

# A POWER EFFICIENT ELECTRONIC IMPLANT FOR A VISUAL CORTICAL STIMULATOR

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## Abstract

*An integrated micro-stimulator designed for a cortical visual prosthesis is presented, along with a pixel reordering algorithm, together minimizing the peak total current and voltage required for stimulation of large number of electrodes at a high rate.*

*In order to maximize the available voltage for stimulation at a given supply voltage for generating biphasic pulses, the device uses monopolar stimulation, where the return electrode voltage is dynamically varied. Thus, voltage available for stimulation is maximized, as opposed to the conventional fixed return voltage monopolar approach, and impedance is significantly lower than what can be achieved using bipolar stimulation with micro-electrodes. This enables the use of a low voltage power supply, minimizing power consumption of the device.*

*An important constraint resulting from this stimulation strategy, however, is that current generation needs to be simultaneous and in-phase for all active parallel channels, imposing heavy stress on the wireless power recovery and regulation circuitry in large electrode count systems such as a visual prosthesis. An ordering algorithm to be implemented in the external controller of the prosthesis is then proposed. Based on the data for each frame of the video signal to be transmitted to the implant, the algorithm minimizes the total generated current standard deviation between time multiplexed stimulations by determining the most appropriate combination of parallel stimulation channels to be activated simultaneously.*

*A stimulator prototype has been implemented in CMOS technology and successfully tested. Execution of the external controller reordering algorithm on an application specific hardware architecture has been verified using a System-On-Chip development platform. Near 75% decrease in the total stimulation current standard deviation was observed with a one-pass algorithm, whereas a recursive variation of the algorithm resulted in a greater than 95% decrease of the same variable.*

## Introduction

Integrated circuits are now used in several biomedical applications as implantable stimulators for rehabilitating physical disorders [1-3]. In many cases, these are controlled by an external processor and they get their supply energy from an inductive link. The available power for these implants is especially limited because the electromagnetic field through tissues is limited by standards for safety, and for avoiding excessive heating, maximum power efficiency is required. Therefore, both current and voltage shall be kept to a minimum.

The voltage required at the output stage of the implant is dictated by the combination of the current used for stimulation and the electrode-tissue interface impedance. In most cases, to provide the stimulator with sufficient voltage compliance, designers have chosen to use relatively high voltage technologies, either aging or non standard [4-5]. However, for complex systems, numerous digital operations need to be performed. If one wants to include flexibility in stimulation patterns with high pulse rates, despite a limited bandwidth imposed by the use of low frequency carrier for reduced absorption by tissues, data compaction shall be used. Also, safety features such as communication error detection and correction capability, as well as implant status monitoring, are highly desirable. Such tasks require significant processing capability. Added to the need for high power efficiency and low physical dimensions, low voltage state-of-the-art technologies are preferred. Unfortunately, the use of high voltages is then either impossible or not reliable for long term usage.

To limit stimulation voltage swing, one can usually still inject sufficient charge with low current, provided that extended pulse period are applied. However, when the total number of sites is very large and stimulation has to be performed at a high rate, as in the case of a visual prosthesis, this results in the need for very high parallelism. Hence, the total current supply need remains important.

We discuss in the next section the several options available for current based stimulation, and select an optimal approach with respect to the voltage compliance of the stimulator output stage. The intended scheme, however, although easily implemented on devices with few channels, brings regulation concerns and affects power efficiency. An algorithmic approach to solve this issue by minimizing the total peak current according to the data to be processed will then be introduced. Implementation results and a summary will follow.

### Low-Voltage Biphasic Stimulation

For chronic stimulation, the preferred approach consists of applying constant current signals, most commonly pulse shaped [6]. To avoid degradation of the tissues, charge balanced biphasic pulses are mandatory. Fig. 1 shows a simplified model of an output stage capable of performing both bipolar and monopolar stimulation, with a simplified electrode-tissue impedance model, in which  $R_S$  is the series ohmic resistance, while  $C_D$  and  $R_D$  are the capacitive and resistive components of the double-charge layer at the electrode-electrolyte interface. Note that the off-chip return electrode is not intended for stimulation, therefore it can be large and its impedance can be neglected.

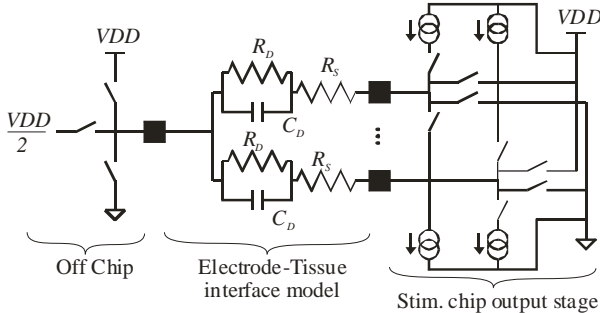


Fig. 1. Simplified schematic of the stimulator output stage for two electrodes on a single channel, with their associated electrode-tissue interface impedances.

Bipolar stimulation presents the advantage of allowing much larger voltage swing than monopolar stimulation at a given supply ( $VDD$ , vs  $VDD/2$ , neglecting current sources saturation voltages), while the latter approach has nearly half the total electrode-tissue impedance. When the stimulation pulse is shorter than what is required for the voltage to reach its theoretical maximum, which is the case in most applications, the higher ohmic resistance of the bipolar path reduces the charge that can be injected/withdrawn in/from the tissues ( $Q_2$  vs  $Q_1$  in Fig. 2).

In the same conditions, if the off-chip return current electrode is set dynamically such that its voltage is  $VDD$  ( $VSS$ ) for cathodic (anodic)

stimulation, both highest voltage swing and lowest impedance are obtained. Note that because of the non-linear rise of the electrode voltage during stimulation, doubling the allowable voltage swing for a given electrode-tissue impedance allows for more than twice the maximum charge ( $Q_3$ ).

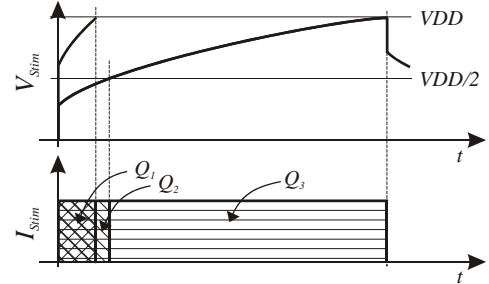


Fig. 2. Typical electrode voltage waveform (a) when applying a constant current pulse (b).

Stimulating in a monopolar configuration with a return electrode alternatively set to  $VDD$  or  $VSS$  has been used in the past [7]. However, serious concerns arise when this has to be applied to a stimulator with a large number of parallel channels. Since, at any time, either of the current sources or sinks is unusable, anodic and cathodic stimulation cannot be performed simultaneously on parallel channels. Therefore, a high instantaneous total current is required, putting heavy strain on the regulating circuitry.

Because of their low noise performance and small size, linear devices are generally the preferred components for voltage regulation. However, their power efficiency is very poor if their voltage drop from input to output is large.

In an effort to minimize the peak current and total current variance, hence reducing the drop-out voltage through the regulator, we propose an algorithm that adapts the scanning sequence depending on stimulation parameters.

### Reordering

Consider a visual prosthesis driving an  $N \times M$  electrode matrix, where  $N$  is the number of parallel channels, each driving  $M$  electrodes in  $M$  successive time periods for forming an  $N \times M$  image. Let  $N=M=8$  and the simple image in Fig. 3 a) be created by relative current intensities represented by integer values in Fig. 3 b).

Scanning parallel rows in a predefined left-to-right manner would result in the total current consumption pattern depicted in Fig. 4 a). A simple yet relatively efficient way of smoothing the total current deviation is to sort the  $M$  elements of odd and even numbered channels in increasing and decreasing order, respectively, prior to sending the stimulation data to the implant. Applying this

operation (Opposite Sort Sum - OSS algorithm) to the example of Fig. 3 leads to the total current consumption pattern of Fig. 4 b).

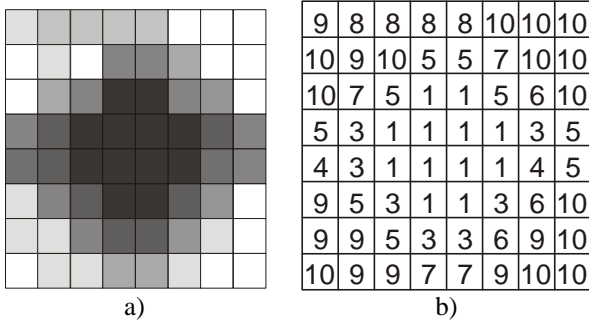


Fig. 3. Simple 8x8 image (a) with its associated current intensities (b).

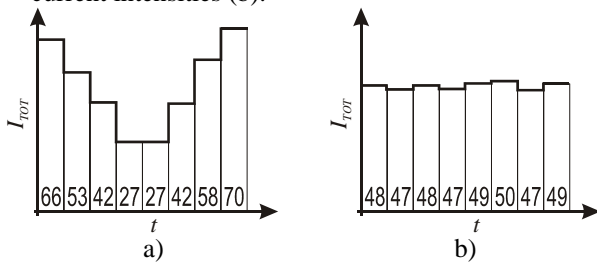


Fig. 4. Total stimulation current before (a) and after (b) OSS algorithm.

Although this technique significantly reduces the maximum instantaneous current consumption and the mean deviation of the total current in many cases, the algorithm is not very effective on inhomogeneous images because of evaluation of data limited to only pairs of lines. To make the algorithm more reliable for any input image, the algorithm can be applied recursively on growing sets of sorted parallel channels.

After a first iteration, identical to that described in the OSS case, pairs of channels are considered together and their  $M$  summed elements are sorted in either increasing or decreasing order. In this second iteration,  $N/2$  sorts of  $M$  elements are performed, where  $N/4$  of them are increasing and as many are decreasing. Subsequent iterations can be performed until single increasing and decreasing sorts are performed on the total currents

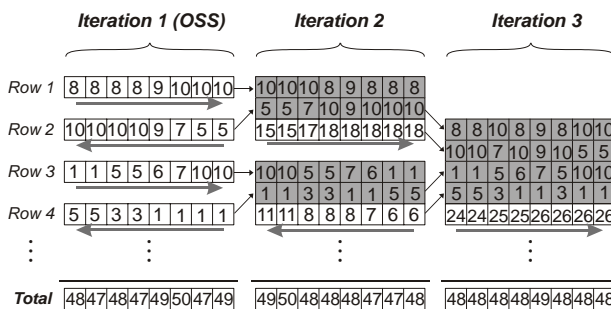


Fig. 5. Data flow of recursive algorithm applied to the upper half of the sample image in Fig. 3.

of two sets of  $N/2$  channels. A near optimal smoothing can be reached after  $\log_2(N)$  iterations. Fig. 5 depicts this processing, named Smoothing Of Set of Opposite Sort summation algorithm (SOSOS), applied on the example used above.

## Implementation Results

Two independent test benches were created. First, an integrated stimulator prototype with 16 stimulation sites in 4 channels driving 4 electrodes each was fabricated in a CMOS 0.18  $\mu\text{m}$  process, as described in [8]. The implant interface module controller was implemented using discrete components and a pattern generator for testing the various stimulation strategies via microelectrodes in a physiological solution.

Complementarily, a dedicated computation unit was implemented on a SOC rapid prototyping platform and tested on a stimulator prototype not intended for implantation. The latter comprises the same hardware structure as the integrated device, but is intended to drive a large matrix of LEDs in order to display images in real-time, enabling the testing of controller hardware and algorithms prior to the availability of a large electrode-count implantable device. The implemented test set-ups are presented in Fig. 6.

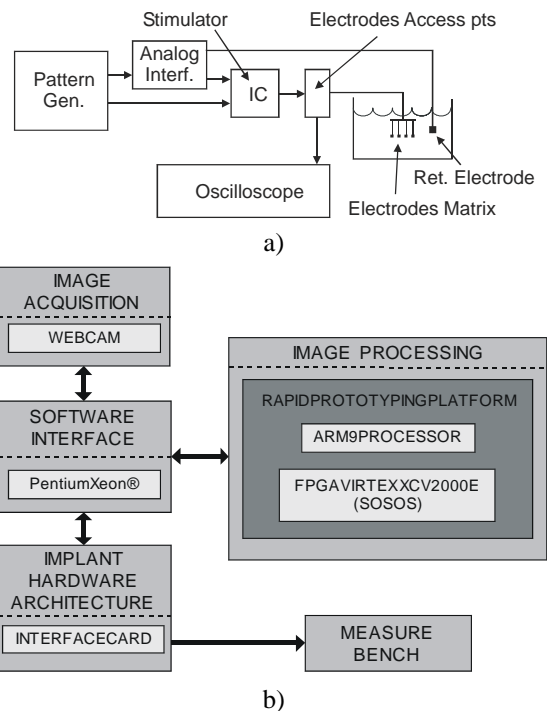


Fig. 6. Test set-ups.

Fig. 7 shows the clear advantage of using dynamic return electrode when the voltage swing is limited by a low supply. The maximum allowable current is more than doubled when current sources saturation voltages are taken into account. Also, maximum charge per phase when the phase duration determines the peak stimulation voltage is

also significantly increased, leading to effective stimulation being possible in greater number of situations.

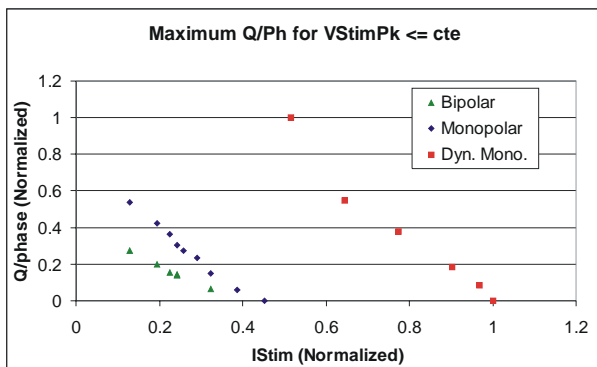


Fig. 7. Maximum charge per phase vs current applied with integrated stimulator ( $VDD = 3.3V$ ) for monopolar, bipolar and dynamic return monopolar stimulations.

Fig. 8 depicts the results of applying the reordering algorithms to pseudo-random and real images prior to sending data to the implant. Both maximum instantaneous consumption and variations are reduced by applying the single step algorithm, and the recursive approach leads to near optimal pre-regulation. Reduction in the total current standard deviation reaches near 75% and more than 95% when applying the OSS and SOSOS algorithms, respectively.

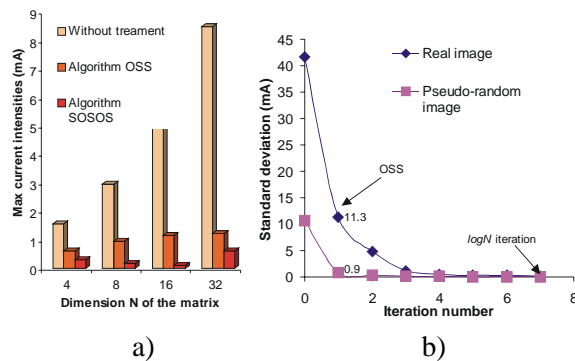


Fig. 8. Peak (a) and standard deviation (b) of total current for square images before and after OSS and SOSOS processing.

## Summary

An effective stimulation strategy for applying constant current pulses has been presented, along with a data processing algorithm that enables smooth current consumption for large electrode-count implantable systems.

Combining these two concepts allows for maximum efficiency at a given supply voltage, and for minimum regulator drop-out, making the use of state-of-the-art technologies for implant fabrication notably efficient and reliable.

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