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ANTENNA ANALYSIS AND OPTIMISATION FOR DEEPLY IMPLANTABLE MEDICAL SENSOR TRANSPONDERS

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ABSTRACT

Deeply implanted sensor transponders are of interest in treatment of cardiovascular diseases. In such systems only small antennas in shape of a stick are supposed. To make a sensor transponder operatable, an optimisation of such an antenna is necessary. Therefor a mathematical expression is derived, that makes optimisation possible. A mathematical modell is derived, to describe physicall effects. Moreover, the influence of encapsulation and human tissue in direct contact to the antenna is analysed. Finally, an optimisation is done for typical requirements of such a system. Measuremts validate the theoretical examinations.

Index Terms— Sensor Transponder Medicine Implanted Antenna Energytransmission Human Tissue Optimisation

1. INTRODUCTION

The use of sensor transponder technologies in medicine opens valuable possibilities in the therapy of human cardiovascular system diseases. Medical studies [1] have shown, that the treatment of cardiovascular disease can be significantly improved by continuous monitoring of parameters such as blood pressure, temperature, and so on. A deeply implanted sensor transponder in human body can measure cardiovascular parameters and send it to a reader outside of the body. Implants normally stay inside the body for a longer period. Thus, a supply by a local battery is not possible, only so-called passive transponder systems are of interest. There are several requirements that have to be kept in mind. For example, a large transmission distance (up to half a meter for corpulent patients), low antenna dimensions (catheter implantation) and the influence of human tissue. Today, no system exist, that meet all these requirements. This work is focused on the analysis and optimisation of transponder antennas for such a system. Antenna characteristics will be investigated influenced by the encapsulation and human tissue. With the help of antenna models and mathematical expressions, that are derived in this work, an optimisation of antenna parameters is possible.

2. INDUCTIVE ENERGY TRANSMISSION

A sensor transponder system consists of a reader located outside the body and the implanted sensor transponder. The reader has a transmitter to produce an alternating magnetic field and a receiver for the transponder data. The sensor transponder consist of an antenna coil, a chip including analogue frontend, logic and integrated pressure and temperature sensor. Previous studies [2] have shown, than a frequency of 6.78MHz is a good choice to transmit power to the transponder. At this frequency the maximum power transmission is possible. The transmission takes place in the so called nearfield. Only the magnetic component is used. Because of that, coils are used as antennas.

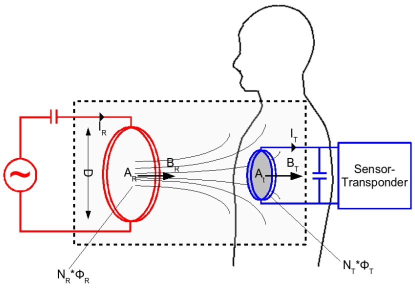

Fig. 1. Sensor Transponder System

Figure 1 illustrates a sensor transponder system. The transmission channel consists of an antenna coil in the reader that produces an alternating magnetic field, the human body and the antenna coil of the transponder. The current in the antenna coil of the reader produces an magnetic flux. A small part of the magnetic flux couples with the transponder coil. In consequence, a voltage is induced in this coil. By this voltage, the electronic of the transponder is supplied with power. This voltage is proportional to the time derivation of the flux $\frac{d\Phi_T}{dt}$. Figure 2 shows an equivalent circuit of the inductive transmission channel. The resistors R_R and R_T model losses in antennas and human tissue. The current consumption of the transponder load is modelled by R_L. The function of the antenna coil in the reader is

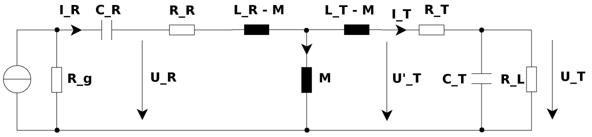

Fig. 2. Equivalent Circuit

to generate a magnetic field at the transponders place, that provides it with enough energy for working. The purpose of the transponder antenna is, to produce the maximum possible voltage with the available magnetic field to provide power to the transponder's electronics. So, the transmission range can be maximised. The channel is modelled by a transformer equivalent circuit. Moreover it includes tuning capacitors at the primary and secondary side. The following mathematical expression is derived from this equivalent circuit that enables an optimisation of the antenna coil. This formula describes the achievable voltage over the load for an available field strength. It includes all parameters that describe the antenna characteristic.

$$\frac{|U_T|}{|B_T|} = \frac{\omega \cdot N_T A_T}{\sqrt{(\frac{R_T}{\omega L_T} + \frac{\omega L_T}{R_L})^2 + (\frac{R_T}{R_L})^2}} \tag{1}$$

The better the antenna is optimised, the larger is the value of this expression. The expression depends on some geometrical parameters, like the diameter and number of windings and electrical parameters, inductance, loss resistance and load resistance. To enable an optimisation of the antenna, it is necessary to have a mathematical model, that describes the dependences between the parameters. Moreover the influence of the human tissue has to be analysed. This is done in the following section.

3. THEORETICAL ANALYSIS OF IMPLANTED ANTENNA COILS

Following, the electrical characteristics of implanted antenna coils are analysed. Particularly, the influence of encapsulation and of human tissue in direct contact to the windings of the transponder coil are considered. For energy transmission, the parameters inductance, stray capacity and loss resistance are of interest. A part of available power is converted to heat. Stray capacity exists, because of the electric field between the windings. The electric field lines penetrate the encapsulation and the human tissue. These materials have higher permittivities. This causes a rise of the stray capacitance and can make the antenna unusable. In the end, these effects reduce the transmission range, which is is not acceptable in this application.

3.1. INDUCTANCE

The human tissue has no direct influence to the inductance, because it has no magnetic behaviour. However the measurable inductance of an antenna coil is influenced by the stray capacity. The following formula shows the interrelation between measurable inductance L_S, the parasitic capacity C and the real inductance L_L.

$$L_S = \frac{L_L}{1 - \omega^2 L_L C} \tag{2}$$

If the parasitic capacitance is known, the measuremable inductance can be predicted. By inserting the so called self resonant frequency $\omega_r = \frac{1}{\sqrt{L_L C}}$ we get:

$$L_S = \frac{L_L}{1 - (\frac{\omega}{\omega_r})^2} \tag{3}$$

If the self resonant drops to the operation frequency ω, the effect of inductance and capacitance will cancel each other. If the operating frequency is higher than the self resonance ω_r, the coil will act as an capacitor.

3.2. STRAY CAPACITY

The windings of the transponder antenna are placed on a ferrite rod. They are surrounded by the encapsulation material and human tissue. Figure 3 shows a schematically structure of an implanted transponder antenna coil. Because of the voltage drop across each winding, an electric field appears. the electric field lines are indicated in the figure. There exist electric field lines between each winding, between the different windings, and to the core. Some of the field lines penetrate the encapsulation and the human tissue. Other field lines are just inside the encapsulation.

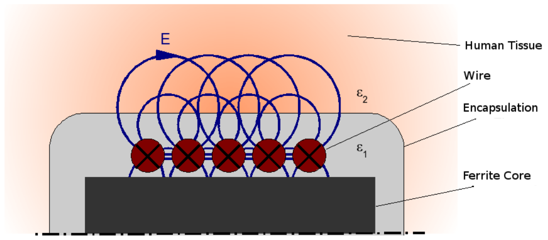

Fig. 3. Electrical stray field of implanted antenna coil

Figure 4 shows the simplified HF equivalent circuit of an antenna coil. It consists of inductivities L_n for each winding, resistors R_n for modelling losses, and capacities. The overall stray capacity is composed of several stray capacities between each winding C_t and between the core C_s. The field lines belonging to C_s penetrate just the encapsulation, whereas the field lines of C_t penetrates the human tissue. With the help of a mathematical description of this modell, the influence of encapsulation and the human tissue can be estimated. Various materials of encapsulation and human tissue can be considered. The influence of geometrical design parameters, like number of windings can be considered, as well. With the following formulas derived from this model [3], the stray capacity can be obtained.

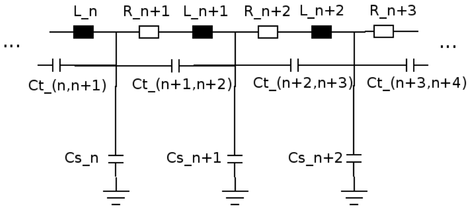

Fig. 4. Equivalent circuit of implanted antenna coil

$$C_t = \frac{\pi^2 D\varepsilon}{ln(p/2r + \sqrt{(p/2r)^2 - 1})} \tag{4}$$

$$C_s = \frac{2\pi^2 D\varepsilon}{ln(h/r + \sqrt{(h/r)^2 - 1})} \tag{5}$$

The overall capacity is composed of all single stray capacities together and can be found out by the following inductive formula:

$$C(n) = \frac{C(n-2)C_t/2}{C(n-2) + C_t/2} + C_s/2 \tag{6}$$

Now, the influence of encapsulation and human tissue can be discussed. Geometrical parameters, like the dimension of the core, are given by the implantation technique. A searched parameter is the optimal number of windings. Additionally, one of the most importand question is, if the number of windings is limited by the parasitic capacity.

First of all, the influence of the human tissue is discussed. With the help of the formulas, the over all stray capacitance is calculated for several number of windings. Figure 5 shows the result. The over all stray capacitance of the transponder antenna is shown for differend kinds of surrounding materials. In all cases, silicone was chosen as encapsulation material. For each material, the corresponding permittivity at the operating frequency was used [4]. First of all, it can be said, that the stray capacitance is affected by the surrounding material. In an antenna coil with two windings, blood causes a value of 18pF, that is 25 times higher than 0.7pF for air. Heart tissue has approximatelly the same effect. The over all capacitance is decreasing with rising number of windings. The reason is, that the over all capacitance of series connected capacities is smaller than the value of one single capacity. Moreover it can by seen, that the capacitance will not change significantly anymore, for more than about 20 windings. In this case, the capacities between the windings and the core C_s are decisively. To verify this, the over all capacitance is calculated for different kind of encapsulation materials. Figure 6 shows the result. It can be said, that the capacitance is not influenced by the capacity C_s for up to three windings. The question is now, how the usability is influenced.

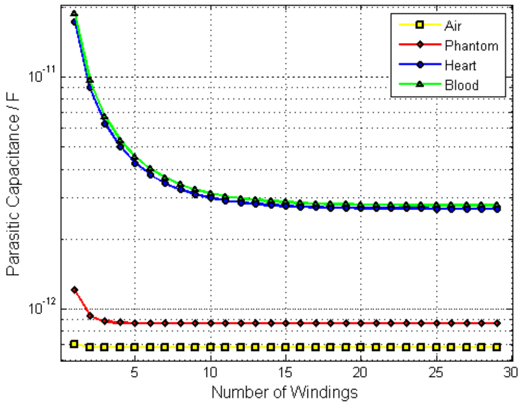

Fig. 5. Stray capacitance over the number of windings for several kind of human tissues

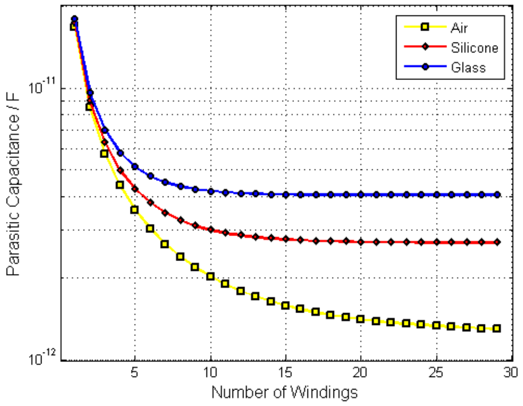

Fig. 6. Dependency of over all capacitance on the number of windings for different encapsulation materials

As described in section 3.1, the measurable inductance of the antenna coil is influenced by the parasitic capacity. In the literature [5] can be found, that an antenna coil is usable, if the measurable inductance is maximal 10% raised by this effect. This means, that the self resonance caused by the inductivity and parasitic capacity should be $\sqrt{11}$ times higher than the operating frequency. Figure 7 shows the maximum recommend operating frequency in dependency to the number of windings.

The values are calculated for a silicone encapsulation and surrounded heart tissue. As can be seen, that the maximum recommend frequency is falling with ris-

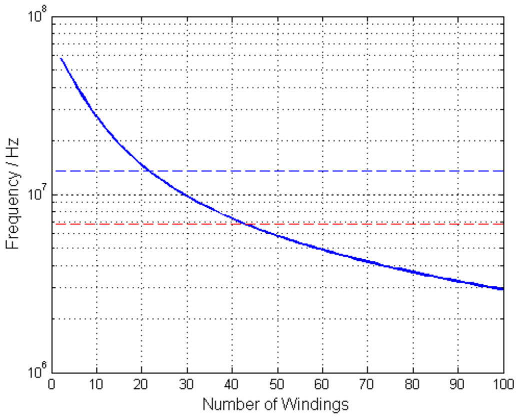

Fig. 7. Maximum Recommend frequency over number of windings

ing number of windings. The reason for this is, that the inductivity rises faster than the parasitic capacitance falls with the number of windings. In this application, an operating frequency of 6.78MHz or 13.56MHz is of interest. These frequencies are shown by the dashed lines. It can be said, that antenna coils with no more than 20 windings can be used for 13.56MHz and not more than 43 windings for 6.78MHz.

3.3. LOSSES

Losses in antenna coils exist in the ferrite core, the wire, and the human tissue around the coil. A part of the energy is converted to heat. Losses in the wire are caused by the ohmic resistance, skin and proximity effects. Ferrite losses are caused by magnetisation of the material and eddy currents in the core. These effects are frequency depended.

DC resistance

The DC or ohmic resistance is caused by the limited conductivity of the wire, that means without frequency depending effects. It depends on the length of the wire, the thickness and the conductivity of the used material. The ohmic resistance should be expressed as a function of the number of windings respectively the inductance. With the following mathematical expression the DC resistance can be calculated:

$$R_{DC} = \frac{N_R D}{\sigma \pi d^2/4} \tag{7}$$

with d diameter of the wire and σ the conductivity of the material. E.g. for cupper $\sigma_{CU} = 57\frac{Sm}{mm^2}$. For a cylindric antenna coil D = 1.5 mm, d = 0.15 mm and N = 10 the DC resistance becomes $46.6 \cdot 10^{-6}\Omega$

Skin Effect

Every electrical current is surrounded by a magnetic field. In case of ac current, eddy current will be induced in every conductive material next to the field. Insight the conductor, such eddy currents are as well. These eddy currents itself cause magnetic fields. These fields in turn interact with the current. In consequence, the current flow is driven to the surface of the wire. The bulk is currentless, and the cross section of the wire is not completely used. The resistance of the wire seems to rise. This effect is called skin effect. The ac resistance caused by this effect could be calculated with the following expression [6]:

$$A_{skin} = R_{DC} \cdot (x + \frac{1}{4} + \frac{3}{64x}),$$
$$mitx = \frac{d}{4}\sqrt{\pi f \sigma \mu}$$

Thus, the losses caused by the skin effect can be calculated.

For example, the dc resistance caused by skin effect for a cylindric antenna coil with D = 1.5 mm, d = 0.15 mm and N = 10 at 6,78 MHz amounts to 9 $m\Omega$.

Proximity Effect

If a wire is arranged to a coil, an additionaly rise of the resistance will be observed. The reason is, that the magnetic field of induced eddy currents interacts with adjacent windings. This effect can be described mathematically. Kelvin-Besselfunctions are necessary. An expression to determine the ac resistance is given in [7]:

$$R_{AC} = R_{DC}\frac{\gamma}{2}[\frac{ber\gamma bei'\gamma - bei\gamma ber'\gamma}{ber'^2\gamma + bei'^2\gamma}$$
$$-2\pi\frac{ber_2\gamma ber'\gamma + bei_2\gamma bei'\gamma}{ber^2\gamma + bei^2\gamma}] \tag{8}$$

with $\gamma = \frac{d}{\delta\sqrt{2}}$ and δ the so called skin depth. “bei”, “ber” are the Kelvin-Besselfuntions. The geometry of the conductor is considered.

Therefore, the losses caused by proximity effect can be described analytically.

Losses in human tissue

The losses inside human tissue for different frequencies were analysed in [2]. It can be said, that about 2% up to 7% of the energy is lost at 6.78MHz. At 13.56MHz about 5% to 24% is lost.

Losses in Ferrite Material

Additionally losses occur in the ferrite core. These are losses caused by eddy currents so called hysteresis losses. These effects are analytically difficult to be described. Because of that, it is more practicable to use an approximation with real measurement results. A polynomial function is fitted to these measurement values. The measurements where done with a 2.5 mm x 10 mm ferrite rod that matches the requirements of the application.

Modelling of antenna coil

Now all loss effects are listed and the behaviour of the used antenna coil can be investigated. It is possible to build a modell that describes the dependences between the physical parameters inductance, frequency and loss resistance. All mathematical expressions and the fitting function where included into a Matlab [8] function. Figure 8 shows the result. The z-axis represents

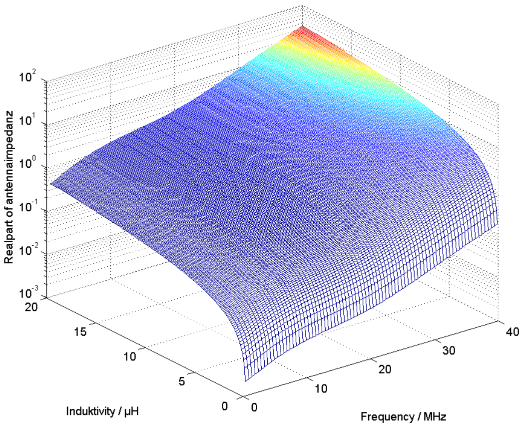

Fig. 8. Modell of the used transponder antenna

the loss resistor. The x-axis is the inductance and y-axis the frequency. For all frequencies and inductivities, the loss resistance is known yet. With this modell and the formula 1, it is possible to do an optimisation. This is done in the following section.

4. OPTIMISATION, CONSTRUCTION AND PRACTICAL VERIFICATION

With the help of the formula derived from the equivalent circuit in section 2 and the models derived in section 3, an optimisation of an implantable antenna coil is possible. With measurements on realized antenna coils inserted into a phantom fluid, the theoretical results are verified.

Geometrical parameters like core length and diameter are limited by the implantation technique. Hence, the number of windings respectively the inductance is optimised. By taking a look at formula 1, it can be seen, that the voltage at the load has a non linear dependence of the inductance. The inductance respectively the number of windings, is searched, for which the voltage is maximal. All voltage values were calculated with an field strength typical for the application. Figure 9 show the results. The reachable voltages at a load of $50k\Omega$ at 6.78MHz are displayed, for inductances from $100nH$ to $20\mu H$. The crossed curve shows the measurement results. The optimal inductance is $4\mu H$. This value is reached with 20 windings. Figure 10 shows a realized antenna. It was build with a 0.15 mm cupper wire on a 1.5mm x 8mm ferrite rod.

Now feasibility of an antenna coil with these parameters should be validated by taking care of stray capacity. By taking a look at figure 7 it can be stated, that this antenna coil is usable for frequencies up to 15MHz.

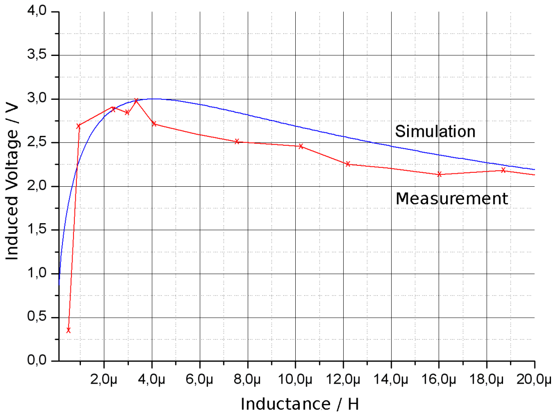

Fig. 9. Equivalent circuit of implanted antenna coil

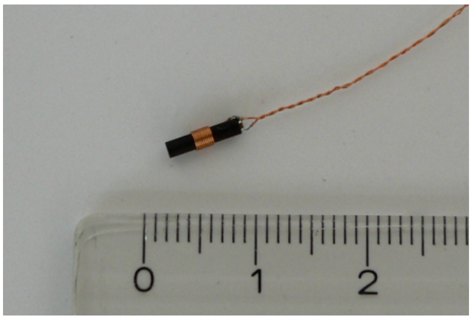

Fig. 10. Realized transponder antenna

The resonant frequency and the effective inductance were measured with a networkanalyser and an LCR-meter. For this, an antenna coil was build with 20 windings on a 1.5mm x 10mm ferrite core. To simulate the influence of the human tissue, the antenna coil was placed inside a phantom fluid. This fluid was prepared following a recipe described in [9]. The dc inductance of the builded antenna coil is about $4\mu H$. The measurements where done at 6.78MHz.

	Air	**Encaps**	**Phantom**
Permittivity	1	2.69	12.54
Measured Ind.	$5,7\mu H$	$5,9\mu H$	$6,3\mu H$
Self Resontantf.	$58MHz$	$46MHz$	$13MHz$

Table 1. Determination of self resonant frequency by measurements

Table 1 shows the results. The measurements show a rise of the measurable inductance for materials with higher permittivities. As discussed in the theoretical part, the measurable inductance increases. The self resonant frequency drops down to 13MHz if the antenna is placed inside the phantom fluid. The stray capacity is proportional to the permittivity. The capacitance should rise in the same manner. The self resonant frequency drops from 58 MHz to 46 MHz. This corresponse to an increase of the capacitance of the factor

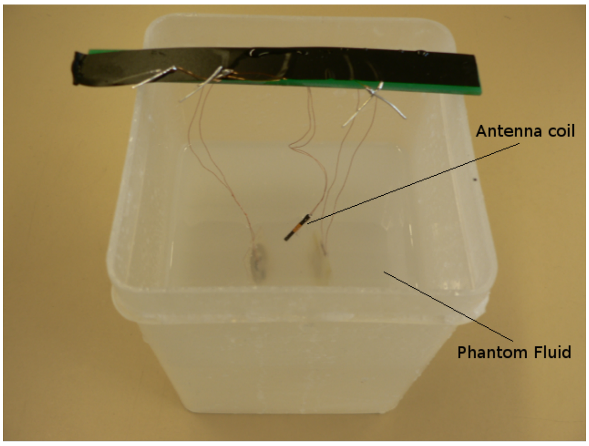

Fig. 11. Measurement of antenna coil with phantom fluid

1.6. The permittivity of silicone is specified with 2,69. Inside the phantom fluid, the self resonant drops additionally around a factor of 12.52. The permittiviy of the fluid is about 12.54.

5. CONCLUSION

With the help of a mathematical expression, derived from an equivalent circuit of the transmission channel, an optimisation of an antenna coil was performed. Loss effects were considered by a developed model. The influence of the encapsulation and the human tissue to the stray capacity was analysed. For the presented application, a ferrite coil with 20 windings is an optimal choice. Usability was validated by determining the self resonant frequency. Practical measurements verified the influence of encapsulation and human tissue.

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