35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A Low Emission, Low Power Non-Linear Frequency Modulation Based Transmitter For Implanted Devices

Ruchir Saraswat and Esther Rodriguez-Villegas

Abstract— **The paper proposes a low emission, non linear frequency modulator for transmitting neural signals. With the advent of embedded medical devices, designers need to start developing low Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) devices. We propose a non-phase locked loop based frequency modulator. The modulator utilizes a ramp to encode the bit stream from the neural amplifier. In addition it utilizes a non linear signal to modulate the encoded signal leading to lowering of peak of power spectrum, a measure of electro-magnetic interference. The proposed algorithm has been implemented on 0.18μ AMS technology and results presented.**

I. INTRODUCTION

The digital age is changing the nature of health care delivery. Medical devices utilizing wireless technologies have seen an explosive growth, some implanted and some worn on the body, to control bodily functions and to measure an array of physiological parameters.

With an increasing number of wireless embedded devices, the devices will need to be designed with low emission so as to minimize interference amongst themselves and external environment. Every medical device, whether implanted or worn on the body, that uses radio technology falls within the regulating body's authority to manage the electromagnetic spectrum. As the frequency band becomes clogged with different devices, the radio frequency interference can be solved by shifting the frequency of operation outside the interfering channel. It is obvious that in such a scenario it would be undesirable to widen the bandwidth of a signal for Electromagnetic Interference (EMI) performance as this would lead to spectrum overlap with the adjacent channel. Thus, there is a need to improved algorithm which could provide a better EMI characteristic having a lower peak power compared to the conventional periodic modulation profiles for the same amount of spread.

Different modulation technologies, such as Impedance Modulation [1], Frequency Shift Keying (FSK) [2], have been used for encoding the data stream to be transmitted wirelessly from an implanted device. FSK has been shown as viable alternative to widely used Amplitude Shift Keying (ASK) where higher bandwidths are required [2]. FSK is one of the common modulation schemes in digital communication, which simply means sending binary data with a sinusoidal carrier at two distinct frequencies which representing logic 1 (mark) and logic 0 (space). Consequently, in the frequency domain, the signal power is centered about these two frequencies. This paper proposes a non-PLL based frequency modulator. This is advantageous in scenarios where a high power consuming voltage controlled oscillator (VCO) is not needed [3].

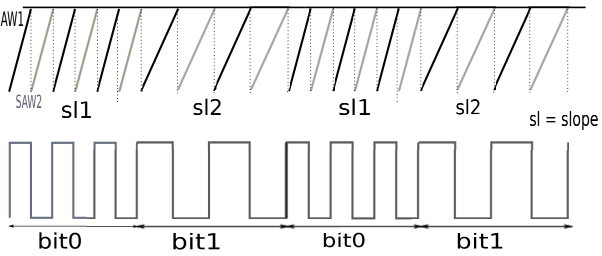

Fig. 1. Generation of modulated signal edges by comparing ramp with a reference signal. The slope of the ramp determine the frequency of resultant encoding signal.

A prototype has been implemented in 0.18μ AMS technology. The chip is under fabrication and a detailed paper is planned for near future publication. Simulations were performed on the extracted layout netlist. Thus, we believe that the simulated results will be in close agreement with the measured results. The paper is organized as follows. Section II discusses the algorithm of the block and the circuit architecture. Section III discusses the simulations results and section IV concludes the paper.

II. DESCRIPTION

A. Algorithm

For reducing the peak power density in signals (a measure of EMI [4]), intentional jitter [5] is introduced in the encoded frequency modulated signal such that the maximum frequency deviation is compatible with the devices timing requirements. Signals produced by chaotic systems are typically a-periodic and broad-band thereby spreading the energy more efficiently in contrast to concentrating them at multiples of periodicity as in the case of conventional periodic modulation profiles such as Hershey Kiss profile. This paper proposes a novel approach utilizes a non-linear signal [6] for modulating the encoded signal.

Figure 1 depicts the algorithm for encoding the bit stream into a frequency modulated signal. Two 180^o out of phase sawtooth waveforms are generated. Two independent saw tooths are utilized to compensate for error resulting due to finite time it takes for the sawtooth to discharge. The sawtooths are compared against a reference signal and an edge is produced at the intersection point. The frequency of

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The authors are with the Department of Electrical and Electronic Engineering, Imperial College London, UK. Email: {`ruchir.saraswat,e.rodriguez`} @ imperial.ac.uk

The research leading to these results has received funding from European Research Council under the European Community's 7^{th} Framework Programme (FP7/2007-2013) / ERC grant agreement no. 239749

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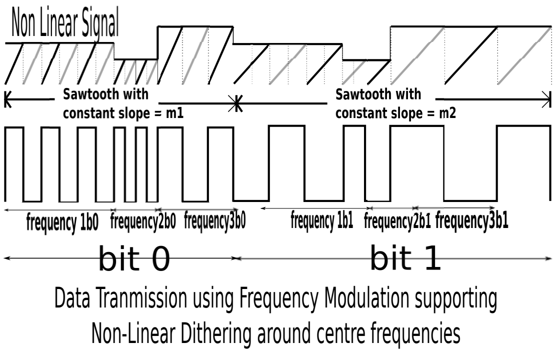

Fig. 2. Chaotic dithering of the encoded signal by comparing the ramp with the chaotic signal.

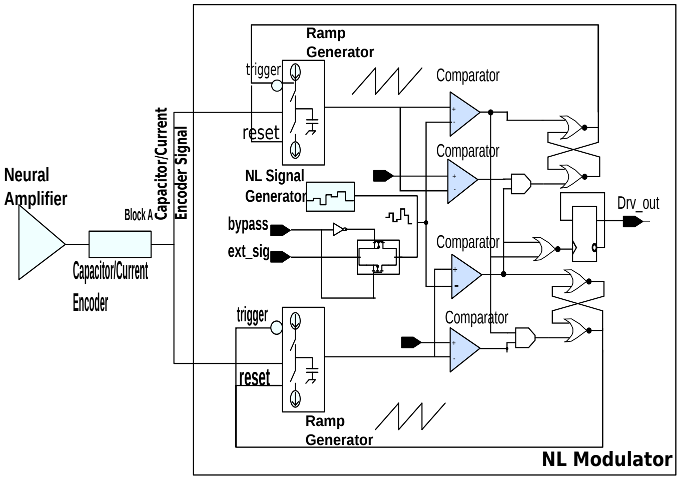

Fig. 3. Non Linear Modulator Block Diagram

the modulated signal can be varied by varying the gradient of the ramp. As depicted in figure 1, gradient values are chosen depending upon the bit to be encoded.

Figure 2 depicts the algorithm for a wide band chaotic modulation of encoded modulated signal around its base frequency. The chaotic noise is a continuous voltage signal with random voltage levels and is generated by the chaotic sequence generator. For the current work, a tent map function (1, 2) has been utilized to generate the chaotic sequence.

$$x_{k+1} = 2x_k \qquad for \quad x_k < V_b \tag{1}$$

$$x_{k+1} = 2(2V_b - x_k) \quad for \quad x_k \geq V_b \tag{2}$$

The frequency of the encoded signal follows the change in voltage level of the non-linear (chaotic) signal as depicted in figure 2. It is important to note that the data is encoded by changing the gradient of the ramp while the chaotic dithering is done by varying the reference level.

B. Block Description

Figure 3 depicts the major blocks of the complete system. It comprises of a neural amplifier (Front End) which amplifies the neural signals. The bit stream (logic 0 or logic 1) is decoded to a pre-defined current code or a capacitor setting. The current code or the load capacitor setting controls the gradient of the ramp as shown in figure 1. The current/load capacitor settings are sent to the NL Modulator. The current paper focuses on NL Modulator block. It consists of a non-linear (chaotic) signal generator, saw tooth waveform generator, comparator's and edge logic for generating the modulated signal. The following sections describe the various blocks in detail.

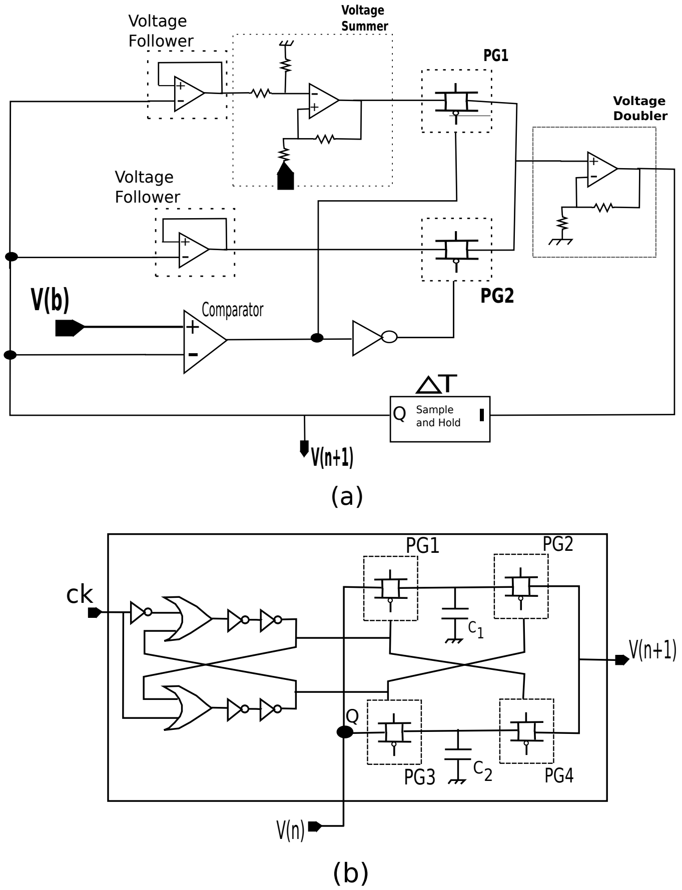

Fig. 4. (a) Block Diagram of Non Linear Signal Generator (b) Analog Sample and Hold Circuit

C. Non Linear Signal (Chaos) Generator

Figure 4 (a) depicts the circuit diagram of chaotic sequence generator (tent map based). The tent map system is modeled as equations 1 and 2. The circuit has been designed with V_b = 0.5V. The V_b can be programmed in the chip so as to enable restricting the frequency range of the encoded modulated signal. The multipliers have been implemented using standard 2 stage operational amplifier. Pass Gates PG1 and PG2 (fig. 4 a) form a multiplexer. They selects either $V(n)$ or $2V_b - V(n)$. The decision is made by the comparator output based on whether $V(n) < V_b$ or $V(n) > V_b$. The output of the multiplexer (formed by pass gates) is passed on to the voltage doubler to obtain the tent map equations given by equations 1 and 2. The output signal generated is sampled and fed as input after a delay ΔT. The delay is implemented by Sample and Hold (S/H) circuit as depicted in figure 4(b). The pass gates in the S/H PG1, PG4 and PG2, PG3 (fig. 4 b)operate out of phase with each other, hence connecting the node Q to one of the capacitors (storing the sampled

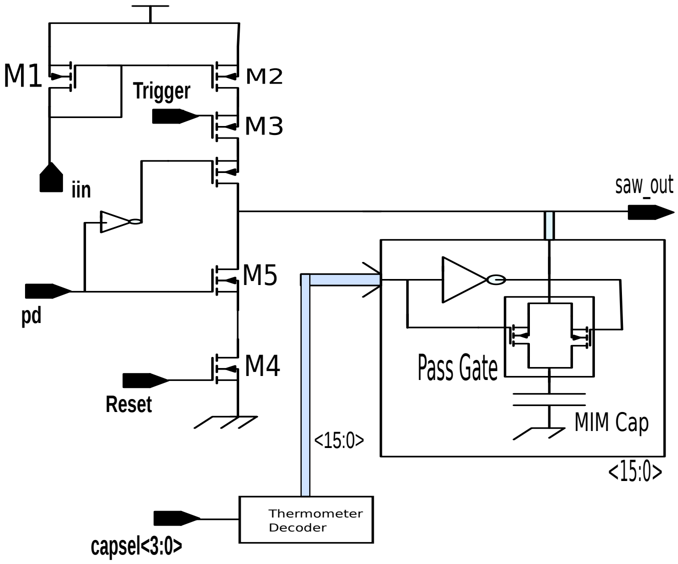

Fig. 5. Block Diagram of Ramp Generator

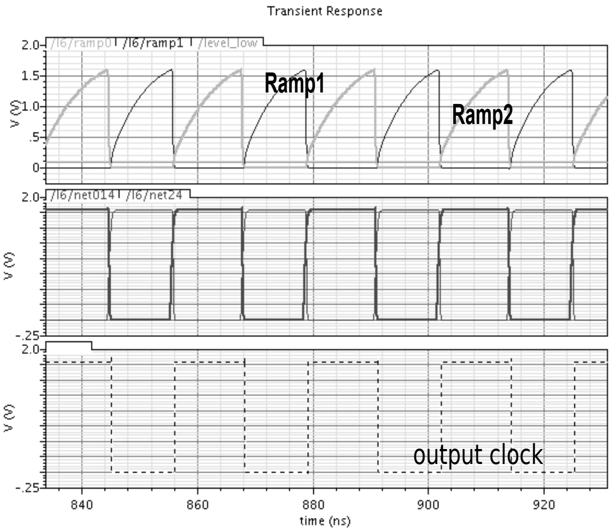

Fig. 6. Sawtooth waveform Generation

input voltage) while the other samples the new value. The node Q is connected to a high impedance terminal to prevent the capacitor from discharging.This has been achieved by connecting the terminal Q to a voltage follower.

D. Sawtooth Generator

The sawtooth generator produces two sawtooths by charging and discharging a capacitor as depicted in figure 5. The width of the sawtooth is a measure of the time period of the encoded frequency. The magnitude of the current and the size of the load cap determines the gradient of the saw and hence the frequency of the modulated signal. The load capacitors have been implemented using Metal In Metal (MIM) capacitors. A 4 bit thermometer decoder has been implemented to select the capacitors. Transistors M1,M2 form the current mirror. M3 and M4 charge and discharge the capacitor respectively. M5 and M6 are used to isolate the capacitance during a power down mode. Since, the discharge current through M5 is not controlled, the discharge gradient is very fast compared to charge gradient. This has been done intentionally as we want the sawtooth to discharge fast to be ready for the next charging cycle as depicted in fig. 6. It can be inferred that the frequency range for encoding the data stream is controlled by the range of the current sources and the load cap.

E. Edge Generator

The final encoded modulated signal is generated through logic depicted in figure 4. A D flip flop is used to toggle every time one of the sawtooth waveforms intersect with the reference signals. Thus, any change in the gradient of the saw tooth or the change of reference signal voltage leads to a change in the frequency.

III. FLOOR PLAN AND SIMULATION RESULTS

A. Floorplan

The current work has been prototyped on 6 metal layer 0.18μ AMS technology on 10mm by 10mm die. Figure 7 depicts the floorplan of the NL modulator. All the comparators have been placed symmetrically for proper matching. Higher metal layers were used for creating a mesh power grid to lower the supply parasitic. The ramp generators are placed symmetrical about x axis to ensure adequate delay matching.

B. Simulation Results

All the simulations were done on extracted netlist from the layout. Figure 8 depicts the output of the non-linear signal generator. It is interesting to see that the sample and hold circuit introduces some error due to leakage in the capacitor. This has been mitigated in the current design as discussed in section II.c.

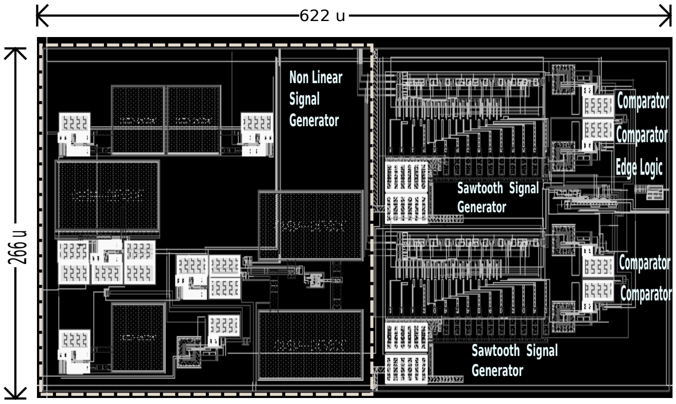

Fig. 7. Layout and Floorplan of the Non Linear Modulator

Fig. 9 depicts the data stream being encoded as frequency. The change in frequency is manipulated by altering the gradient of the saw tooth waveforms. This has been achieved by changing the charging current. This could also be done by changing the capacitive load of the saw tooth generator by changing the 4 bit thermometer decoder input.

As seen in Fig. 10 the modulated frequency of the encoded signal follows the chaotic signal. A source of error in the

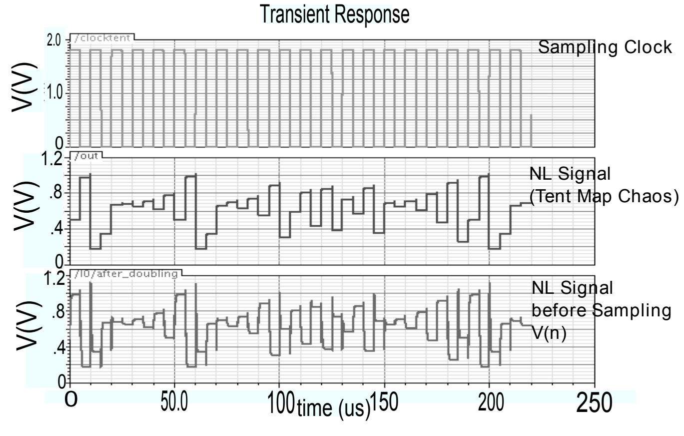

Fig. 8. Non Linear Signal (Tent Map) Generation. It can be seen that impact of the capacitor leakage is minimal after sample/hold due to the high impedance node inserted in the path.

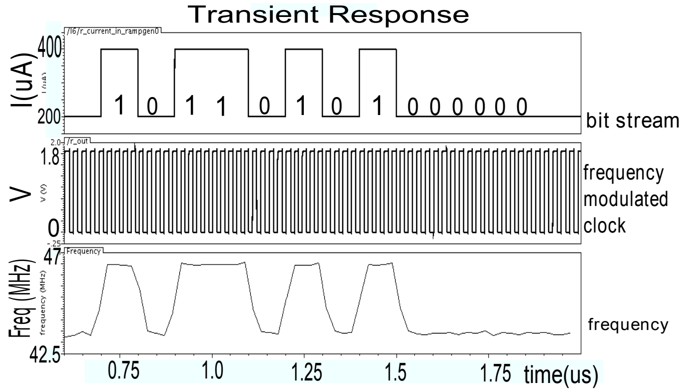

Fig. 9. Encoded Data stream into the frequency

modulated signal frequency is the the comparator delay and the delay due to the edge logic. This error results in a frequency offset and can be modeled as $(t_{Comparator} + t_{edgelogic})_{risingedge} + (t_{Comparator} + t_{edgelogic})_{fallingedge}$ where $t_{\{\}}$ depicts the delay. However, this error is easily taken care by reducing modulated frequency specification of the modulated signal by the same amount.

Figure 11 shows the power spectrum of the un-encoded non linear modulated signal and a periodically modulated signal. The encoding information has been taking out of the spectrum as during the chaotic modulation, the base frequency remains constant. It can be observed that the power spectral density (PSD) of the chaotic modulation profile is flatter and denser compared to the periodic modulation profile resulting in a 8dB lowering of the peak.

IV. CONCLUSIONS

The paper presents a non-PLL based frequency modulator for encoding a bit stream. The paper also presents a novel modulation architecture for reducing the electromagnetic signature of the transmitter. Simulation results on extracted netlist have been presented which have shown over a $8dB$ improvement in reducing the peak of the signal power spectrum. A prototype is under fabricated in 0.18μ AMS technology and a detailed paper is planned for publication with silicon results.

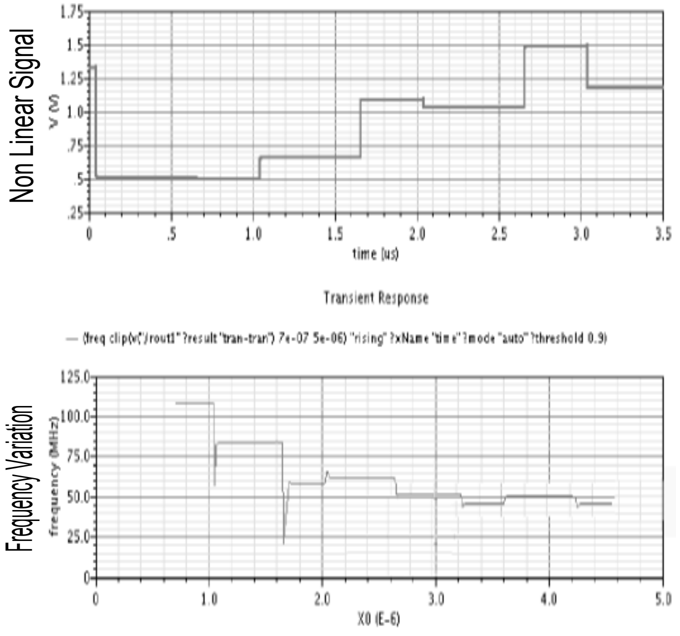

Fig. 10. Change in frequency according to the chaotic signal

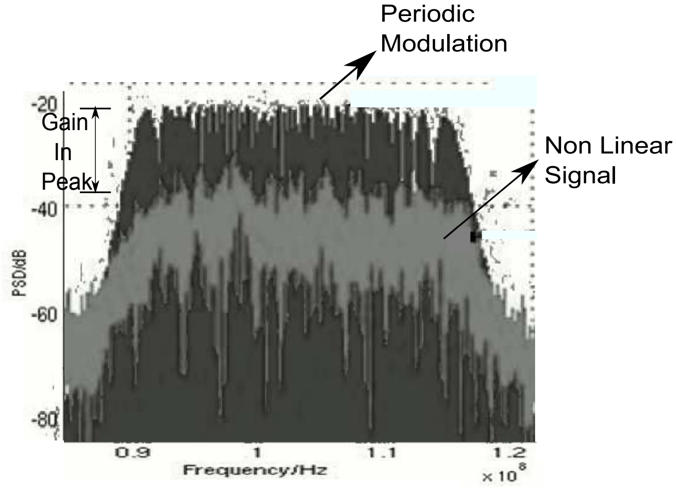

Fig. 11. Power Spectral density of the modulated signal.

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