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Implantable system for electrical stimulation and recording

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Abstract

This paper presents the design of an Application Specific Integrated Circuit (ASIC) for neural recording and stimulation for applications in the(Peripheral Nervous System (PNS). This ASIC consists of 8 channels stimulator with independent anode-cathode selection, 4 recording amplifiers, two step-up voltage regulators and a digital control to program and command the analog parts. The main characteristics of the stimulator are: fully programmable for stimuli waveform (monophasic, biphasic), wide frequency range from 7 to 350 Hz with .1 Hz resolution at low frequencies and current range from 2μA to 5mA with 6 bits resolution in four scales. The characteristics for the recording amplifier are: very low noise (5nV/√Hz), high CMRR (94 dB) as well as gain and bandwidth being digitally programmable. This ASIC has been designed in a high voltage CMOS technology.

1. INTRODUCTION

Electrical stimulation and recording has been an important research activity for decades and is widely considered as a key question for better understanding, controlling, and eventually restoring neurological functions using a neuroprostheses (NP). A generic NP [1] consists of sensors (natural or artificial) used to sense any physiological measurement such as motor or sensory activity, an electrical stimulator for stimuli generation and a set of electrodes providing the stimuli to the nerve or muscle. With these NP a lot of applications have been developed most of them related with neuromuscular stimulators for the treatment of some illness like epilepsy, stroke, pain, essential tremor or spinal cord injury like bladder control, drop foot and grasping [2,3] regaining the lost motor activity. Although the majority of neuroprostheses are stimulators of the nervous system, there is an increasing interest in enabling neural signals as inputs for controlling the stimulators or to provide a feedback in closed loop systems. Neural signals recorded by any kind of electrode (cuff, sieve, life,) can be used instead of artificial sensors in FES systems to obtain information related with slipping, hardness, heat, etc. With this objective, a neural stimulator and a recording amplifier as well as the high voltage regulators needed have been designed, implemented on the same substrate and tested to assess this possibility and analyse problems arising on recording circuitry due to stimulator interferences. A simplified blocks diagram for this implantable system is shown in Fig. 1.

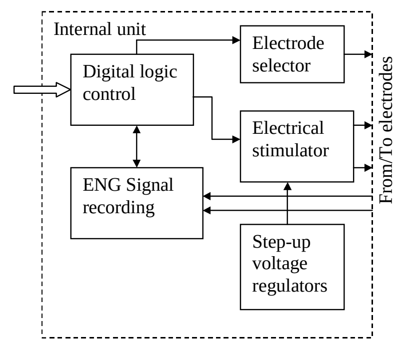

Fig. 1: Simplified blocks diagram

2. METHODS

This system is part of a wireless system thought to work with different electrode and it is not fixed to an specific biomedical application. This ASIC does not include the telemetry module although the digital control has been designed using a general strategy.

2.1 Stimulator description

The hierarchical methodology followed in the design of the first version [4] permitted to increase the number of channels from 4 to 8. Moreover, the initial current range was also increased with the objective of extending the usefulness to other electrode types such as cuff or micro needle. This electrical stimulator is based in a binary weighted current converter with 6 bits resolution giving a current resolution of 2 μA, the three additional ranges with 5, 20 and 50 μA resolution, have been implemented with current amplifiers at the output. The stimulator can be programmed with 16 different waveforms. A waveform is any kind of biphasic or monopolar stimuli with or without prepulse, train of pulses and/or a stimulation sequence with different channels, etc. It is possible to select any anode-cathode combination giving a potential spatial selectivity when using cuff electrodes.

The same current source is used for the stimulation and recovery phases such that the charge delivered in the two phases are very similar and the small differences are only due to the finite resolution in amplitude and pulse width definition. To avoid that, an exponential charge recovery process has been implemented short-circuiting the two electrode terminals.

Moreover, due to CMOS transistors used as switches at the output to control the current flow, high current spikes appear at the output when switching them. This stimulator has been implemented with a specific activation sequence and hardware to avoid these undesirable current spikes.

This ASIC also includes the control part of two DC-DC step/up regulators to generate the high voltages needed and optimize the area for the implantable device reducing the number of external components and only requiring a 5V power supply. These step/up can be disabled digitally reducing the power requirements when the stimulator is not used. The step/up voltages obtained depends on the electrode that is used.

2.2 Recording description

The same circuit includes 4 identical 3 stages ENG amplifiers. Each stage consists of a gain and first order high pass filter with a zero at the origin [6]. The total input referred noise is 350 nVrms being the bandwidth 100 Hz to 5 kHz. That makes possible to record ENG signals μV [6], eliminate ±500 mV DC component from the electrode and reduce signals outside the band. The low cut-off frequency can be moved among 4 possible values digitally programmed and the roll-off is 60 dB/dec of attenuation. The circuit also includes an ADC and the digital control.

2.3 Internal structure for the control

The digital control has been designed with the main objective being the reduction in size and power consumption, then its internal structure has been optimized. Fig 2 represents a simplified schema of the internal structure. It is based on an internal bus that connects the different modules and each module can communicate with any other using the bus. The main blocks are:

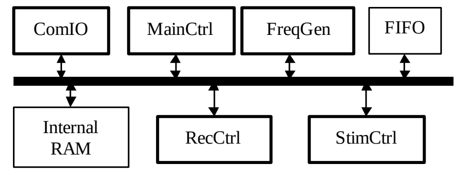

Fig. 2: Internal structure for the stimulator and recording controls.

- **MainControl**: This block controls the access to the bus.
- **Ram**: This is a ram of 256 words used to store all the stimulator parameters
- **ComIO**: This module implements the communication between the internal bus and the external world. A synchronous serial and a parallel connection have been implemented.
- **FreqGen**: This module generates 16 independent frequencies. When a frequency event is generated this module sends the command, to start the stimulus, to the StimCtrl across an internal FIFO.
- **StimCtrl**: This module generates all the signals that are necessary for the stimulator. It works like a processor where instructions are the stimuli parameters, for this reason it is possible to program any kind of stimuli.
- **RecCtrl**: It generates all the control signals required for: amplifier activation, electrode selection, sampling rate, ADC conversion and storage of digital data in specific registers for a posterior transmission to the exterior.

Single stimulus or bursts at the programmed frequency can be generated. The process for a stimulus generation follows the sequence below:

1. Module *FreqGen* finish the count for a frequency
2. Module *FreqGen* write in the *FIFO* the frequency identifier
3. If the *FIFO* is not empty, the *StimCtrl* reads from the *FIFO* the pointer to one of the 16 waveforms
4. *StimCtrl* reads the initial *RAM* address for this waveform
5. *StimCtrl* reads the parameter and execute the sequence for stimulus generation
6. The *RAM* address is increased to the next one
7. Step 5 and 6 are repeated as many times as the number of parameters in the waveform
8. If the *RAM* contents is equal 0 then the waveform is finished and next position in the *FIFO* is read.

3. RESULTS

This circuit has been implemented in a high voltage CMOS 0.7µm and used to design a monolithic opto-coupled stimulator that can be programmed and controlled from a computer using an USB interface. This system is useful at the laboratory and acute experiments in animals. It is programmed from the computer to generate any complex waveform using specific software. In Fig. 3 stimuli pulses through 3 channels, at the top, and the expanded time scale at the bottom are shown. These stimuli have been programmed with two different frequencies (50 and 100 Hz) highlighting the collisions treatment. Three biphasic waveforms with prepulse in the stimulation phase and different shape for the recovery phase have been programmed.

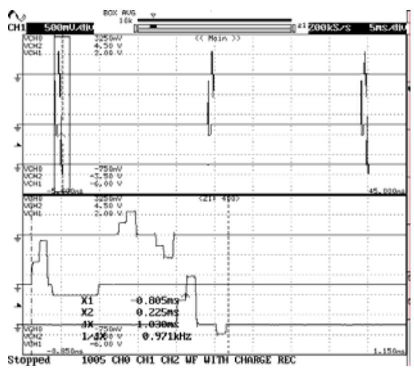

Fig. 3: Stimulation waveforms programmed at internal channels Ch0, Ch1 and Ch2 with different parameters.

This amplifier is an improved version of a previous work [5] where only one channel was implemented and the full performances were presented. The most important parameters for this new prototype are an input referred noise of 350nVrms and a CMRR@1kHz 94dB. In Fig. 4 the bode diagram for a programmed gain of 80 dB and for the four low cut-off frequencies is shown.

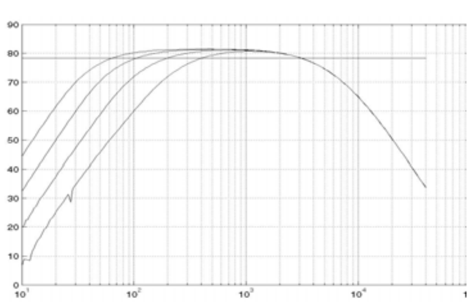

Fig. 4: Bode for the recording amplifier.

This ASIC has also been used to implement an implantable device like that shown in Fig 5. Two stimulation and recording channels are accessible and has been developed to be used with sieve electrodes (including a multiplexer for external electrode selection) allowing the access to any of the available active points in the electrode.

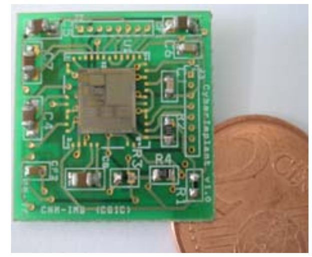

Fig. 5: Implant for sieve electrodes. The size is 20x20mm^2. Die size 5.9x6.0 mm^2

4. CONCLUSIONS

The design of an 8-channels stimulator, 4-channels ENG signals amplifier with filter and two final applications, (a monolithic stimulator for connecting from a PC and an implantable stimulator for sieve electrodes) using this ASIC has been presented. The characteristics of stimulator make it an ideal circuit for an implantable device for studying and analyse different kind of stimuli in a chronic experiment and also to verify the electrode and implant evolution along the time.

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