TP 12.6 A Wireless Single-Chip Telemetry-Powered Neural Stimulation System

Jeffrey A. Von Arx*, Khalil Najafi

University of Michigan, Ann Arbor, MI
* Currently With: Guidant Corporation, St. Paul, MN

Remotely-powered microsystems are increasingly needed in applications including biomedical, remote sensing, tracking, security, and inventory control. Many of these applications require several tens of milliwatts to operate data transceivers, control circuitry, sensors, and/or actuators. To satisfy these power requirements, most existing wireless microsystems utilize a discrete receiver coil for power and data transfer. However, integrating the receiver coil and all of the electronics for voltage regulation, data detection, clock generation, and digital and analog functions can result in drastic reductions in size, weight, and assembly and testing cost. This fully-integrated single-chip inductively-powered microsystem is capable of providing milliwatts for wireless operation. The chip is for an implantable multichannel neural microstimulator, but can be also used in other emerging applications for sensing and actuation microsystems.

The block diagram and specifications of this fully-integrated neuromuscular electrical stimulation system (FINESS) are shown in Figure 12.6.1 and Table 12.6.1. This system is for use in peripheral nerve stimulation and will be attached to cuff electrodes that interface to the nerve for delivery of a bi-phasic stimulation pulse. FINESS receives all power and data through inductive coupling with an integrated, on-chip coil. Figure 12.6.2 shows die photographs of the circuitry before and after fabrication of the on-chip coil.

FINESS is powered by a 4MHz RF signal generated by an external source. This maximizes the receiver Q while minimizing the energy absorbed by the body. The integrated receiver coil is a planar spiral design and consists of a 10μm-thick electroplated copper winding, and an 8μm-thick electroplated NiFe (80% Ni) core [1]. It is fabricated by low temperature processing steps after the standard Bi-CMOS process is complete and passivated using polyimide. The 2x8.7mm^2 17-turn coil has 2.9μH inductance (Q=2.6 at 4MHz), and is optimized for receiving power from an 8cm diameter planar transmitter coil which is 3cm away. The on-chip coil, along with integrated 4V regulated DC conversion circuitry, is capable of supplying over 20mW DC to the FINESS circuitry at implant depths up to 3cm.

Data is transmitted to the FINESS chip at 8.3kb/s by pulse-width encoded amplitude modulation of the 4MHz carrier. Forty data bits, five error detection bits, and two unique synchronization pulses are transmitted for each stimulation event. The telemetry link is unidirectional. Strict error detection is used, and any detected error causes the system to abort stimulation.

The neuromuscular stimulating output of the FINESS chip is a biphasic current waveform with programmable interphase delay. Each phase has a 5b programmable amplitude of up to 2mA, and a 10b programmable duration of up to 2ms. The system is capable of stimulation frequencies over 150Hz, and delivers full scale stimulation to loads up to 1.7 kΩ. FINESS selectively stimulates up to 8 pairs of attached electrodes.

The system mixed-mode Bi-CMOS circuitry contains 3,100 transistors, and is 2.0x8.7mm^2. Bi-CMOS offers high voltage protection (the on-chip receiver coil generates up to 30V) and allows full-wave rectification of the received RF signal. The circuitry is in 3μm, double poly, p-well CMOS.

The analog front end of FINESS includes an RF receiver with on-chip coil. This receiver is tuned by laser trimming a 1nF integrated tuning capacitor. The circuitry includes a 4V regulated DC supply generated from the full-wave rectified received RF signal (Figure 12.6.3). This supply uses a Zener reference and has <3mV ripple. The front-end circuitry also includes a 500kHz clock generator, chosen to reduce power while maintaining 2μs resolution for the system's stimulating output. The clock is generated by rectifying the received RF signal and dividing it down. Generating the clock in this way ensures that it does not drift with respect to the external transmitter and control circuitry. The analog front end also includes data demodulation circuitry, which extracts the envelope of the received RF signal by band pass filtering (Figure 12.6.4). It is sensitive only to a modulation depth of 10% or greater in order to minimize errors from sources such as tissue movement. Finally, the front-end circuitry consists of a power-on detector for reset.

The digital portion of the FINESS chip is strictly CMOS and has four functions. First, it recovers the pulse width encoded data from the demodulated envelope. Second, it stores the recovered data. Third, it checks the received data for proper start codes, device address, and parity. Finally, it controls all timing, amplitudes, and switching of the output to the electrodes. The system logic block diagram is shown in Figure 12.6.5. It contains 5 major blocks: a single 10b counter, logic to decode the counter value, a 45b data register, logic to check parity and device address, and a 16-state finite state machine for overall control.

The analog output portion of FINESS consists of a 5b DAC output current source, and low resistance output switches. The output current is generated by binary weighted FETs that are operated in the linear region to minimize the voltage drop across them, allowing larger loads to be stimulated than if they were in saturation. Feedback fixes the V_{ds} of these transistors. When the current source is turned on, the output settles to 97.5% of its programmed value within 1μs. The output current is directed to one of eight possible pairs of attached electrodes by the output switches. Both phases of the output current are generated from the single 4V supply. During the first phase, the current source sinks current from the cathodic electrode while the anode is held at V_{dd}, and during the second phase the same current source sinks current from the anode while the cathode is held at V_{dd}. Using the same current source for both stimulation phases ensures matching between the two phases.

This chip consumes 14.8mW from the 4 V supply during full-scale 2mA stimulation, and 6.28mW when not stimulating. Power savings are obtained over previous implantable stimulation systems by reducing system clock speed, reducing bias currents, and by running the entire circuit from a single 4V supply [2, 3]. Figure 12.6.6 shows an oscilloscope trace of the system RF input and the biphasic stimulating current output.

Acknowledgments:
This work was supported by the NIH Neural Prosthesis Program, contract # NIH-N01-NS-4-2319.

References:
[1] J. Von Arx, K. Najafi, "On-Chip Coils With Integrated Cores For Remote Inductive Powering Of Integrated Microsystems" Proceedings, 9th Int. Conf. on Solid-State Sensors and Actuators, Chicago, June 1997.
[2] B. Ziaie, et al., "A Single-Channel Implantable Microstimulator for Functional Neuromuscular Stimulation," IEEE Trans. Biomed. Eng. Vol. 44, Num. 10, Oct. 1997.
[3] M. Nardin, K. Najafi, "A Multichannel Neuromuscular Microstimulator with Bi-Directional Telemetry" Proceedings, 8th Int. Conf. on Solid-State Sensors and Actuators, Stockholm, Sweden, June 1995.

 0-7803-5126-6/99 / $10.00 / © IEEE

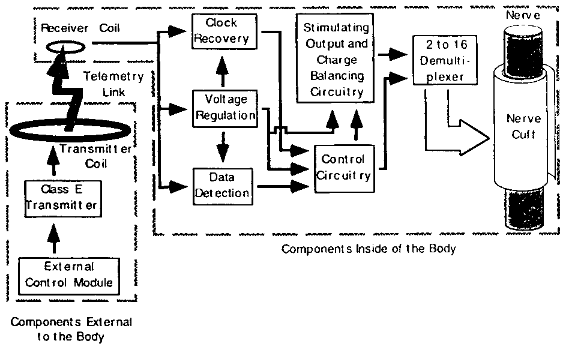

Figure 12.6.1: Block diagram of the FINESS chip.

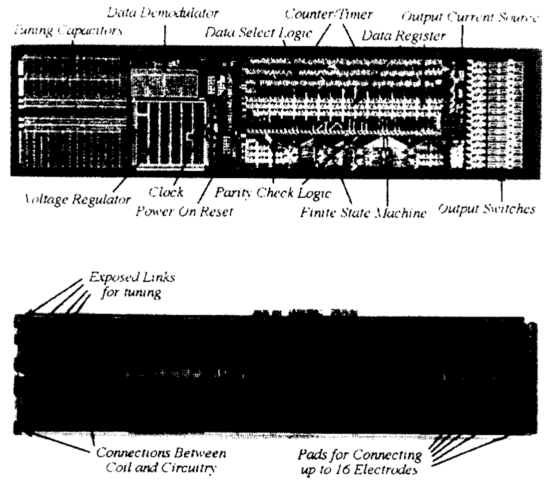

Figure 12.6.2: Die micrographs of FINESS.

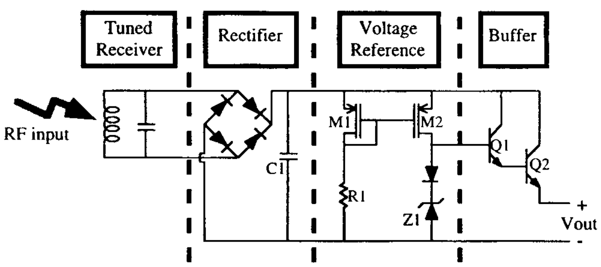

Figure 12.6.3: 4V regulated DC power supply.

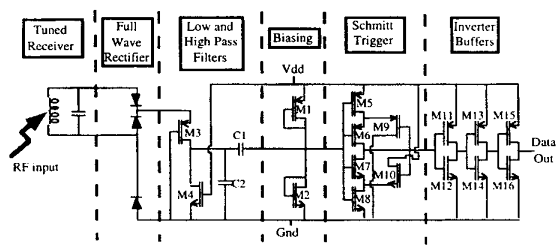

Figure 12.6.4: Data demodulation circuitry.

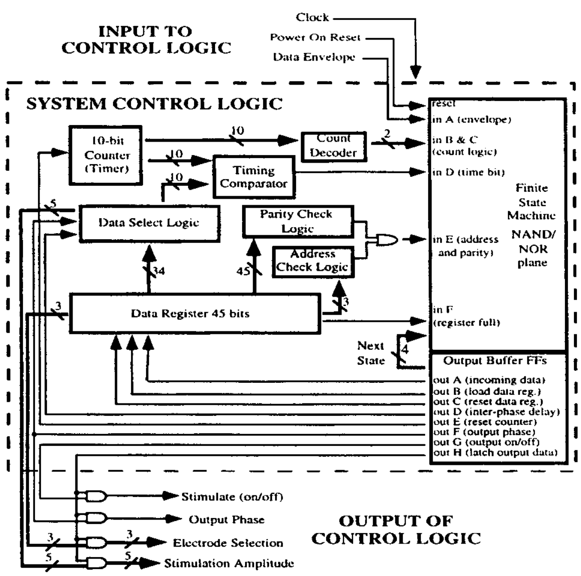

Figure 12.6.5: FINESS digital logic block diagram.

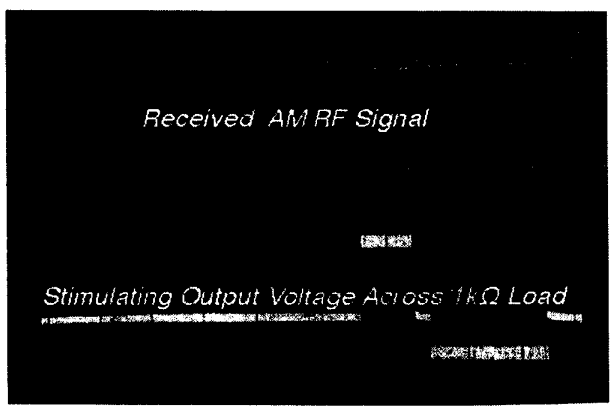

Figure 12.6.6: Received RF signal and stimulating output.

Table 12.6.1: **See page 462.**

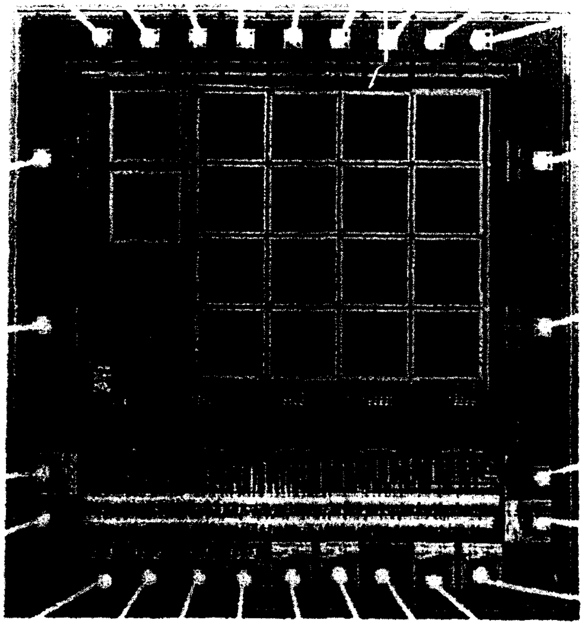

Figure 12.3.6: Chip micrograph.

General	
Circuit Area = 2.0 mm X 8.5 mm	Power Delivery = Telemetry
Power Consumption <15 mW, 4 V supply	On-Chip Power Supply = 4 Volts, Gnd
Telemetry Link	
Receiver Coil = On-chip (2.0 mm X 8.0 mm)	Range (coil-coil distance of link) = 3 cm
Transmitter Coil = Planar, air core (80 mm dia.)	Carrier Frequency = 4 MHz
Modulation Frequency = 1 kHz to 50 kHz	Modulation = ASK, Pulse width encoded
Addressability = up to 8 individually addressable devices per transmitter	
Stimulation	
Stimulation waveform = Two independent phases of opposite polarity	
Duration (each phase) = 4 to 2050 µs (2 µs steps)	Amplitude = 0 to 2 mA (64.5 µA steps)
Output Channels = 8	Inter-phase delay = 12 to 1932 µs (16 steps)
Stimulation Frequency ≤ 170 Hz	Maximum Output Load = 1.7 kΩ

Table 12.6.1: Features.

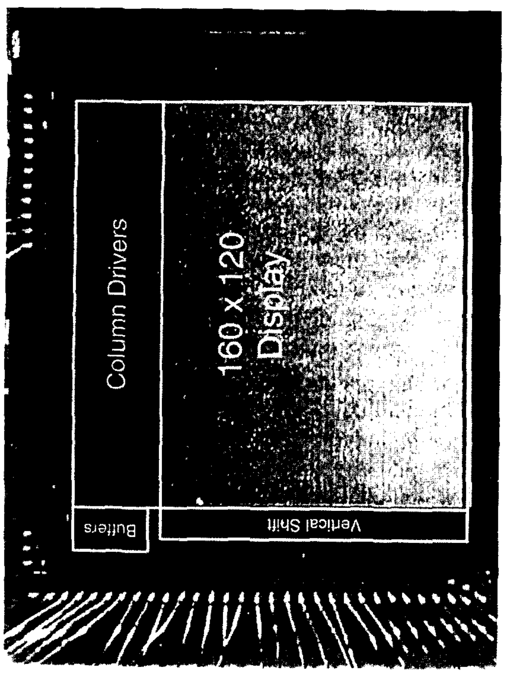

Figure 12.5.5: 160x120 display micrograph.

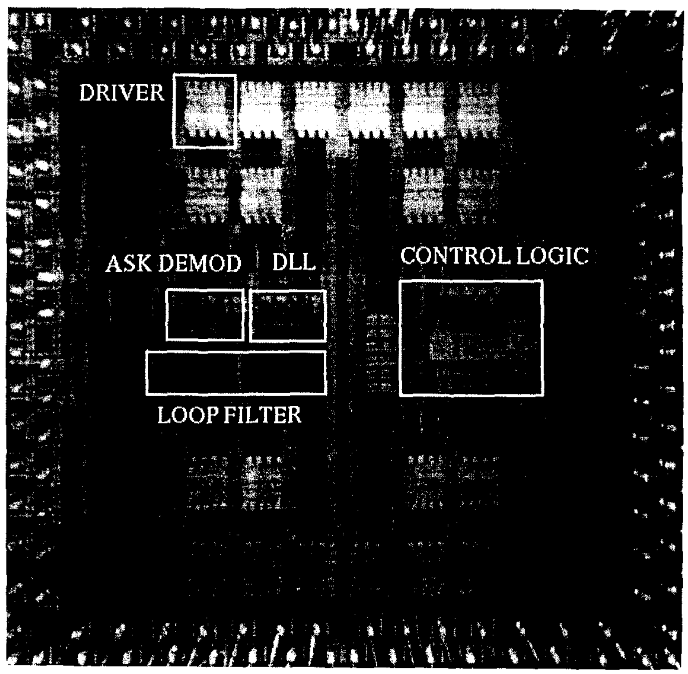

Figure 12.7.7: Die micrograph.