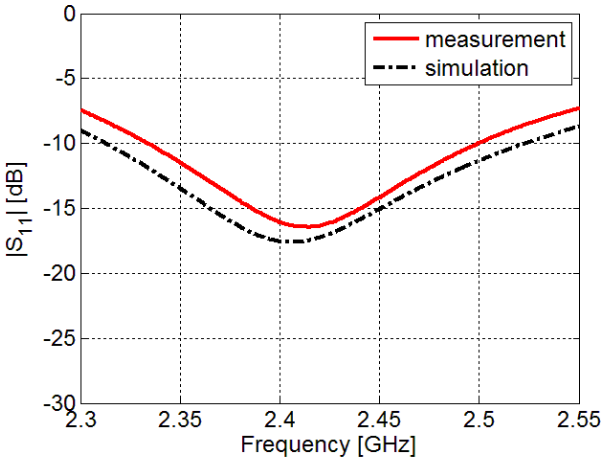

Figure 5: input reflection coefficient (ISM Band)

The simulated gain of this antenna is of -17.5 in the ISM band and -29.4 in the *MedRadio* band. Those numbers were corroborated by system measurements, were reading distances of 5 m in the ISM band and 14 m in the *MedRadio* bands were achieved. For these tests, the capsule was placed in liquid mimicking muscle properties for each working band.

V. Measurement issues

Antennas for biocompatible implants are electrically small antennas, and thus meet all the difficulties linked to the proper measurement of such devices: ill defined interfaces, current circulating on the outer conductor of the feeding cable, etc. A little easier are in vitro system assessments, were the host body is replaced by an appropriate phantom. As the implant has to be placed into this phantom, it is often made by a container filled by a liquid or gel having the dielectric property of biological tissues. The shape of this container can be more or less complicated, from a simple cylinder or parallelepiped to a human shape. The liquid or gel used is homogeneous or made of 3 materials [21] and can thus only be an approximation of the complex layered structure of biological tissues.

The factor of merit obtained during system characterization can be of different type (e.g., reading distance, bit error rate, etc.) but will only give information about the overall performances of the entire system but not of the individual components. However, for the antenna designer it is sometimes very helpful to be able to check the radiating performances of the antenna directly. This can often be done, at least qualitatively, if the effected of cable currents are mitigated by avoiding a direct contact between the cable and the lossy biological phantom. A procedure for a proper qualitative characterization of the antenna could be:

1. Design the antenna using a feed model close to the actual feed in the system. Use a simple body phantom made of a cylinder containing a liquid with an appropriate dielectric permittivity.
2. Replace the feed in the simulation with a coaxial cable and check for differences in the results. If the results differ from the former, minimize the cable effects by insulating the cable from the lossy liquid using for instance a small tube filled with void [22].
3. After prototyping the antenna, measure the latter in the same scenario than the simulation of point 2, which can be easily translated to measurement. If the measured and simulated results agree well, the antenna designed with the proper system feed (point 1) should also have good results once integrated into the system. The antenna can now be fine tuned in simulations using a more refined body phantom.
4. Once these preliminary checks are done on the antenna, system checks in vitro, using again a simple body phantom as in point 2 can be performed.

Once all the test steps above give satisfactory results, in vivo testing can be considered.

VI. Conclusions

A design strategy for antennas implantable in biological tissues has been presented. It has been shown that such antennas are electrically small antennas, and that thus all the knowledge developed in the past for such devices is very relevant, but that additional difficulties occur due to the lossy nature of the body hosting the antenna. By understanding properly the loss mechanisms involved, design guidelines leading to efficient antennas have been proposed and illustrated on a practical example. Finally, the specific difficulties related to the electromagnetic characterization of antennas embedded in a lossy medium have been highlighted, and some mitigation strategies proposed.

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