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ASIC-BASED BATTERYLESS IMPLANTABLE TELEMETRY MICROSYSTEM FOR RECORDING PURPOSES

J. Parramon[1], P. Doguet[2], D. Marin[1], M. Verleyssen[2], R. Muñoz[3], L. Leija[3], E. Valderrama[1]
[1]CNM-Barcelona, [2]UCL-Lovain la Neuve, [3]CINVESTAV-Mexico
parramon@cnm.es

Abstract. This paper presents an implantable *batteryless telemetric* microsystem for EMG recording, based on a single 30mm^2 high-voltage 2.5µm BiCMOS *ASIC*, which includes telemetric and two-channels recording circuits. It has been developed within the framework of an European project, where this device is implanted in rabbits for research studies related to control of prosthesis through muscular biosignals. Power is transferred with a 10MHz *inductive link* using an efficient Class-E driver. Data is transmitted bi-directionally reaching elevate bit-rates. Microimplant volume is about 1cm^3 (including power and transmitter coil) with an overall current consumption of 4,5mA. Despite problems detected with the EMG recording circuitry a functional transcutaneous batteryless implantable telemetric system has been achieved successfully. Power and digital data communication results are presented through in-vitro and in-vivo experiments (in rabbits). A new improved version of the ASIC is under fabrication, thus for the EMBS'97 meeting EMG biosignals recorded through the presented telemetric device are expected.

INTRODUCTION

Implantable microsystems are nowadays of great interest in the biomedical research field. New microtechnologies permit to develop sophisticated electronic systems with very good performances in volume and power consumption. In conjunction with useful isolation materials, reliable long-term implantable microsystems can be achieved. On that point the inclusion of a wireless communication circuitry interfacing with the external world offers a wide range of advantages. The primary approach uses a wire connection which carries many problems related to infections and mechanical breakage's specially for long-term applications. A telemetry system permits to interact on-line with the internal unit without any skin damage, increasing the health-level of the patient which don't suffer of any discomfort. In such systems, power becomes critical when long-term applications are required. There are two main approaches for solving this: (1) to use a battery [1] or (2) to RF power the microsystem [2] [3]. Battery problems related to its life-time (change means surgical operation) and its volume make the second option very attractive. Main applications of implantable microsystems are centered in recording biosignals (EMG, neural, ...) or for stimulating not only muscles but also nerves, using several types of electrodes. The work here presented has been done in the framework of the ITUBR[1] project, which aims to develop an implantable device for telemeter muscle signals in order to control an artificial prosthesis via electromyographic signals. Miniaturization of the system requires microelectronics technologies. An integrated circuit containing telemetric and EMG recording circuits has been designed to join several passive elements in order to conform a hybrid microsystem totally implantable. Thus in this paper an overview of the work done is presented dealing meanly in the telemetric circuit, which permit to transmit digital data bi-directionally at the same time the implant is powered by RF.

METHODS

The ITUBR system is based on the following parts: (1) an internal unit formed by a telemetric part (IC and coils basically) and a recording part (sensor and IC) and (2) and external unit formed by a telemetric part (receiver and transmitter) and a data acquisition unit controlled by a PC. In order to save area (not only silicon but specially PCB bonding area due to the reduction of the number of pads) a unique chip has been designed with the telemetric (TC) and conditioning (CC) circuitry. Next picture shows a diagram of the ITUBR system.

External Unit: the DAta Processing Unit (DAPU) is based on

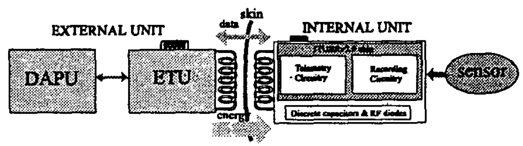

Fig. 1. ITUBR system block diagram

several programmable chips and a PC, interfacing between the user and the External Telemetric Unit (ETU). Currently in this version the connection between DAPU and ETU is not done by telemetry. But to give a reasonable level of portability this is something to do in future. Thus the power will become more critical (battery powered). The DAPU makes all the data treatment (codifier, decodifier, data storage, ..) and the ETU (close to the skin) only contains the minimum circuitry to operate in order to reduce power consumption and size. This unit contains a RF power and data transmitter and a receiver. The transmitter is based on a Class E driver [4]. This choice is

[1] ITUBR: Implantable Telemetry Unit for Biomedical Research is a #950917 INCO european project, leadered by the CNM (Barcelona) and acting as partners the CINVESTAV (Mexico), the UCL (Belgique), the CCC (Uruguay) and the ULA (Colombia)

due to its high efficiency (100% theoretically), its independence on power transistor drain-source capacitance and its easy modulation if an ASK modulation is requested. The carrier frequency has been fixed at 10MHz, higher than the usual for powering, in order to reach a high data rate, despite lower frequencies would be preferred to avoid a RF tissue absorption, to obtain more easily the optimum classE operating point as well as to decrease the frequency crosstalk with the on-chip transmitter carrier. The ETU also contains a 30MHz Binary Phase Shift Keying receiver to pick up the data coming from the implant.

Internal Unit: First an overview of the microsystem will be shown. Afterwards a more detailed explanation on the ASIC development will follow.

Microsystem design: The implant its based on a hybrid system where most of the circuits are integrated in an ASIC designed for the project. But additional passive SMD elements (big capacitors for fine regulation and RF diodes for rectifying) as well as the coils are required. Next figure shows a layout of

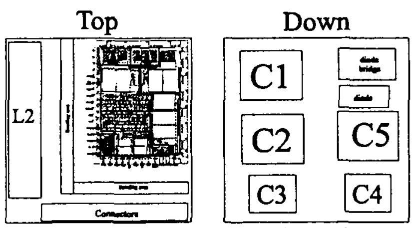

Fig. 2 Hybrid system PCB design

the double-sided PCB circuit. Final area is 1.09x1.09 cm^2. ASIC pads for only testing purposes (so no bonding to the PCB) are aligned together in two sides to reduce the bonding area on the card. In Top there's the chip, the transmitting magnetic-cored coil and the connectors to the electrodes. In Bottom the rest of SMD elements. The power coil can be fixed just over the board (within the silastic package) or if cross-talk problems are too important can be placed separately to the rest of the implant.

ASIC design:

Within the chip there are the telemetric and the application specific parts. This paper focuses on the chip telemetry circuits. Nevertheless some brief explanation about the EMG recording circuitry follows:

Recording circuitry: The global scheme of the conditioning circuitry is given below at figure 3. The *amplification part* consists of two channels. Each channel amplifies and filters the differential signal from a pair of electrodes implanted in muscles. These two channels are selected by sending control data from outside the body to the control unit of the conditioning circuitry. Choosing either one, two or no channels is possible. As the two channels can be selected, a time-multiplexing must be performed. The A/D conversion is performed in current mode, thus a previous VI converter is required. A final logic stage sends the required lines to the telemetric circuit.

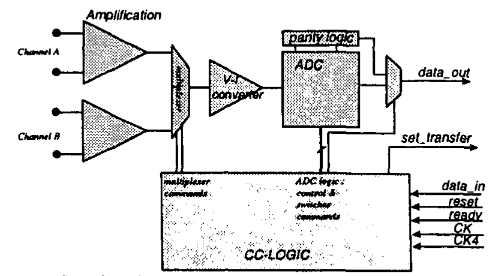

Fig. 3. Block diagram of the EMG circuitry.

Telemetric circuitry: The telemetric part is build on four main[2] blocks: (1) energy, (2) receiver, (3) transmitter and (4) control unit.

-Energy block: RF Power is transmitted through an inductive link formed by two coupled coils (one external and the other implanted). The amount of power transmitted and its efficiency depend mainly on the coupling factor (k) between both coils, which depend on the geometry and orientation of the inductors. Accurated power coils design has been done to optimize the mutual inductance [5] in the requested operating distance (10mm), for a given implanted coil diameter of 8mm. As shown in figure 4 a maximum in coupling appears approximately for an external coil of 25mm of diameter.

The IC receives a full-rectified secondary voltage and through a line regulator provides to the whole chip the supply voltage and several current references. A zener-based pre-regulator with an output voltage centered near 11.7V provides not only a pretty-stable input voltage to the final regulation step but also acts as an useful high-voltage protector, permitting secondary voltages up to 50V. Next there's the final bandgap-based regulator. A very low load-sensitive 5V regulator has been implemented. A high PSRR OpAmp supplies to the whole circuitry the 5V. Two supply lines are required in order to obtain a stable enough voltage for the analog recording circuitry. A 8 bits A/D converter working at 5V needs a 20mV maximum ripple of the supply. So a 5V power line supplies this critical part and the rest of the chip is fed through another 5V line. Additionally several current references have been implemented

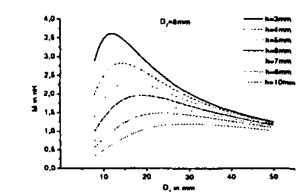

Fig. 4. Coupling vs geometries

-Receiver: Amplitude Shift Keying (ASK) has been the choice for modulating the RF carrier which at the same time powers the system. Thus an envelop detector is required to demodulate the signal. Filtering and schmitt-triggering the single diode input, one can obtain the envelop of the ac induced voltage. The design of this block has done taking care about the wide variation of receiver induced voltages that can

[2] Also a power-on reset with a 5μs time constant has been designed. No details on this paper.

be achieved, thus being able to demodulated for a reasonable range of modulation depths.

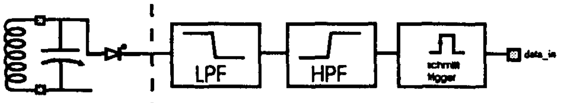

Fig. 5 ASK demodulator

-Transmitter block: The internal-to-external transmission is achieved by BPSK modulation (due to low sensibility to noise, easy modulation and not very difficult demodulation). Two dephased paths are commuted according to the modulator signal. Special effort on reducing the relative path delay has been done in order to obtain a clear π change of phase. The on-chip RF generator is obtained through a Class-B driver in a resonant parallel LC tuned circuit. The inductor is external but the capacitor is integrated with a value of 12pF. The RF electromagnetic-wave magnitude depends directly on the peak current through the coil. This value is a function of (1) the quality factor Q of the coil, (2) the dropping voltage through the LC and (3) the geometry of the current source transistor. Fixed the LC dropping voltage at 5V and considering a serial coil resistance near 50Ω's at 30MHz, one can obtain the relation between transistor geometry and the peak current through the coil. Two bits program the coil current. The on-chip 30MHz generator is produced by a seven-stages resetable CMOS ring oscillator. Despite this configuration cannot assure a very stable frequency the system is not so much sensitive to small variations on the base-clock. As the communication is asynchronous and the quality factor of the transmitter is not extremely high the use of a crystal quartz seems rather unnecessary.

-Control Unit block: Data flow is mainly from the internal to the external. The communication protocol behaves as follows in next diagram: the internal unit stands-by up to receiving an asynchronous reset signal; then decodes the next incoming eight bits, send them as an echo frame and afterwards starts to send indefinitely the recorded data including every 8 bytes a synchro byte. According to the established protocol, this unit will provide to CC (1) the input data properly decoded, (2) the reset signal, (3) the base-clock , (4) a four times faster clock and finally (5) a ready signal for starting the AD conversion. In it's turn the CC will send (1) the digitized recorded data for being sent to the outside and (2) the synchro-frame time-interval. Due to its reasonable complexity the semi-custom design has been carried out without using any synthesis tool. Logic simulation have been implemented through Verilog. Next follows the main modules of the control unit:

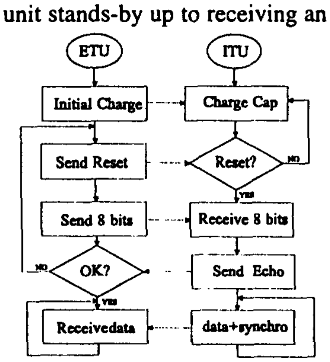

Fig 6. Protocol

i) Decoder: this circuit decodes the incoming envelop detected data according to the following codification criteria:
A return-to-zero pulse width modulation has been chosen. Using several 3.75MHz clocked counters on can derive if comes a '0' a '1' or a reset-init signal. Data is updated every negative edge of the demodulated line.

ii) Synchro adapter: this circuit converts the incoming ETU clocked data to a digital data synchronized with the internal on-chip oscillator using a serial-parallel load.

iii) Clock generator: all the internal unit is synchronized by a signal generated internally. The basic synchro signal is the same 30 MHz carrier frequency. For providing the required clock signals to the whole circuit, a six-stages clock divider has been designed, hence obtaining the 2-submultiples of 30MHz down to 234kHz.

iv) Coder: this circuit takes the digitized recorded data, codifies it and send it to the BPSK modulator, including the synchro frame. The bit rate can be programmed at 468kbps or 234kbps.

Top Design. The final chip design (including the EMG circuit) was completed with 22 bondpads. The final chip area is about 30 mm^2.

RESULTS

Next figure shows the ASIC already fabricated and tested. The overall consumption of the chip is about 4.5mA. But there is a dependence on the induced secondary voltage. The higher the input voltage the higher the current consumption in the regulator. With an internal power coil of 10mm of diameter and using an external coil of 20mm we are able to power the chip up to 15mm with no misalignment. This is enough for our application requirements (distances down to 10mm). Through the Bandgap regulator this chip gives an analog voltage supply of 4.97V and a digital supply of 4.99V. DC input voltage sensibility is very low (less than 1mV per Volt).

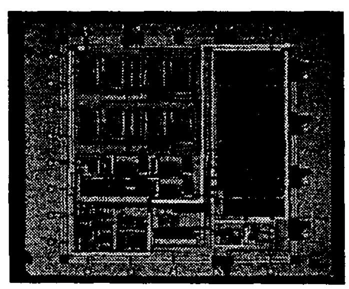

Fig. 7. ASIC microphotograph

Related to the data transmission, the InLink (data coming to the inside), next figure shows an oscilloscope waveform when sending a '11000100' frame to the implant at the same time the system was powered by RF and up to 15mm of ETU-ITU distance. *Line1* is the reset and the data knowledge for the EMG part. *Line2* is the data line once demodulated and decoded. And *data_out* is the line which modulates the 30MHz to send to the outside. Once the data comes in there is the echo transmission to the ETU. Afterwards the implant start to send recorded data including every eight bytes a synchro byte.

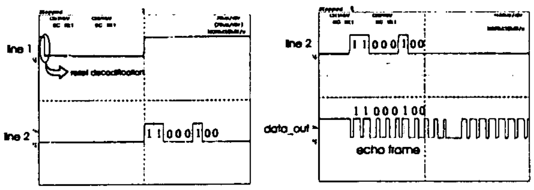

Fig. 8. Oscilloscope waveforms for InLink communication

OutLink transmission shows a problem related to the BPSK modulation, not permitting to use a 30MHz carrier frequency. As a consequence of that, *data_out* is the output of the modulator, which is the gate voltage of the NMOS driver. Every transition of this voltage defines a self-oscillation of the LC circuit that can be detected in the external receiver. Thus, communication up to 10mm has been achieved in this way and it's showed in the next picture. Left side there is the internal coil current and in the right side appears the received voltage in the external unit. Every transition in the data_out means a peak in the external received voltage. Due to the same 30MHz problem all the internal clocks have been divided by a factor two so the InLink bit rate is 120kbps and the OutLink bit rate can be programmed at 117kbs or 234kbps.

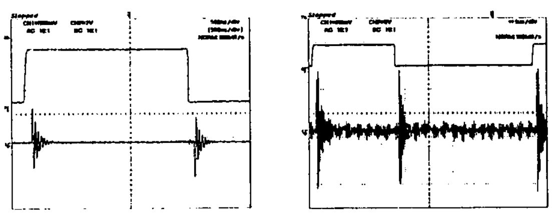

Fig 9. Oscilloscope waveforms for OutLink communication

Next photograph shows the implanted system used for in-vivo experiments related to the energy transmission at 10MHz carrier. In order to evaluate the induced secondary voltage versus distance range a wire-link connecting the implant and the external unit has been used. Left side of the photograph shows the cables going to the outside through the skin of the rabbit used in this evaluation implant; in the right side the $1cm^3$ silastic package containing the power and transmitter coil. The implant is positioned between the posterior cervical area and the skin. In this region a free movement of the rabbit is guaranteed and moreover through the use of a necklace containing the external unit a minimum coil to coil distance is assured. After two months of implantation the in-vivo power transference shows an slightly decrease of 15% of efficiency due to tissue absorption. These experiments proved the capability of powering the microsystem in the required range for the specific application.

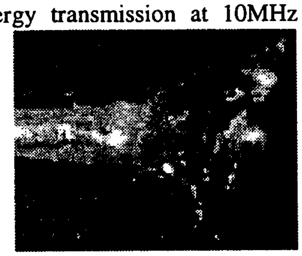

Fig. 10. Implant photograph

DISCUSSION

Once obtained the results here presented a new chip has been already designed and is currently on fabrication steps. This chip includes a new improved modulator which is programmable to several carrier frequencies (going from 20MHz to 40MHz) and an additional oscillator to provide the internal clock. Also it is possible to use the technique of transmitting burst of signals using the self-oscillation transitory current on the LC, offering a very high power efficiency (higher than 99%) in transmitting digital information. But only useful for these short-range (few mm's) communication systems, due to the decrease of S/N ratio with distance. Big effort will be held in future to increase the bit-rate (up to 1Mbps) and to improve the efficiency in power transference through the use of a close-loop control of the induced secondary voltage.

CONCLUSION

This paper has presented the work done within the ITUBR project for developing an implantable telemetric device. A first prototype containing an ASIC with telemetry and recording circuitry has been set up. Data and power transference from the external unit has been successfully achieved in the lab for the application range. Additional in-vivo studies of the energy transference have been done, showing good results. Despite a problem detected in the on-chip modulator, also the data transmission from the implant has been accomplished, but reducing the pretended bit rate in a factor by two. Anyway data rates of this link are considerably elevate. A new chip correcting the detected problems has been already designed and is currently in fabrication. For the EMBS meeting the final version of the microsystem packaged in silastic and with a total size of $1.1x1.1x0.7\ cm^3$ will be presented.

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