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A power and data front-end IC for biomedical monitoring systems

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ABSTRACT

To enable the evolution towards electronically assisted healthcare, future medical implants require sensors and processing circuitry to inform patient and doctor on the rehabilitation status. An important branch of systems are those where implant strain is monitored through strain gauges. Since batteries inside the human body are avoided as much as possible, a transcutaneous power link is used to wirelessly power the implant. The same RF link provides an elegant way of establishing bi-directional data communication between the external base station and the medical device. This paper describes a front-end IC that manages both power reception and bi-directional data communication. It has a clock generation circuit on board to drive additional digital processing circuits. A new architecture that uses a current driven data demodulation principle is introduced. It is able to detect an AM signal with modulation depth of a mere 4%, which is better than recent similar systems in the field. The IC is fabricated in a solid 0.35 μm HVCMOS technology and consumes only 0.56 mA.

1. Introduction

The ageing population has a strong impact on our future health care policy. On the basis of an unchanged pattern of care, the number of elderly in residential care homes and nursing homes is projected to rise by around 23% between 2000 and 2020. Most of this projected rise will occur in the second half of this period [1]. One way to cope with the increasing need for rehabilitation and increased demand for care is through e-health [2]. e-Health is generally defined as the improvement of health care through the use of electronics. By monitoring orthopaedic implants throughout the rehabilitation phase, doctors are able to tailor the program to a specific patient and shorten their hospital stay. Patients can return to their homes faster and still be under supervision, by means of IT (Information Technology).

These new types of medical (orthopaedic) implants, which form the basic motivation for the work in this paper, will host a sensing element, in many cases a strain gauge, and processing electronics. A typical processing chain consists of analog amplification, sensor calibration and A/D conversion. A digital block performs basic calculations to limit the overall data rate. The digital processor requires a stable digital clock signal, whose speed depends on the algorithm complexity. To avoid the use of batteries inside the human body, the electronics are inductively powered. An external coil is placed against the skin and transmits an electromagnetic field towards an implanted coil. The latter picks up the RF field and converts it into a stable DC voltage. To perform the necessary monitoring tasks, a data channel is implemented using LSK (Load Shift Keying), also known as absorption modulation. The internal coil is short-circuited, resulting in an impedance change, which is reflected as a change in voltage at the primary (external) coil. The use of LSK makes an extra antenna redundant thereby simplifying the system complexity [3]. After placing the implant, a calibration is performed to balance the strain gauge to a zero load condition. The commands are sent to the implant using a reliable AM (Amplitude Modulation) technique.

Fig. 1 depicts an overview of the medical monitoring architecture. This paper discusses the miniaturisation of the front-end circuitry which handles power reception, bi-directional data transfer and clock generation. The first section elaborates on the specific needs for the development of a biomedical IC, as this differs from classical requirements of analog designers. A section on transcutaneous power transfer focuses on RF carrier rectification and regulation towards a stable 3.3 V voltage. A subsequent section deals with data and clock modulation (and demodulation) techniques and introduces a novel architecture for AM demodulation. Finally the IC is experimentally verified and the results are discussed. The paper ends by summarising the major contributions to state-of-the-art biomedical systems.

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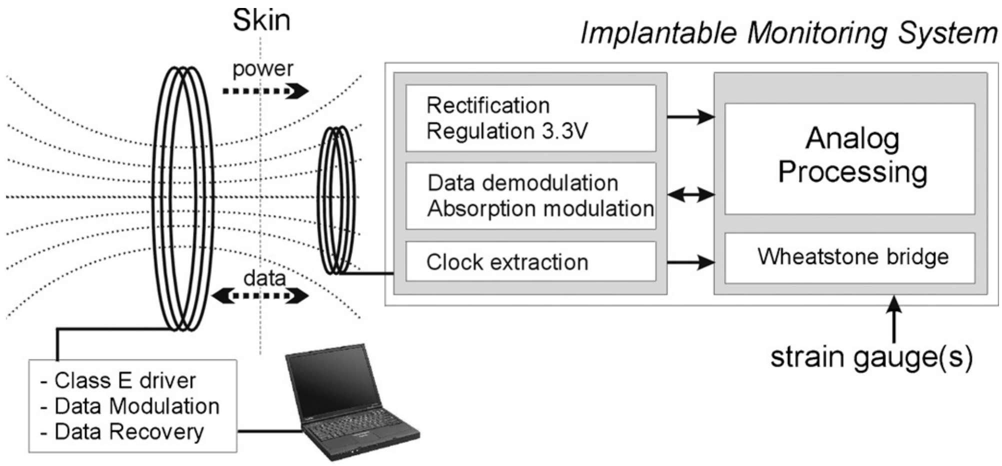

Fig. 1. Overview of the front-end IC as part of a medical monitoring architecture. A transcutaneous link powers the implantable electronics.

2. Technology choice

The first step in the design of an IC is the selection of the technology that will be used, as it has a great impact on design decisions throughout the rest of the process. While analog IC designers continuously strive to downscale the process in order to reduce overall dimensions (thus costs) and to increase operational speed, the opposite is true when designing a biomedical IC. The explanation is threefold:

- *Carrier frequency limitations*: in contrast to recent chips for use in high-speed data communication or ADC's [4], the maximum frequency is always limited by two factors. Firstly, digital processing requirements are moderate because of the typical low frequencies encountered in biomedical signals. Hence, these digital circuits do not require high-speed clocking. Secondly, analog data and power rectification is tailored to the RF carrier frequency, which is always below several MHz. The latter is a result of the fact that higher frequencies are not efficient for power transfer as the body absorbs too much energy [5]. Extremely fast technologies (180 nm, 90 nm or beyond) are not required.
- *Reliability*: while performance parameters determine the success of media devices such as the MP3 player of mobile phone, the medical market is strictly regulated and requires highly reliable products in a solid and mature technology to guarantee its operation at all times.
- *High voltage requirements*: Fig. 2 depicts a classical inductive link scheme where L_1 represents the primary coil and L_2 represents the implanted coil. The coupling factor between both is denoted as k. Eqs. (1) and (2) below are known as the link equations and give the relation between primary and secondary voltages and currents through the coils.

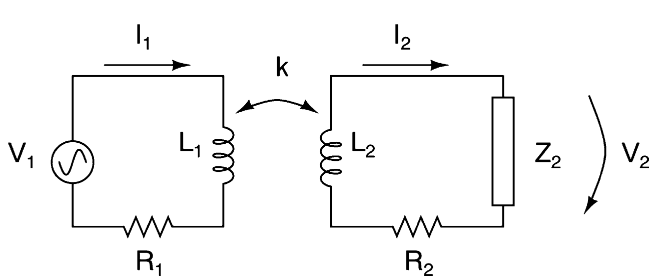

Fig. 2. Inductive link scheme (L_1 is the external coil, L_2 is the implanted coil).

$$V_1 = j\omega L_1 I_1 + j\omega k\sqrt{L_1 L_2} I_2 \quad (1)$$

$$V_2 = j\omega L_2 I_2 + j\omega k\sqrt{L_1 L_2} I_1 \quad (2)$$

It can be seen that variations in the coupling factor (which always occur in real life situations) lead to a higher voltage V_2, possibly overruling the breakdown limits of standard IC technologies.

The preferred technology is thus a mature process with increased breakdown voltages. When high performance digital and analog processing is required, it is still possible to use two different IC technologies where the front-end IC uses a mature technology, and analog and digital processing is done on a less mature but more performant chip. In that case both ICs can be stacked to form a SIP (System In Package) or MCM (Multi Chip Module) [6]. In this design, only the front-end IC is elaborated. A HV (High Voltage) extension on the 0.35 μm process is selected. Its breakdown limits are extended to 80 V.

3. Transcutaneous power transfer

In specific implants the use of batteries is encouraged, e.g. in implants which have limited lifetime and which are retracted after rehabilitation. In that case, of course, the battery should over span the monitoring period. Other examples include monitoring devices where the battery is easily replaced [7]. Some implants, such as the pacemaker, not only perform passive monitoring, but they provide a life-sustaining pacing action that requires the use of a permanent power source. In the case of an orthopaedic implant, external powering may be preferred, avoiding the need for batteries. The primary coil in the inductive link scheme of Fig. 2 is typically driven using a Class-E driver due to its high efficiency [8]. The incoming RF wave (1 MHz) is first rectified to a semi-stable DC voltage. The next block regulates this voltage to a stable and temperature-independent voltage of 3.3 V, able to deliver at least 50 mW of power, sufficient to power a strain gauge equipped implant [9].

3.1. Rectification

The RF carrier is rectified to obtain a DC voltage. Integrating rectifier elements on chip introduces the problem of creating a parasitic diode from substrate towards anode (Fig. 3 shows a cross-section of the 0.35 μm I3T80 technology, where a NPN transistor is used to define a diode). Indeed, the substrate is connected to the