# A Multichannel Monolithic Wireless Microstimulator

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Abstract—A 64-site wireless current microstimulator chip (Interestim-2B) and a prototype implant based on this chip have been developed for neural prosthesis applications. Modular stand-alone architecture allows up to 32 such chips to be connected in parallel to drive 2048 sites. The only off-chip components are a receiver inductive-capacitive (LC) tank and microelectrode arrays such as silicon probes for intracortical stimulation. The implant receives inductive power and data at 2.5 Mb/sec from a frequency shift keyed carrier to generate up to 65800 stimulus pulses/sec. Each chip contains 16 current drivers with 270  $\mu$ A full-scale current, 5-bit resolution, 100 MΩ output impedance, and a dynamic range that extends within 150 mV of the 5 V supply rail. The chip and implant (without probes) measure  $4.6 \times 4.6 \times 0.5$  and  $19 \times 14 \times 6$  (mm), respectively.

### Keywords-Implant, microstimulator, modular, wireless

#### I. INTRODUCTION

Auditory function restoration in profoundly deaf individuals has been successfully achieved by implanting wireless stimulators capable of electrically stimulating the cochlea and auditory brain stem. Visual prostheses however, have not yet been widely utilized in the blind despite their longer history than some commercialized implantable devices such as deep brain stimulators [1]. The reason is the complexity of the visual system, which imposes severe technological challenges on an implant in terms of the number of stimulating sites, bandwidth, size, power, and stimulation protocol. Several researchers have addressed the above problems with limited success [1], [2]. This paper presents Interestim-2B (IS-2B), a multichannel monolithic wireless microstimulator ASIC with a modular architecture, which advances the state-of-the-art in nearly all of the above directions. IS-2B can be assembled in a 64module  $\times$  32-site wireless stimulating microsystem to address up to 2048 stimulating sites. Our ultimate goal is to develop button-sized wireless microstimulating 3D arrays by mounting IS-2B chips on micromachined platforms, connected to passive probes, or by implementing IS-2B circuitry on the backend of active silicon probes [3].

## II. INTERESTIM-2B ARCHITECTURE

## A. Interestim-2B Chip

Fig. 1 shows the block diagram of an IS-2B module [3]. There are two identical modules in each IS-2B chip, supporting a total of 64 stimulating sites. A hybrid receiver LC-tank circuit ( $L_rC_r$ ), which can be shared between up to 32 chips via a pair of common inputs (C1, C2), provides each module with inductively attained power and data. Implant size reduction is achieved by utilizing a fully integrated full-wave CMOS rectifier [5] followed by an on-chip 430 pF capacitor. A 10 nF off-chip capacitor is used in parallel with the on-chip capacitor to achieve further ripple rejection. A regulator stabilizes  $V_{CC}$  at 5 V for unregulated

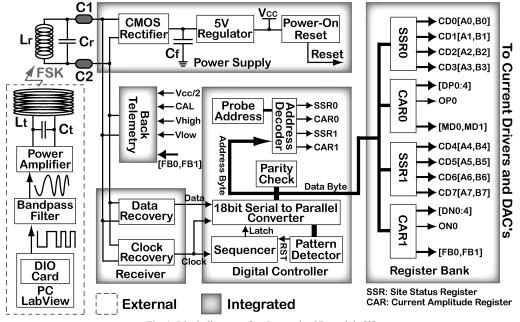


Fig. 1. Block diagram of an Interestim-2B module [3].

inputs > 6.7 V, while supplying 1.65 mA to each module. In order to ensure safe operation, the power-on-reset (POR) circuit continuously monitors  $V_{CC}$  and releases the reset line 70 µs after the regulator voltage > 4.8 V. It also shuts the entire stimulator down when  $V_{CC} < 3.4$  V.

The carrier frequency should be kept < 20 MHz due to the implanted coil self resonance and excessive power absorption in the tissue at higher frequencies. To achieve data rates comparable to the carrier frequency, FSK modulation scheme was utilized. Using a new FSK demodulator, data bits were detected by directly measuring the duration of each received carrier cycle [4]. The demodulator also derives a constant frequency clock from the FSK carrier. As a result, IS-2B is able to wirelessly receive 2.5 Mbps using an FSK carrier that switches between 5 and 10 MHz for logic 1 and 0, respectively.

Isochronous communication scheme is adopted to provide a fast, steady, and uninterrupted data stream, which is preferred for video applications. The IS-2B's 18-bit command frames, which consist of data and address bytes each accompanied by a parity bit, are transmitted back to back, separated by 1-bit spacers. An 18-bit shift register and a sequencer convert the serial bit-stream to parallel, while a pattern detector resets the sequencer upon receiving a unique frame (OFF0FFh) to maintain synchronization with the transmitter. The address byte consists of a 6-bit module-address and a 2-bit register-address. The moduleaddress is compared to the module's hardwired userprogrammable address, and if they match and there is no parity error, the data byte is stored in one of the four internal registers that is defined by the register-address. Otherwise, the received command frame is ignored.

Each module has eight current drivers (CD) that are enclosed in dashed boxes in Fig. 2. Each CD has both nMOS current sink ( $M_1$ ) and pMOS current source ( $M_3$ ) versions of a novel circuit topology that utilizes the above transistors in deep triode region as linearized voltagecontrolled resistors (VCR) by applying a larger than

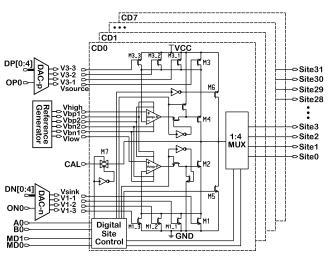


Fig. 2. Current drivers schematic and block diagram [3], [6].

threshold  $V_{GS}$ , while actively maintaining their  $V_{DS}$  at 80 mV [6]. Linearity is achieved by using saturated auxiliary transistors in parallel with M<sub>1</sub> and M<sub>3</sub>. The stimulus current amplitudes of all CDs are controlled by a dual pair of 5-bit voltage-mode DACs (DAC-n and DAC-p) with an additional bit for adjusting the offset current.

Each CD<sub>n</sub>, multiplexed among four stimulating sites, is controlled by two specific status-bits (A<sub>n</sub>, B<sub>n</sub>) and two shared mode-bits (MD<sub>0</sub>, MD<sub>1</sub>) as shown in Fig. 2. Combinations of these bits in four operating modes connect each site to  $V_{CC}$ , current source, *GND*, current sink, common analog line (*CAL*), or keep it at high-Z. The result is a wide variety of stimulation strategies that can be applied depending on the application. *CAL* can be used for charge balancing, recording from sites, or site impedance measurement. There is also a reference line, controlled by FB<sub>0</sub> and FB<sub>1</sub> bits, which stays at high-Z in bipolar stimulation and can be connected to  $V_{CC}$ , *GND*, or *CAL* for monopolar stimulation or impedance measurement [7].

#### B. Interestim-2B Implant

The IS-2B implant consists of the IS-2B wireless microstimulator ASIC, one or more stimulating microelectrode arrays,  $L_rC_r$ -tank, a platform, and packaging. Physical design of the package, platform, and stimulating probes highly depend on the application. Prototype IS-2B implants that are shown in Fig. 3 are designed for acute wireless intracortical microstimulation. Therefore, they were only coated with epoxy and silicone (Nusil Technology, CA) as a temporary package. Double layer, 0.4mm-thick printed circuit board (PCB) was used for the platform with 76.2µm minimum feature size. Two conservatively designed platforms, which include edge connectors for direct access to the sites as well as the ASIC test-points, are 18 mm  $\times$  18 mm and 18 mm  $\times$  13 mm in size and support two and four microelectrode arrays, respectively. The platform can be shrunk to 10 mm on each side by using a multilayer PCB and eliminating the edge connectors.

16-site micromachined silicon passive microelectrode arrays (called Rat-2) with 1cm flexible ribbon cables, which specifications are summarized in Table 1 [8], were glued to the platform with wax before being bonded. Unlike most other probes that have polysilicon interconnects running on their shanks and ribbon cable, these probes are equipped with metal (platinum) interconnects to minimize the access resistance to the stimulating sites. This is important in wireless microstimulators, where the implant supply voltage is limited and voltage dropout across the stimulating sites access lines can saturate the current drivers before achieving the desired stimulus current levels.

The receiver coil  $(L_r)$ , which specifications are shown in Table 1, is wound around a ferrite core (Fair-Rite, NY) to intensify the electromagnetic field and increase the coupling with an external transmitter coil  $(L_t)$ .  $L_r$  is attached to the backside of the platform using double-sticky tape. Parasitic

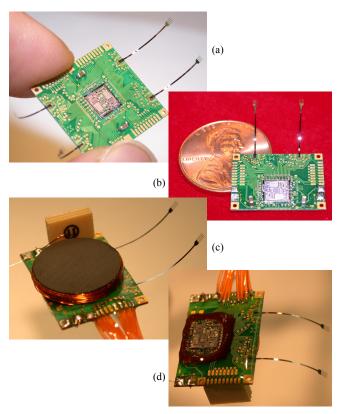


Fig. 3. (a) 64-site wireless microstimulator with 18 mm × 18 mm PCB platform (b) 32-site wireless microstimulator on a US penny (c)  $L_r$  coil is mounted on the backside of the platform (d) IS-2B implant is coated with epoxy and silicone for acute experiments.

capacitors of  $L_r$  and IS-2B rectifier input [4], in parallel, are usually enough to shape the carrier frequency spectrum across  $L_r$ . Therefore,  $C_r$  is not needed as an off-chip component. However, to decrease the rectifier ripple a 10 nF surface mount capacitor is added in parallel to  $C_f$  in Fig. 1.

#### C. External Components

The external components of the IS-2B microstimulating system are shown in a dashed box on the left side of Fig. 1. Digitized image or sound information, acquired by a miniature camera or microphone for a visual or an auditory prosthesis, respectively, is transferred to a portable computer or PDA. The computer processes the incoming information in real-time and generates a series of stimulation command frames based on the adopted stimulation and communication protocols [7]. In the experimental setup, these commands are generated from stimulation parameters that are entered into a graphical user interface (GUI) in LabView environment. The command frames are arranged into bursts of serial data bit-stream, which are then converted into a digital frequency shift keyed (DFSK) signal at 5/10 MHz by a high-speed digital I/O card (National Instruments DIO-6534). The square-wave DFSK signal passes through a bandpass filter (10 kHz ~ 5.6 MHz) to turn into a sinusoidal FSK before being amplified by a wideband power amplifier

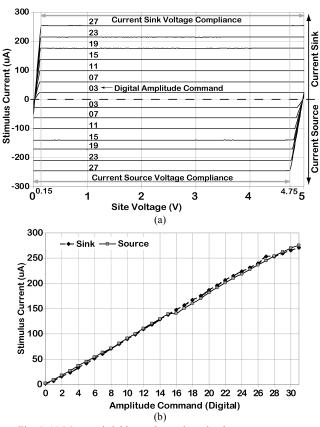


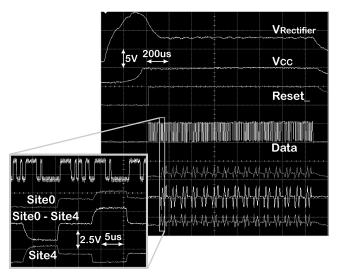
Fig. 4. (a) Measured sinking and sourcing stimulus currents versus stimulating site voltage, swept from ground to  $V_{CC}$  at different 5-bit amplitude commands. (b) Stimulus current vs. amplitude commands, showing the linearity and matching of sinking and sourcing currents.

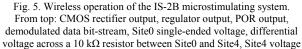
(Amplifier Research, NJ). Finally, the amplified FSK carrier, which contains both data and power for the implant, is transmitted through the  $L_tC_t$ -tank circuit that is inductively coupled to the receiver  $L_rC_r$ -tank.

#### **III. MEASUREMENT RESULTS**

Fig. 4 shows measured sinking and sourcing currents, while sweeping a site voltage from ground to  $V_{CC}$ , and changing DACs digital amplitude command inputs. Fig. 4a shows that the VCR current sink (source) can achieve a voltage compliance of 97% (95%) of the supply voltage (5V), while maintaining high output impedance in 100 M $\Omega$  range to keep the stimulus currents constant within 1% of the intended value, irrespective of the site and tissue impedances. Fig. 4b shows the linearity and matching of the sinking and sourcing stimulus currents, which are key parameters in charge balancing [6].

Fig. 5 shows a sample measured stimulation burst. The two upper traces show the rectifier and regulator outputs. It takes ~ 350 µs for the regulator to startup and sink current. The POR releases the reset ( $3^{rd}$  trace) 70 µs after  $V_{CC} > 4.8$  V to safely start digital circuitry from a known state. The receiver block immediately starts recovering the serial data bit-stream at 2.5 Mbps ( $4^{th}$  trace), which consists of back-to-





back command frames. The stimulation burst, shown on the three lower traces, starts as soon as the digital block synchronizes with the transmitter by detecting the unique frame that is sent between every 2 stimulation pulses in this specific example. A 10 k $\Omega$  load, resembling sites and tissue impedances, is connected between Site0 and Site4. Singleended voltages at these sites and their subtraction are shown in Fig. 5 three lower traces, which are also magnified in Fig. 5 inset. Three initialization commands set the sourcing and sinking stimulus amplitudes to full-scale and connect CD<sub>0</sub> and CD<sub>1</sub> outputs to Site0 and Site4 (see Fig. 2). The  $1^{st}$ stimulation command connects Site4 (Site0) to a source (sink). As a result, 270 µA flows from Site4 to Site0 in the cathodic phase. The 2<sup>nd</sup> command puts both sites in the high-Z state for an interphase delay. The 3<sup>rd</sup> command swaps the sites status and 270 µA flows back from Site0 to Site4 in the anodic phase. Finally, the 4<sup>th</sup> command returns both sites to high-Z. The duration of every command, including the spacer bit, is 7.6 µs. Therefore, considering that at least two commands are needed per stimulation phase, IS-2B can generate up to 65800 pulses per second.

# IV. CONCLUSION

A multichannel monolithic wireless microstimulating system (Interestim-2B) is developed for neural prosthesis applications by integrating all the required circuitry on an ASIC except for the receiver LC-tank. Each IS-2B chip drives 64 stimulating sites, and its modular stand-alone architecture makes it possible to address up to 32 chips in parallel to drive 2048 sites. Table 1 summarizes the specs of a prototype implant based on IS-2B for acute intracortical stimulation. Experimental *in vitro* and *in vivo* results with IS-2B microsystem are discussed in [7].

IS-2B ASIC	
Process technology	AMI 1.5-µm CMOS
Die size	$4.6 \times 4.6 \times 0.5 \text{ (mm)}$
Module per chip	2
Current drivers per module	8
Stimulating sites per module	32
Max number of addressable modules	64
Total number of addressable sites	2048
Power and data source	Inductive coupling
Power consumption per module	8.25 mW @ 5 V
Number of transistors per module	6500
Telemetry	
Communication scheme	Isochronous
Modulation scheme	FSK
Carrier frequency	5/10 MHz
Command frame size	18-bits + 1-spacer
Data rate / Bit error rate (BER)	2.5 Mbps / 10 ppm
Nominal coupling distance	5 mm
Receiver Coil Size	Ø13 × 3 (mm)
Number of turns / $L_r$	15 / 9 µH
Stimulation	
Supported stimulation protocols	8
Full-scale stimulation current	270 µA
Stimulation amplitude resolution	8.43 µA (5-bits)
Current source/sink compliance voltage	4.75 V / 4.85 V
Current driver output impedance	$\sim 100 \text{ M}\Omega$
Timing resolution / accuracy	7.6 μs / 50 ns
Max stimulation pulse rate	65800 pulses/sec
Silicon Microelectrode Array (Rat-2)	
Number of stimulating sites / Array	16 / 4 × 4
Site coating	Iridium Oxide
Average site impedance before/after activation	210 kΩ / 45 kΩ
Site area / Spacing	$\sim 1000 \ \mu m^2 / 250 \ \mu m$
Shank size	$1500 \times 80 \times 15$ (µm)
Ribbon cable size	10 mm × 250 μm
IS-2B Implant	
Backend size (without probes)	$19 \times 14 \times 6 \text{ (mm)}$
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TABLE 1 INTERESTIM-2B SPECIFICATIONS

#### REFERENCES

- R.A. Normann, "Sight restoration for individuals with profound blindness," Available: http://www.bioen.utah.edu/cni/projects
- [2] W. Liu *et al.*, "A neuro-stimulus chip with telemetry unit for retinal prosthetic device," *IEEE J. Solid-State Circuits*, vol. 35, no. 10, pp. 1487-1497, Oct. 2001.
- [3] M. Ghovanloo and K. Najafi, "A modular 32-site wireless neural stimulation microsystem," *IEEE Solid-State Circuits Conference*, Digest of technical papers, pp. 226-227, Feb. 2004.
- [4] —, "Fully integrated wideband high-current rectifiers for inductively powered biomedical implants," *IEEE Journal on Solid-State Circuits*, accepted for publication.
- [5] —, "A fully digital frequency shift keying demodulator chip for the wireless biomedical implants," *Proc. IEEE Southwest Symp. Mixed-Signal Design*, pp. 223-227, Feb. 2003.
- [6] —, "A small size large voltage compliance programmable current source for biomedical implantable microstimulators," *Proc. IEEE 25<sup>th</sup> EMBS Conf.*, pp. 1979-1982, Sep. 2003.
- [7] M. Ghovanloo, K.J. Otto, D.R. Kipke, and K. Najafi, "In Vitro and In Vivo Testing of a Wireless Multichannel Stimulating Telemetry Microsystem," Unpublished.
- [8] Center for Neural Communication Technology (CNCT), Available: http://www.engin.umich.edu/center/cnct/