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Design and Analysis of a Transcutaneous Telemetry Device for Brain Stimulator

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Abstract—**This paper proposes a transcutaneous bidirectional telemetry solution using resonant electromagnetic coupling and pulse interval modulation for low power loss and high performance in neuro-stimulator. The resonant electromagnetic coupling model is established on the base of resonance electromagnetism theory, and relationships between coupling coefficient, displacement tolerance, resonance frequency and telemetry distance are studied experimentally. One air-core coil is used as a time-shared transmitter and receiver antenna for controller, and one ferrite-core coil is used as the counter part for implantable device, which decreases the volume of the implantable part. Experiments verified that the average power consumption was about 33 uW for implantable part in this device under the testing condition of over 10cm telemetry distance between the implantable part in titanium container and controller. Simultaneously, telemetry device is with good displacement tolerance.**

I. Introduction

MORE and more intellectualized implantable medical devices are clinically applied, e.g. cardiac pacemakers and neuro-stimulators such as brain stimulator. Transcutaneous wireless telemetry is a key technology for programmable and controllable implantable medical devices.

Electromagnetic coupling between coils is often used for data exchange between implantable medical device and out-body controller. N. de N. Donaldson[1] presented the theory analysis of magnetic coupling resonant coils in transcutaneous data transfer, that was further studied in reference [2] and [3] , but the above studies are based on air-core coils and the maximal telemetry distance is 4cm usually. The power consumption is not low enough usually. In this paper, ferrite-core coil is used in implantable telemetry part and the telemetry distance is nearly 20cm that is convenient to animal telemetry experiment and further clinical application. For air-core coil, ${d_1}^2 = d_2^2 + 4D^2$ (d_1 is diameter of outside coil, d_2 is diameter of inner coil and D is maximal telemetry distance) is usually used in describing the relationship between coil diameters and maximal telemetry distance[1,4]. The result in our design is far better than above formula, with low power consumption at the same time.

Based on above analyses, a telemetry device solution is presented for low power loss and good telemetry performance, in which resonant electromagnetic coupling is the key of the whole design realizing and studied with emphasis in this paper.

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II. Outline of the Device

Shown in Fig.1 is the circuit architecture of telemetry device. It mainly consists of PDA, external controller and implanted telemetry part.

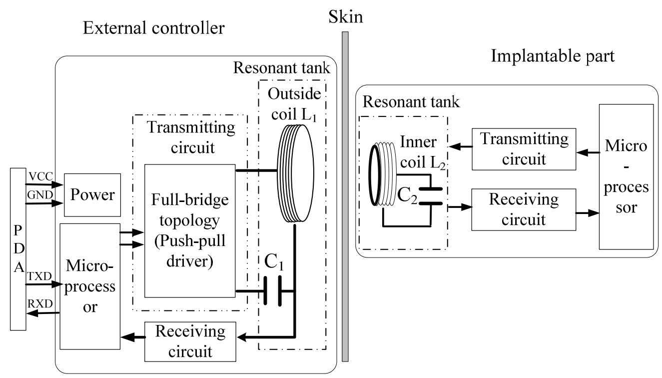

Fig. 1. Telemetry circuit architecture.

The key telemetry parts are two sets of coils, one is mounted in out-body external controller (called outside coil) and the other is located in implantable device (called inner coil). That is, this bidirectional telemetry device employs a resonant electromagnetic coupling to transfer data transcutaneously and wirelessly.

The controller mainly consists of microprocessor, transmitting circuit, receiving circuit and resonant tank (outside air-core coil L_1 and C_1), as shown in Fig.1. Similarly, implantable telemetry part mainly consists of microprocessor, transmitting circuit, receiving circuit and resonant tank (inner ferrite-core coil L_2 and C_2). The controller was powered by the +5V power of PDA USB bus.

For controller, the microprocessor is used time-sharedly in transmitting coding or receiving decoding during bidirectional telemetry, and the situation is the same for microprocessor in implantable telemetry part.

For controller, the resonant tank is used time-shared in transmitting and receiving signal for volume saving. And, the situation is the same for resonant tank in implantable part.

A high efficiency full-bridge topology with push-pull driver is used in transmitting circuit of controller, as shown in Fig.1.

A pulse interval modulation scheme has been adopted for power saving and simplified data coding and decoding during telemetry.

III. Theory Analysis of Resonant Electromagnetic Coupling

The main issue that we focus on in this section is to find how to improve the telemetry performance. Resonant electromagnetic coupling relationship is studied in detail.

Fig.2 represents equivalent circuit of telemetry device. As shown in Fig.2, L_1 is inductance of outside coil, L_2 is inductance of inner coil, R_1 mainly includes outside coil resistor and MOSFET Rds(on) of full-bridge topology, R_2 is inner coil resistor and R_L is equivalent load resistor. R_T ,C_T and L_T is the equivalent circuit of titanium container.

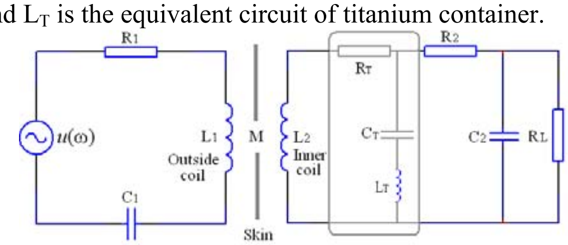

Fig. 2. Equivalent circuit used in the experiment.

A sinusoidal voltage source $u(\omega)$ is used to instead of actual square wave source in theory analysis due to the filtering of resonant tank [1].

LC resonant circuit is expressed generally by the equation:

$$\frac{d^2u}{dt^2}+\omega_0^2\cdot u=0 \tag{1}$$

Where ω_0 is resonant angular frequency.

The uncoupled first-order differential equations, by defining the complex variables, $a_{\pm}=\sqrt{\frac{C}{2}}(u\pm j\sqrt{\frac{L}{C}}i)$ [5]:

$$\begin{aligned}\frac{da_+}{dt}&=j\omega_0 a_+\\ \frac{da_-}{dt}&=-j\omega_0 a_-\end{aligned} \tag{2}$$

To understand the meaning of amplitudes a_+ and a_-, $|a_+|^2=\frac{C}{2}|V|^2=W$, where V is the peak amplitude.

So, coupling of two resonator modes can be expressed by:

$$\begin{aligned}\frac{da_1}{dt}&=-j(\omega_1-j\Gamma_1)a_1+\kappa\cdot a_2\\ \frac{da_2}{dt}&=-j(\omega_2-j\Gamma_2)a_2+\kappa\cdot a_1\end{aligned} \tag{3}$$

where $\omega_{1,2}$ is the resonant angular frequency of outside coil and inner coil respectively. $\Gamma_{1,2}=R_{1,2}/2L_{1,2}=\omega/2Q$, is the delay rate due to loss, κ is coupling coefficient[6].

The efficiency η for two resonant coils can be expressed by equation (4):

$$\begin{aligned}\eta&=\frac{\Gamma_L|a_2|^2}{\Gamma_1|a_1|^2+(\Gamma_2+\Gamma_L)|a_2|^2}\\ &=\frac{\frac{\Gamma_L}{\Gamma_2}\cdot\frac{1}{\Gamma_1\Gamma_2}}{\left[(1+\frac{\Gamma_L}{\Gamma_2})\cdot\frac{1}{\Gamma_1\Gamma_2}\right]+\left[(1+\frac{\Gamma_L}{\Gamma_2})^2\cdot\frac{1}{\kappa^2}\right]}\end{aligned} \tag{4}$$

where, Γ_L is the delay rate with R_L. Γ_L can be thought as constant value because R_L varies little in the designed telemetry device.

η would increase with increasing κ from equation (4). It is easy to know that κ is a key factor to efficiency η in this telemetry device, in which Γ_L, Γ_1 and Γ_2 remain constant with a certain outside coil and inner coil combination.

Higher efficiency η means the increased maximal telemetry distance at a certain transmitting power.

According to equation (3), matching between ω_1 and ω_2 influences κ greatly when Γ_1 and Γ_2 remaining constant.

R_T, C_T and L_T is the equivalent circuit of titanium container, being essentially equal to increasing R_2 and C_2 and decreasing L_2, which results to increasing Γ_2, so η decreases according to equation(4). Once carrier frequency and titanium container thickness remain constant, the titanium container's influence to η is sure. Titanium container would make the maximal telemetry distance shorter.

IV. Results and Discussion of Resonant Electromagnetic Coupling

A prototype device has been built and tested to verify the telemetry functionality. This section focuses on the experimental study for electromagnetic coupling rules between coils in brain stimulator application.

A. *Relationship Between Coupling Coefficient κ and Telemetry Distance*

The experimental parameters of outside and inner coils are shown in Table. I.

TABLE I
COIL SPECIFICATIONS

Parameters	Outside coil (columned shape)			Inner coil (columned shape)
	Outside coil1	Outside coil2	Outside coil3	Inner coil1
Average diameter	56 mm	50 mm	84 mm	3.8 mm
Minimal diameter	53 mm	48 mm	80 mm	2.6 mm
Maximal diameter	59 mm	52 mm	88 mm	5 mm
Thickness	3 mm	4 mm	3 mm	3 mm
Number of turns	18	21	14	150
Inductance	33μH	33.4μH	34.3μH	560μH
Equivalent series Resistance	0.94	0.966	0.5	7.5
Core type	air-core	air-core	air-core	ferrite -core

Measured relationships between coupling coefficient κ and telemetry distance for several given combinations of outside coils and inner coil are shown in Fig.3 and Table II. Inner coil and outside coil are aligned coaxially. The power on transmitting coil and load on receiving coil remains constant during experiment.

Coupling coefficient κ is calculated according to $\kappa = M/\sqrt{L_1 \cdot L_2}$, in which mutual coefficient M is measured using the method shown in reference [7].

From Fig.3, coupling coefficient κ decreases with the increasing telemetry distance. At a certain telemetry distance, larger outside coil diameter results in higher κ at certain distance due to the increasing coupling area, and the maximal telemetry distance increases corresponding to coil diameter increasing, as shown in Table II.

So, improving coupling coefficient κ benefits maximal telemetry distance, which is consistent with theory analysis.

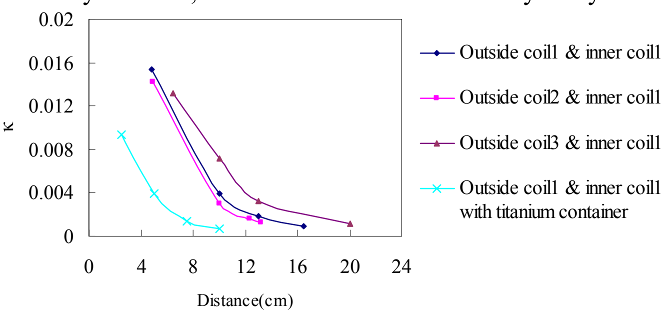

Fig. 3. Coupling coefficient κ versus transcutanous bidirectional telemetry distance for coils which are aligned coaxially.

TABLE II
MAXIMAL TELEMETRY DISTANCE

Parameters	Outside coil1	Outside coil2	Outside coil3
Maximal telemetry distance	17 cm	13.8 cm	21 cm

Compared with the situation without titanium container, the coupling coefficient κ with titanium container decreases 25.96% and 17.72% at 5cm and 10cm telemetry distance respectively, which makes maximal telemetry distance decreased from 17cm to 11cm for outside coil1 and inner coil1 combination.

Experiment was also carried out to find out the relationship between efficiency and telemetry distance, the result is shown as Fig.4.

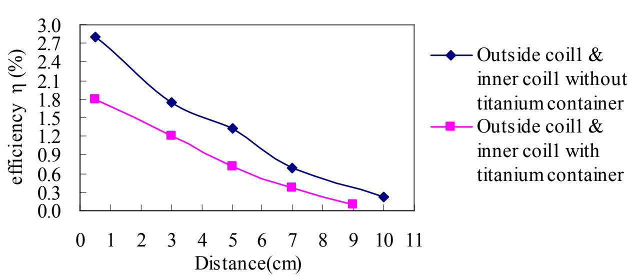

Fig. 4. Efficiency according to variation of telemetry distance

B. Displacement Tolerance Experiment

Comparison of experimental value for κ as a function of the transcutaneous bidirectional telemetry distance when outside coil and inner coil are aligned coaxially and when outside coil is rotated by 45 degree with respect to coaxial alignment is shown in Fig.5. Fig. 5 shows the experiments with titanium container and without titanium container.

From Fig.5, the κ decreases less than 10% when outside coil is rotated by 45 degree compared with coaxial alignment, no matter with titanium container or not.

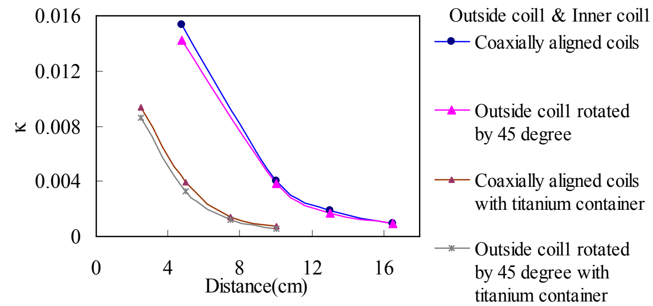

Fig. 5. Experimental value for κ as a function of the distance between when coaxially aligned outside coil and inner coil & when outside coil rotated by 45 degree with respect to coaxial alignment with titanium container and not.

Experimental coupling coefficient κ against transcutanous bidirectional telemetry distance with different radial distance for coils which are aligned coaxially with titanium container is shown in Fig.6.

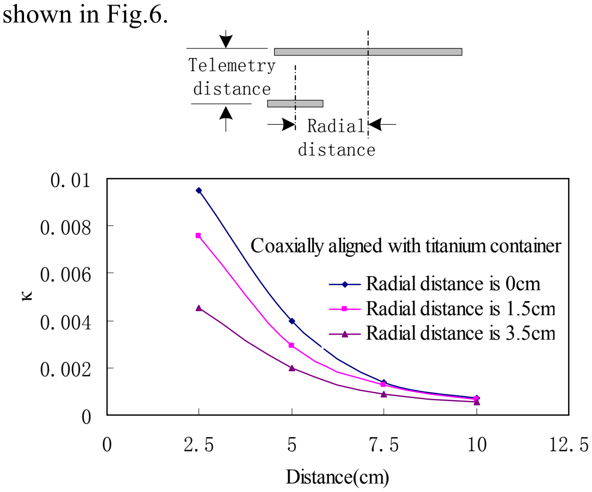

Fig. 6. Coupling coefficient κ against transcutanous bidirectional telemetry distance with different radial distance with respect to coaxial alignment for coils which are aligned coaxially with titanium container.

From Fig.6, Coupling coefficient κ decreases with the increasing of radial distance (with respect to coaxial alignment) at a certain telemetry distance.

The measured relationships between radial distance and telemetry distance for coils combination aligned coaxially are shown in Fig.7.

The experimental data in Fig.7 can be expressed as following equation in this paper:

$$y = -a(x-b) \qquad (5)$$

where x is telemetry distance, and y is radial distance. The a is 0.78, 0.7 and 0.58 respectively for the upper three curves, and b, the corresponding maximal telemetry distance, is about 20 without titanium container as shown in Fig. 6. The reliable telemetry area consists of x axial, y axial and corresponding experimental curve in Fig.7, such as the shadow for outside coil1 and inner coil1 with titanium container.

From Fig.7, the radial telemetry distance increases with the decreasing telemetry distance. The conclusion is also suitable to the situation with titanium container, as shown in Fig.7.

From above experiment, the designed coils are with good displacement tolerance. Larger the maximal telemetry distance, better the displacement tolerance at a certain telemetry distance. So, strong anti-displacement performance (namely good displacement tolerance) of coils at a certain telemetry distance can be obtained by increasing maximal telemetry distance, namely increasing κ.

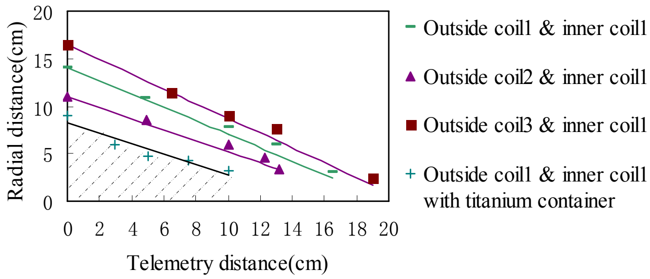

Fig. 7. Telemetry distance against radial distance for coils which are aligned coaxially.

C. *Relationship Between Telemetry Distance and frequency*

According to equation (3), match of ω_1 and ω_2 influences κ greatly. Relationship between frequency and maximal telemetry distance with titanium container or not is tested, and coil size, power on transmitting coil and load on receiving coil remain constant during experiment. The results are shown in Table III.

TABLE III
RELATION BETWEEN RESONANT FREQUENCY AND MAXIMAL TELEMETRY DISTANCE (OUTSIDE COIL1 AND INNER COIL1 COMBINATION IN TABLE. I.)

Inner resonant frequency	Outside resonant frequency	Maximal telemetry distance without titanium container	Maximal telemetry distance with titanium container
142.1 kHz	152.4 kHz	17 cm	11 cm
142.1 kHz	166.5 kHz	15.6 cm	10.1 cm
142.1 kHz	175.2 kHz	15 cm	9.6 cm
142.1 kHz	122.3 kHz	9.8 cm	6.5 cm
142.1 kHz	118.2 kHz	8.9 cm	5.9 cm

From Table III, when ω_1 and ω_2 is close, the value of maximal telemetry distance is maximum, which is consistent with theory analysis.

V. DEVICE VERIFICATION

The average power consumption of brain stimulator device (implanted part) during telemetry is less than 33μW under all experiments in this paper. Because the telemetry power consumption is low and pulsed, we measured the average power consumption of the circuit during telemetry and during telemetry stop respectively, then calculation.

Adult male rhesus monkeys weighting 9~11kg were used throughout the experiments. They were housed collectively in cages under controlled environmental conditions (20~22ºC) before experiment, with free access to food and water. All animal treatments were performed in strict accordance with the Capital Medical University Guide for the Care and Use of Laboratory Animals.

Hemiparkinsonism rhesus monkey model was established by MPTP injected in net artery at the qualified laboratory at Tiantan Hospital of Capital Medical University with the permission of animal trials, and then brain stimulator with titanium container was implanted in the back of rhesus monkey connected by extension and lead for Parkinson disease treatment. The implantation process was according to clinical surgery.

One week after implantation, the stimulation was started, and all tests of neuro-stimulation were carried out successfully. The telemetry experiment carried out, in which bidirectional telemetry distance was about 8.5cm. And over three months telemetry was done, which validated functionality and reliability of designed device.

VI. CONCLUSION

We have developed a transcutaneous bidirectional telemetry device for brain stimulator application. This device has the advantages of simple design and low power consumption. Electromagnetic coupling model between coils is set up, and rules are studied based on theory analysis and experiment. The relationship between coupled κ, frequency, displacement tolerance and telemetry distance is studied experimentally. Increasing κ was helpful to improve telemetry performance, including maximal telemetry distance and displacement tolerance. Matching of inner and external resonant frequency plays an important role in telemetry.

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