Characterization of Simple Wireless Neurostimulators and Sensors

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Abstract— **A single diode with a wireless power source and electrodes can act as an implantable stimulator or sensor. We have built such devices using RF and ultrasound power coupling. These simple devices could drastically reduce the size, weight, and cost of implants for applications where efficiency is not critical. However, a shortcoming has been a lack of control: any movement of the external power source would change the power coupling, thereby changing the stimulation current or modulating the sensor response.**

To correct for changes in power and signal coupling, we propose to use harmonic signals from the device. The diode acts as a frequency multiplier, and the harmonics it emits contain information about the drive level and bias.

A simplified model suggests that estimation of power, electrode bias, and electrode resistance is possible from information contained in radiated harmonics even in the presence of significant noise. We also built a simple RF-powered stimulator with an onboard voltage limiter.

I. Introduction

USING wireless power for sensing or stimulating implants avoids the use of batteries and lead wires, which can break or scar into tissue and tug on the electrode. Commercial wireless implants typically use active digital circuitry, are powered by induction at MHz, and communicate at several hundred MHz. These systems allow high-power multichannel stimulation and sensing, but for less stringent applications, we find simple passive circuits allow for smaller implants.

Most passive sensors send digital data by load-switching, as in radiofrequency identification (RFID). Digital communication is efficient and robust, but the supporting circuitry can still limit the minimum size and power. Further reducing sensor size can simplify the implant surgery, possibly allowing injection of the sensor by needle. Also, digital fabrication is expensive, especially for custom devices for animal research.

A. Passive Wireless Stimulators

A simple neurostimulator needs an implanted power capture method (such as a small dipole antenna or a piezoelectric element), a rectifier, and electrodes. We find that rectifying alone is sufficient for neurostimulation, with no need for smoothing. The high frequency monophasic waveform has a low frequency component that is effective for stimulation. This approach can reduce size, weight, and cost for applications where efficiency is not critical. We have built an implantable stimulator using an RF antenna with a single diode (a rectenna), and a charge-balancing capacitor [1] as well as simple ultrasound-powered stimulators [2], [3]. Inductive power also has been reported [4], and volume conduction power [5]. The method here should work for all types.

B. Passive Wireless Analog Sensors

Passive analog sensors use a variety of methods to sense and telemeter signals. SAW (surface acoustic wave) sensors respond to a radio pulse with several delayed reflections, each modulated by changes in the load impedance [6]. Inductor-capacitor (LC) sensors present a resonant load to the external reader (grid-dip meter). A variable capacitor changes the sensor resonance. LC sensors can be read at a fixed frequency as an AM signal, or by frequency sweep [7].

A diode can be used as a biopotential sensing element [8], [9] The diode mixes the local tissue signal with a carrier wave to give an AM signal. A diode mixer has loss, so the carrier modulation is smaller than the original signal. SAWs, inductors, and capacitors are all much larger than a diode, so diode mixing can theoretically allow for very small devices, though inefficient modulation may negate this advantage.

C. Power Variation Problem

For the single-diode stimulator and sensor, a major problem is that body movements would change the power coupling between the power emitter and the implant. Stimulator current must be controlled to deliver safe, consistent current. If the implant itself has no control of the current delivered to tissue, this must be done by external exciter power adjustment. So, a signal must be received on the skin. Because our single-diode wireless stimulators do not remove the high-frequency carrier component from the stimulation current, a signal can be detected by volume conduction through tissue [10]. However, this signal is not directly useful for stimulator control or for sensors: variation due to movement will interfere with AM, since a change in the output attenuation will scale the carrier indistinguishably from the true signal.

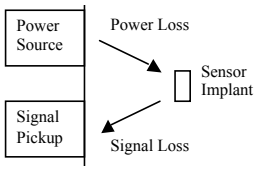

Fig. 1. Movement of the body changes the attenuation in tissue, which would change the current from a single-diode stimulator.

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D. Diode harmonics

Besides AM mixing, a diode can also be used as a frequency multiplier. As a diode rectifies an applied voltage it distorts the wave. This nonlinearity shows in the spectrum as harmonics: new frequency components at multiples of the drive frequency [11]. These harmonics propagate through tissue, and with RF power they can emit through skin. The harmonics vary with the AC drive, DC bias, and load of the multiplier. This work investigates use the harmonics to remotely determine the diode current flow during a neurostimulation pulse and as a potential method of feedback for the control of an external exciter system.

This approach is based on the hypothesis that the relative amplitudes ratios of the detectable harmonics to each other can, in principle, uniquely define the implanted diode operating conditions.

II. Methods

A. Harmonics from a piezoelectric diode sensor

For measuring harmonics from the ultrasound-powered voltage sensor, the setup is similar to previous work [8] but with the components separated for access.

- **Piezoelectric**: PVDF-TrFE (Ktech Inc.) 5 layers, 90µm x 5mm x 5mm.
- **Diode**: Low-bias Schottky (Skyworks CDC 7621)
- **Sensor and Bias electrodes**: Pt, 0.5 by 1 mm
- **Pickup electrodes:** Ag/AgCl
- **Transducer**: Undamped PZT
- **Power amplifier**: Common-source power FET
- **Pulse timer and Bias current driver**: AM systems 2100
- **Function generator**: Wavetek 145
- **Signal amplifier**: Panametrics 5800

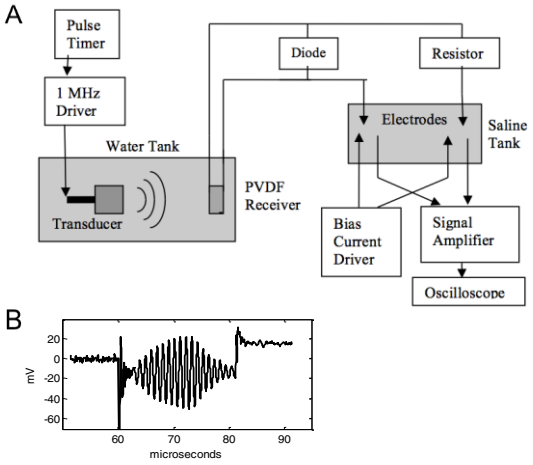

Fig. 2. A: Setup for measuring the drive- and bias-dependent harmonics driven in solution by a piezoelectric-powered diode. B: Example waveform picked up in saline.

An ultrasound pulse (1 MHz, 10 µs) travels to the sensor's PDVF stack. The PVDF voltage drives the sensor electrodes, in parallel with the diode. The bias voltage (50 mV, 20 µs) is also driven in saline. The sensor current is amplified, filtered (+20dB, 100kHz to 10MHz), and averaged (256 times). The response in fig 3B shows the ring-up and ring-down of the transducer, and the offset from the bias current. Waveform asymmetry from the diode is not visible. The ultrasound power was increased in ten steps, and a resistor was used to simulate tissue impedance changes. The harmonics were taken from the FFT of each step and normalized.

B. Harmonic decoder simulation

The results of testing the diode sensor suggested that each condition might make unique harmonic curves. If so, we could build a lookup table to back-calculate the parameters from the curves. We tested this method using a model rather than real measurements so that we could build a lookup table using a wide range of parameters to test for regions of ambiguity. We simplified the power receiver as a voltage source and the electrodes as a resistor for modeling in Matlab (fig. 3).

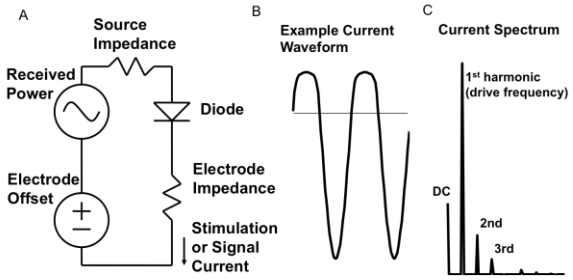

Fig. 3. A: simplified circuit model for the single-diode sensor or stimulator. B: time-domain output, showing the distortion of the sine wave input. C: frequency-domain output, showing the harmonic peaks.

As simulated in fig. 4, different input amplitudes produce different harmonic spectra. When the peaks are plotted against drive, the harmonics increase nonlinearly with drive amplitude – note the rapid increase in the 2nd above the diode threshold voltage. The hypothesis is that their frequency spectrum allows unique identification of the current flow assuming we know electrode impedance despite unknown coupling losses.

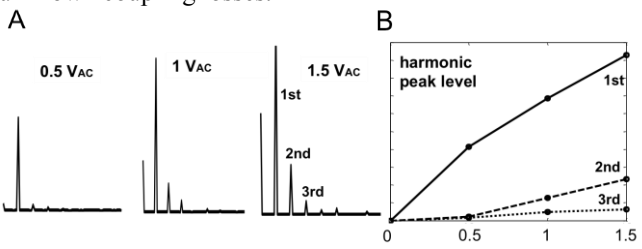

Fig. 4. Simulation showing the variation in harmonics with applied power. A: The full spectra at three different drive levels. B: The extracted peaks plotted vs. drive, showing nonlinearity.

To make the curves in fig. 5, the AC power is ramped from 10% to 100%. We chose to model a system (such as RF) where the harmonics could have different losses in tissue and so would be normalized separately.

For the lookup table to work, each curve must be unique: if different parameters can produce identical curves, the decoder will fail. The less similar the curves, the better the

decoder will perform under noisy conditions.

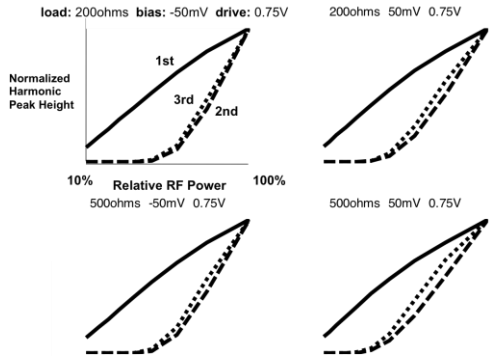

Fig. 5. Simulation of normalized harmonics vs. drive power under varying conditions. The curves appear unique, which would allow a decoder to find the condition.

After building a lookup table using a wide range of parameters, we tested the decoder with a new curve (chosen within the range of table parameters, but not exactly equal to any pre-calculated curve). Fig. 6 describes the simulation: test parameters are chosen, response waveform is calculated, noise is added, harmonics extracted, then the lookup table tries to match the curve to the table (minimum sum-absolute-value distance, equal weight to all points). Estimated values are compared to the true values to find decoder error.

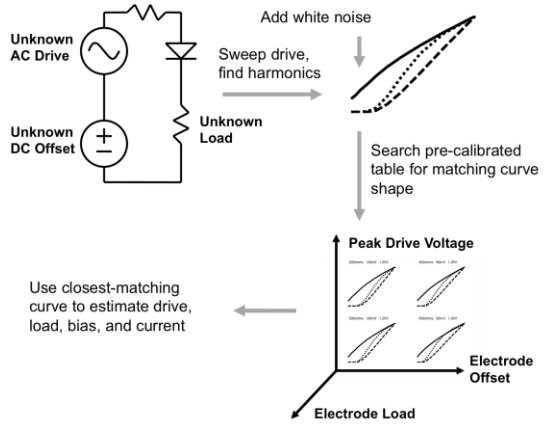

Fig. 6. Simulation of using harmonics to find conditions at the implant by a lookup table. Noise added to test robustness.

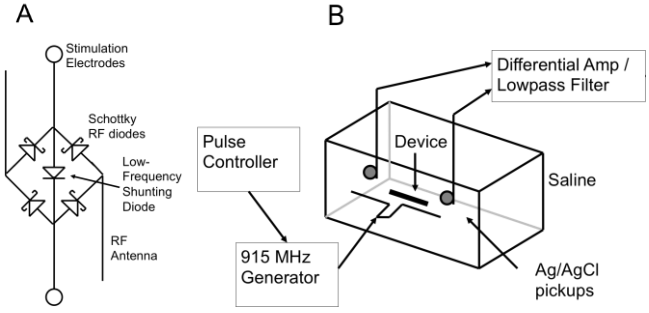

Fig. 7. A: circuit diagram of RF-powered stimulator with a PN diode limiter. B: Setup for measuring the stimulator response in a saline tank model of tissue.

C. *Voltage limited stimulator*

Rather than using harmonics as a feedback signal to control a stimulator, another solution to the unknown power loss is a fixed voltage limit. To test voltage limiting, we built a new RF-powered stimulator. We used a full-wave bridge of Schottky diodes to rectify the RF, and a p-n junction diode to limit the stimulation. The diode shunts all voltage above a fixed threshold and its capacitance filters out the RF of the rectified voltage. The bridge arrangement of RF diodes keeps this capacitance from shorting the antenna.

III. RESULTS

A. *Harmonics from a piezoelectric diode sensor*

Testing the ultrasound-powered single-diode stimulator (fig. 2), we plotted the first three harmonics vs. normalized ultrasound drive. The curves appear unique, which suggests the harmonics might contain usable information about local conditions (resistance and bias) even after being normalized.

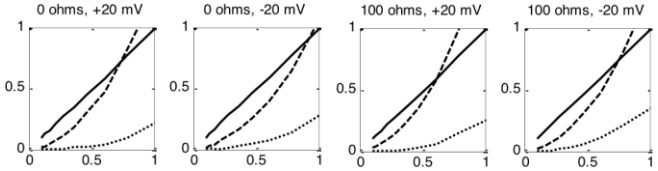

Fig. 8. Measured responses from ultrasound-powered stimulator for several bias and resistance values. 1st harmonic (solid), 2nd (dashed), and 3rd (dotted). 2nd and 3rd scaled 10x for visibility.

B. *Harmonic decoder simulation*

The lookup table was successfully able to match the harmonic curves to the circuit parameters, for this particular range of parameters, if given better than 30 dB SNR.

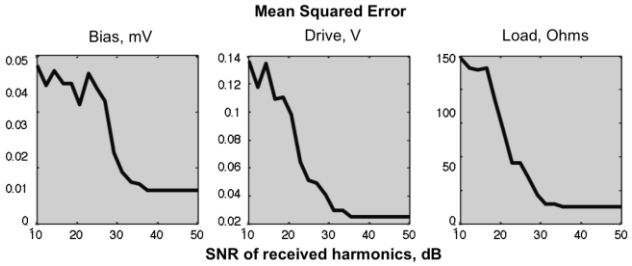

Fig. 9. Decoder simulation. Error of the parameter estimates, vs. the noise added to the harmonics signal.

The upper and lower limits of the error show shortcomings of the simulation: at high noise, the error is partially constrained by the range of the lookup table. At low noise, the error cannot approach zero due to finite resolution.

C. *Voltage limited stimulator*

To test the limiter, we applied a ramped RF pulse. At high power, the stimulation reaches the limit (fig. 10, top right). A stimulator with a fixed voltage could be usable if pulse width can be adjusted freely and a higher drive power applied to give a working range of control but this is not always desirable. To avoid this we used pulse width modulation (PWM). If the RF is pulsed quickly (0.1 to 10 usec), then the

shunting diode controls the peak voltage while the nerve responds to the average voltage. This allows the effective stimulation power to be adjusted (fig. 11).

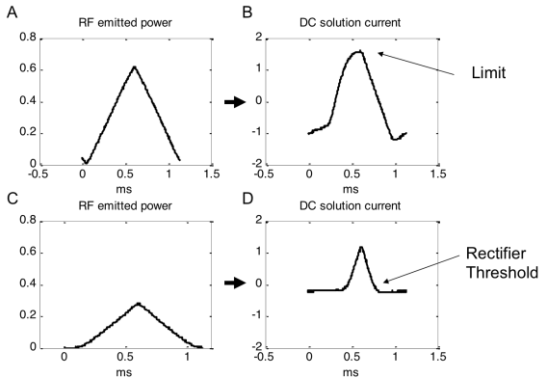

Fig. 10. A and C: RF drive power. B and D: stimulator current. C shows that the PN diode successfully shunts excess stimulation voltage. D shows the diode threshold near turn-on.

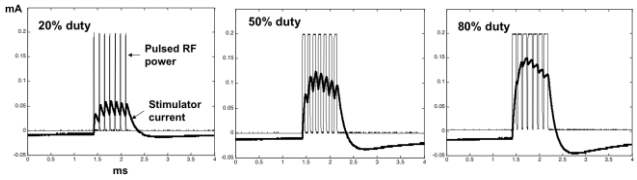

Fig. 11. Output of the RF stimulator using a diode limiter, with fast-chopped RF pulses. The stimulation current (dark trace) is filtered to represent stimulus experienced by a nerve. Chopping scales down the stimulation voltage, proportional to duty cycle.

IV. Discussion

A. Proposed System for Harmonic Feedback

Detection of the harmonic spectrum emitting from implanted diode-type neural devices can provide information about implant current flow and other parameters independent of varying coupling losses. For stimulation monitoring, a series of interrogation pulses would find the parameters (power loss, tissue load, and offset), then a pulse would be chosen for the desired current (figs. 12 and 13)

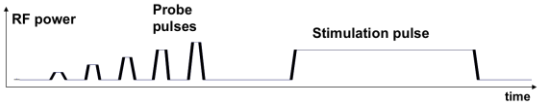

Fig. 12. Interrogation strategy to use harmonics as control for a stimulator. The system would find the correct power before stimulating. A sensor would use probe pulses only.

Errors in drive, bias, or load estimation are tolerable in some applications. The ideal decoder will depend on the application, and on the parameter variance with motion.

It is unclear if diode modeling using manufacturer's specifications can be accurate enough to build a calibration table. If not, an apparatus like fig. 2 could test the physical system across a range of parameters. Our simulation swept drive, bias, and load, but many other parameters might affect the physical system such as electrode capacitance.

These general strategies should apply to RF, ultrasound, and volume-conduction, though ultrasound might also allow direct position sensing [12] as well as harmonic feedback.

A voltage-limited stimulator can also perform power estimation and feedback by ramping probe pulses and sensing when the response fails to increase [13].

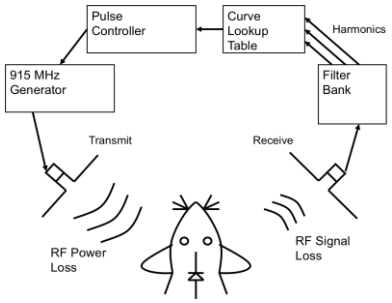

Fig. 13. Proposed system for a harmonic-controlled stimulator.

V. Conclusion

Control of implanted single-diode devices can be achieved by a number of methods including harmonic analysis and pulse width modulation with limiting. Such systems increase the complexity of the external exciter system, but allow for real-time control over pulse parameters. The simplicity and very small chip size of single-diode devices may be useful for minimally invasive, potentially low-cost, flexible, or biodegradable implants with an external exciter.

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