MEMS ANTENNA FOR WIRELESS BIOMEDICAL MICROSYSTEMS

Extremely Small Antenna for RF Receivers in Implantable Devices

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Abstract: This paper presents an extremely small antenna, together with its model, for wireless biomedical devices. Most of the implantable devices require very small dimensions. On way to achieve it is to use microtechnologies to obtain the required size reduction. One of the most challenging devices to integrate is the antenna, required if we want to communicate with the device trough a wireless link. The proposed antenna uses a MEMS structure to convert the incoming electromagnetic field into a voltage. This antenna allows the reception of signals using a carrier in the kHz range and uses only a chip area of 2x2 mm^2.

1 INTRODUCTION

Invasive and implantable biomedical devices used for diagnostic and therapy, ranging from neural prosthesis to video-capsule endoscopy (VCE) systems, are emerging innovative technologies and they are expected to originate significant business activity in the near future. The success of such systems is in part due to the advent of microtechnologies, which made possible the miniaturization of several sensors and actuators, as well their integration with readout and communication electronics.

Several people from all ages suffer from incontinence or other urinary pathologies. The bladder and the intestines perform their function in an autonomous way, independently from the individual will. However, any disorder in the healthy behavior leads to the problem of urinary incontinence, bladder infections, low bladder capability and fecal incontinency.

The healthy working of the urinary tract is essential for health and well being in general, and even more critical for patients with lesions in the spinal cord. In this situation, catheters are commonly used to control the daily volume of urine inside the bladder. However, the complications related to the use of catheters, together with the fact that, most of the times, the spinal segments which controls the bladder are intact, are driving the development of several devices to improve the control the inferior urinary system (Gaunt and Prochazka, 2005).

The new biomedical devices offer the possibility of improved quality of life, as well cost savings associated with health care services. However, one open challenge is to communicate to and from a biomedical device placed inside the human body with devices outside the human body. The lack of antennas, small enough to be integrated with the sensing microsystem, is a difficult task to overcome because such communications must be made at relatively low frequencies, due to live tissue signal attenuation (Kitchen, 1993). The straightforward solution is to increase the devices size to dimensions where it becomes possible to integrate an antenna. Up to now solutions, use conventional antennas together with miniaturization techniques to achieve the smallest antennas possible. However, the size of such devices is usually limited by the antenna and, is some cases, also by the batteries size.

In this paper, it is first discussed the need for small wireless biomedical devices, paying special attention to patients suffering from urinary

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pathologies. Afterwards, MEMS structures, previously used for non-conventional front-ends, will be introduced and investigated, having in mind the new application. The MEMS structure will be modeled when operating as an antenna.

2 IMPLANTABLE DEVICE

In patients with spinal cord injury at a level that leaves the sacral segments intact, detrusor hyperreflexia and detrusor sphincter dyssynergia (DSD) develops after an initial phase of spinal shock. This type of bladder is responsible for important morbidity. The hyperreflexia impairs the reservoir function of the bladder and the DSD causes a high resistance against micturition. This results in reflex incontinence, recurrent urinary tract infection, and autonomic dysreflexia in high lesions and threatens these patients with renal failure.

All of these severe disturbances may be well managed by sacral deafferentation (SDAF) and implantation of an anterior root stimulator (SARS).

2.1 Electrical Stimulation

Fig. 1 shows the commonly adopted system architecture to control the inferior urinary system.

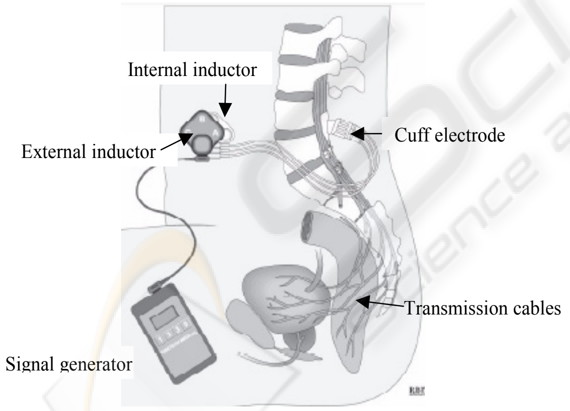

Figure 1: Schematic view of the overall system used for bladder control.

The system has a signal generator that generates the appropriate stimulus to activate, e.g., the bladder. That stimulus is transmitted to the external coil, which induces the signal in the internal coil. Reaching the biologic environment, a receiver module delivers the stimulus trough the transmission cables that carry the signal to the cuff electrode.

Since the internal coil is placed in the frontal region and the electrodes are in the back, the transmission cables must go through the body and are one main cause of system failure. Moreover, the existence of these cables requires a small opening in the duramater, not good for the spinal cord integrity. One main benefit of the microsystem approach is the possibility to avoid cables trespassing the duramater.

2.2 Anatomy of spinal cord

Fig. 2 shows the anatomy of the spinal cord. This is the place where the microsystem must be designed to operate.

Figure 2: Spinal cord cut, showing the region where the microdevice must be placed (1– intervertebral disk, 2- vertebral body, 3- duramater, 4– epidural space, 5- spinal medulla, 6- subarachnoid space).

From the figure we see that the microdevice must fit in a very small region, inside the duramater. It can be placed in two places, or in region 4 or in region 6. The best place is 6, the subarachnoid space, since the duramater can be totally closed after surgical intervention. The available space in region 6 varies between 3 mm and 9 mm [4]. This is room enough to accommodate a small microdevice.

The conventional surgical procedure requires the duramater opening to place the electrodes in contact with the sacral roots (Fig. 3).

The electrodes are connected to the leads coming from the stimulator, leaving a small opening in the duramater. As we can see from Fig. 3, there is plenty of room to place the microsystem in the implant region.

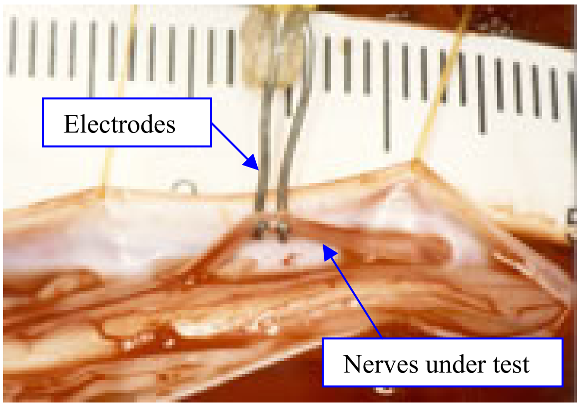

Figure 3: Placement of electrodes (testing the nerves to be used).

3 MICROSYSTEM

The need to reduce the failure associated with long wires that are used, to reduce the risk of infection or shifts in the wires is driving researchers to find a solution using microthecnologies. Also, and very important, is the internment period associated with the surgical intervention. Due to the highly invasive intervention that is required using the traditional technique, the patients, even when there are no complications, are required to stay a few days in the hospital. The availability of a device to allow a less invasive method would be more comfortable for the patient, reducing also the hospital costs associated to the surgery.

To make it possible to use, the device must be small enough to fit inside the spinal cord, it must be able to deliver the required stimulus (power and timing) and it must be possible to communicate with the device using a radio-frequency signal. This requires the use of a microsystem completely integrated, from sensors to communications, thus requiring the use of integrated antennas. Moreover, the antenna integration requires the availability of an electrically small antenna fabricated on materials compatible with the fabrication of integrated circuits. This integration requires the use MEMS techniques, like micromachining and wafer level packaging.

The microsystem must be designed taking into account the place where it will be required to operate because we cannot change the human body electrical system. As we saw, the human body anatomy will place constrains on available room for the microdevice, on power required for system powering and/or telemetry, and on required power for stimulation.

The final device to implant must not fail during its lifetime, must be stable and must be biocompatible (citotoxity, sensibilization, genotoxity, chronic toxity, carciginosity, and intracutaneous irritation).

3.1 CMOS Microsystem

The most suitable technology to implement the microsystem is the CMOS technology. It is the cheapest technology, with low power consumption, and adequate for this device since there are no high power delivery requirements.

In face of constrains, we have three solutions to design the microsystem. One is to design a chip, which acts only as a stimulus converter. The second option is to implement a full microsystem, with the ability to be remotely powered and controlled (Piella, 2001). The third is to use a microsystem with local power and a wireless receiver (Carmo *et al.*, 2006). The first solution is the simplest, however the second and third are more flexible and, despite its higher complexity, fit in the available room for implant. The main drawback of third solution is the need of a local source of energy, battery or energy harvesting.

3.2 Wireless link

Antenna integration is a hard task to accomplish since it requires joining the knowledge from antennas, microwaves, circuit design, and materials. Moreover, the on-chip antenna integration requires an electrically small antenna, due to wafer cost and devices size constrains, and operating on a substrate that was not initially intended for that purpose (Mendes and Correia, 2007).

Despite it is used to transmit data or to power the device, it is necessary to have a wireless link operating at one frequency. As is well known, the human body shows higher attenuation to higher frequencies. This means that, the lower the frequency, the higher the power we receive in the implant. Moreover, the attenuation is highly dependent on water content in tissues. The water content depends on the type of tissue and part of the body.

Micro-Electro-Mechanical Systems (MEMS) are becoming an available option for RF communication systems since they can offer, simultaneously, devices with improved performance and they use IC-compatible materials, allowing their integration in a silicon chip, side by side with semiconductor circuits. Up to now, MEMS have been used for antenna applications to obtain non-conventional front-ends with improved, or new characteristics. However, some preliminary tests have shown that some MEMS structures could have the ability to operate as an antenna itself and this solution would have the potential to be smaller than the conventional antennas.

The basic principle of micromachined cantilevers offers an interesting possibility to measure a variety of physical parameters (Lange *et al.*, 2002). When used as a sensor, a MEMS structure requires the use of a sensing mechanism and the most widely used is the capacitive method. The moving structure, and a fixed plate, forms a parallel plate capacitor, where the structure movement is translated into a capacity change.

4 MEMS ANTENNA

4.1 Cantilever Antenna

The U-shaped cantilever, proposed to detect a time-varying magnetic field, is presented in Fig. 4.

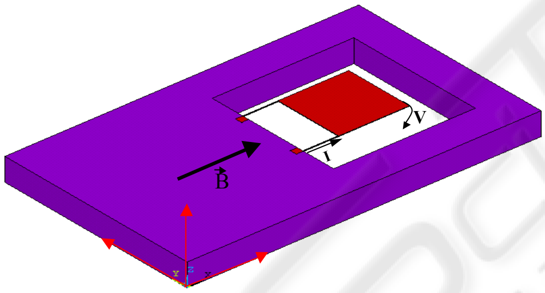

Figure 4: Cantilever used to detect a time-varying magnetic field.

To measure magnetic fields with cantilever structures, the Lorentz-force is used on a current carrying lead (Keplinger, 2004). A cantilever of this type measures only the magnetic flux density in the direction parallel to the arms of the cantilever, i. e., x-axis of Fig. 4. The Lorentz-force acting on a lead is used to bend a micromachined cantilever. Deflections, which are small compared to the length of the cantilever, are a directly proportional measure of the applied force. To reach the highest possible sensitivity it is advisable to use a resonant mechanism, where the cantilever is excited by an AC current with a frequency equal to an eigen-frequency of the elastic structure. Due to the high quality factors of Si structures, which are at least several hundred, this is an efficient way to enhance the sensitivity.

Electromagnetic field can be sensed using an optical, capacitive, or piezoelectric sensing solution. The most attractive options are capacitive and piezoelectric. These solutions can be easily integrated with the MEMS structure and have the potential for low power consumption (except the optical solution). Since the desirable displacement depends on structure dimensions and material properties, electrostatic actuation can be used as the actuation mechanism for MEMS micro-antennas. However, if large displacements are required or if the MEMS structure area becomes too small for capacitive detection, the use of a piezoelectric material can be the solution since it can act both as sensor and actuator. Moreover, the operation is only voltage based, leading to low power driving operation. Furthermore, it produces a voltage in response to a deflection leading to simple readout electronics.

4.2 Antenna Packaging

Fig. 5 shows a solution to integrate the proposed antenna structure. It consists of three stacked wafers, where the bottom wafer is used to place the reading and controlling electronics, the middle wafer is used to implement the U-shaped cantilever, and the bottom wafer encapsulates the device, enabling a very small microsystem with integrated antenna.

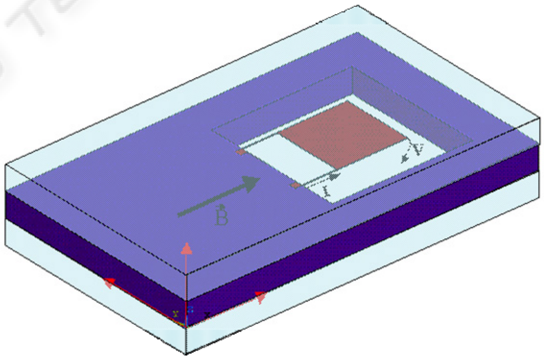

Figure 5: Use of WLCSP to integrate the proposed MEMS antenna.

4.3 Antenna Modelling

The proposed MEMS structures were engineered to have the desired electrical and geometrical properties, as well the requirements to be used in a post-process module compatible with integrated circuit (IC) fabrication.

Fig. 6 shows the 3D FEM (finite element modelling) model being used to analyse the receiving properties for a cantilever operating as an antenna. FEM modelling is a very powerful technique to predict the interaction between different domains (electrical, mechanical, and electromagnetic).

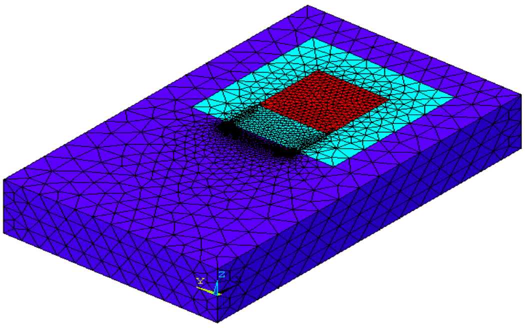

Figure 6: Model of structure used to sense the electromagnetic field.

However, it is also very time consuming and, in this case, very complex to set up a simulation and get data we can rely on it. In this way, a simple model was derived to understand the requirements and potentials of a structure like this one, if operated as an antenna.

4.4 Modulation Modelling

Considering the structure proposed in Fig. 4, we can represent it using the simplified model of Fig. 7. The electrical behaviour is modelled by the beam of length L and the current I, whereas the mechanical behaviour can be described using the spring k.

Considering that the magnetic field, B, is applied perpendicularly to the current I, trough the length L, the resulting Lorentz force, F_L, will be given by:

$$F_L = (B \times I)L \tag{1}$$

The MEMS structure will move when the Lorentz force becomes higher then the elastic force (Rocha *et al.*, 2004).

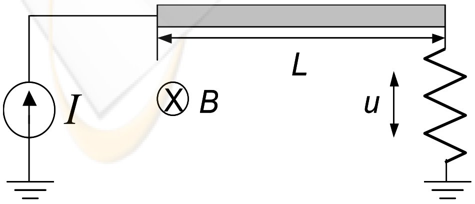

Figure 7: Simplified model of a cantilever operating as an antenna.

Due to the applied force F_L, the structure will move, and the following equation can be written:

$$F_L = (B \times I)L = ku = F_e \tag{2}$$

where F_e stands for elastic force, u for displacement and k is the spring constant of the structure. From the previous equation, we can find the displacement:

$$u = \frac{(B \times I)L}{k} \tag{3}$$

Independent of the detection method, optical or capacitive, the displacement will give origin to a received voltage, V_R, which will be proportional to the applied magnetic field, B.

$$V_R \propto u \propto B \tag{4}$$

If the magnetic field was originated by a modulated signal:

$$B(t) = A(t)\cos(2\pi f(t) + \phi(t)) \tag{5}$$

the received voltage will be:

$$V_R(t) = G\frac{LI}{k}A(t)\cos(2\pi f(t) + \phi(t)) \tag{6}$$

where G represent the system gain.

4.5 Antenna Analysis

From equation 6 it is possible to conclude that the proposed device will actuate as a signal receiver if the spectral properties of the modulated signal are chosen to fall inside the device operating frequency limit.

The first parameter requiring analysis is the force such a structure can produce when in presence of a magnetic field. From equation 2, if we consider I = 100 mA, L = 1,1 mm and B = 10 mT, then the resulting force will be 1.1 µN. This is enough force to produce movement in this kind of structure.

A key advantage of this solution is that it can deliver gain trough the increase of the current I. If the resistivity of the beam material is kept low, then we can have a low power device, since the voltage drop will be small.

The other requirement is that the modulation type must be selected carefully. Even if the modulating signal bandwidth is inside the MEMS device bandwidth, if we chose, e.g., FSK, the resulting bandwidth may be outside the structure bandwidth due to the instantaneous required frequency shifts. In this way, a continuous modulating method must be used instead.

To check the ability to operate as a radiating element, some preliminary tests were also conducted, where it was used a scaled model of the proposed structure. A commercially available magnetic sensor was connected to a signal acquisition board that was connected to a personal computer. A current was injected into a scaled structure of Fig. 4, and the signal was recorded with the magnetic sensor. When the transmitting structure was oscillating at 100 KHz, it was possible to easily detect that signal with the magnetic sensor.

5 CONCLUSIONS

This paper described the design, and modelling of chip-size MEMS antennas for short-range wireless microsystems. These antennas allow the fabrication of an implantable microsystem with integrated wireless communications. The antenna integration is based on wafer-level packaging techniques, which enables the integration of new materials with the standard silicon processing steps, as well the fabrication of complex three-dimensional structures, in an economically acceptable way.

MEMS were explored as a new solution to obtain structures that can sense electromagnetic fields. Thus, instead of having the need to design very advanced antenna structures to achieve antenna size reduction, the standard MEMS devices, e.g. cantilevers, will be used to save system space and improve system integration. A novel electrically very small antenna using MEMS structures, and a model to describe the operation of that structure; is presented.

The present solution envisions power saving, smaller volume, lower cost, and increased system lifetime, which are very important features in biomedical microsystems for diagnosis and therapy.

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REFERENCES

Carmo, J. P., Mendes, P..M., Couto, C., Correia, J.H., 2006, “5.7 GHz on-chip antenna/RF CMOS transceiver for wireless sensors network,” Journal Sensors and Actuators A, Elsevier Science, Vol. 132, pp. 47-51,

Gaunt, R. A, and Prochazka, A., 2005, “Control of urinary bladder function with devices: successes and failures,” Progress in Brain Research, Elsevier, Vol. 152, pp. 163-194.

Keplinger, F., Kvasnica, S., Jachimowicz, A., Kohl, F., Steurer, J., and Hauser, H., 2004, “Lorentz force based magnetic field sensor with optical readout,” *Sens. Actuators A,* 110, (1–3):112–118.

Kitchen, R, 1993, *RF Radiation Safety Handbook*, Butterworth-Heinemann.

Lange, D., Brand, O., and Baltes, H., 2002, *CMOS Cantilever Sensor Systems: Atomic Force Microscopy and Gas Sensing Applications*., Springer.

Mendes, P. .M., and Coreeia, J. H., 2007, "MEMS Micro-Antennas for Wireless Biomedical Systems," in "Wireless Communications Research Trends", ISBN: 1-60021-674-9, 2007, edited by Tong S. Lee, Nova Publishers.

Piella, J. P., 2001, Energy management, wireless and system solutions for highly intregated implantable devices. PhD Thesis, Universitat Autónoma de Barcelona, Barcelona.

Rocha, L. A., Cretu, E., Wolffenbuttel, R. F. 2004, “Analysis and Analytical Modeling of Static Pull-In With Application to MEMS-Based Voltage Reference and Process Monitoring,” Journal Of Microelectromechanical Systems, Vol. 13, No. 2, pp. 342-354.