A New Microstimulator with Pulse Width Modulation

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Abstract

A novel implantable microstimulator has been designed, fabricated, and characterized. The pulse width modulation (PWM) has been used to control the output current source for changing the duration of output waveform. The frequency of output stimulus current can be controlled by a Schmitt trigger based relaxation oscillator. Finally, the intensity of output stimulus current can be programmed by a 5-bit digital code. This circuitry can operate in only 2.5V low voltage to improve the disadvantage of conventional microstimulator that is not suitable in low voltage. In the architecture of circuitry, it reduces the circuit complexity formed by typical microstimulators adopting mircoprocessors as the control unit. The measured results of the proposed microstimulator chip show that this system is quite feasible for different stimulus modes including regular, random and burst modes. This circuitry has been simulated with HSPICE and fabricated in a 0.35μm 2P4M CMOS process.

***Keywords*:** Microstimulator, PWM, CMOS process

Introduction

Implantable microstimulators have extensively been used in many therapies for chronic diseases through electric current stimulation to change natural response of human neural system [1, 2] and then to gain curative effects for human tissue, muscle, organ or psychiatric state. Electrical stimulation was applied to treatment for the drop foot of apoplectic patients in 1960. Recently, electrical stimulation therapy was also gradually applied to patients who had spinal cord injury [3] to help them carry out the rehabilitation of functional action. Owing to the progress of CMOS technology in very large scale integrated circuits (VLSI), it not only improves the functions of microstimulator but reduces its die size and power consumption to make microstimulator more suitable in implantable and clinical applications.

Electrical stimulation is a way to induce excitation of nerves or muscle. There are also other ways like hot stimulation, mechanical stimulation, and chemical stimulation etc. However, microstimulators are easy to control the stimulus intensity and duration, and similar with excitative process in physiology. Therefore the electric stimulation for nerves and muscle is used frequently. Microstimulators usually adopt the rectangular monophasic or biphasic periodic pulse waveforms which have three basic parameters：Stimulus pulse amplitude, pulse frequency, and pulse width. The physiological meanings of these parameters are described as follows：

(1) Intensity：After being stimulated, cells can induce the voltage difference. According to “all or none” principle, currents lower than the threshold can’t induce any action potential; once stimulation is strong enough, it could induce the largest action potential. The intensity of electric current can be increased gradually until it exactly induces the responses of nerves, and then we named it the threshold stimulus.

(2) Duration: The stimulus duration must be long enough to inspire effective stimulations and induce the responses of nerves. The shortest time which can induce responses of nerves is called the excitation time. The larger intensity of the stimulations is, the less time of the stimulations needed. However, if the stimulus time were too short, no matter how the intensity of the stimulations is, the responses of nerves couldn’t be induced.

(3) Frequency: If one nerve were stimulated more than one minute by direct current of moderate intensity, the nerve only responds in the initial period, and couldn’t respond to the rest of time. The reason is nerve cells make an accommodation to stimulus time, and let the potential of membrane be stable. So the frequency must be over the lowest requirement [4]. Whatever the nerves or muscle, the excited frequency has limitations during a period of time. For the nerves, the excitation per second can’t be over one thousand [5].

Principles and Methods

Figure 1 describes a basic architecture of conventional microstimulators [6]. The external unit of microstimulators

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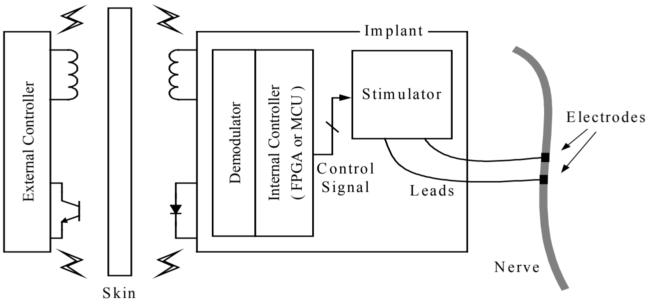

Figure 1. The basic architecture of microstimulators [6]

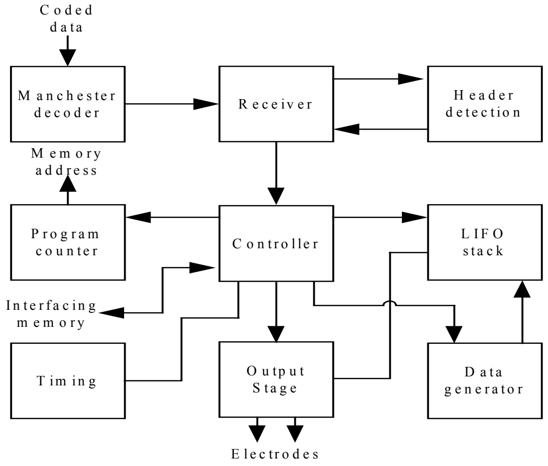

Figure 2. The control unit of microstimulators [3]

transmits signals and power to the control unit through wireless communication. After the control unit receiving signals, it outputs the relative stimulus waveform. The schemes and control of stimulus waveform [2, 7-9] compile the targeting stimulus waveforms with program, and deliver a series of control signals to electric stimulator system to decode, and then shake hands with the micro controller. After operational analysis of micro controller, it drives output circuit source to generate stimulus circuit waveforms.

In general, microcontroller is the center of microstimulators shown in Figure 2. In hardware design of micro controller, we must collocate with software (program language) properly in order to encode, decode, and address the bus and I/O ports. Every output data package must include error correction codes to confirm the data delivered and received are coincident, and efficiently to act the push/pop operation and the programmer counter (PC) for delivering programming codes to register or arithmetic logic unit (ALU) to operate.

Although the stimulus waveform and parameters of the implantable microstimulators are simpler than Transcutaneous Electrical Nerve Stimulation (TENS), but the complexity of the microstimulators would be heavy. Besides, they need professionals to maintain program and set parameters. Therefore, block diagram of a novel microstimulator system has been proposed in Figure 3 to improve the complicated architecture mentioned above.

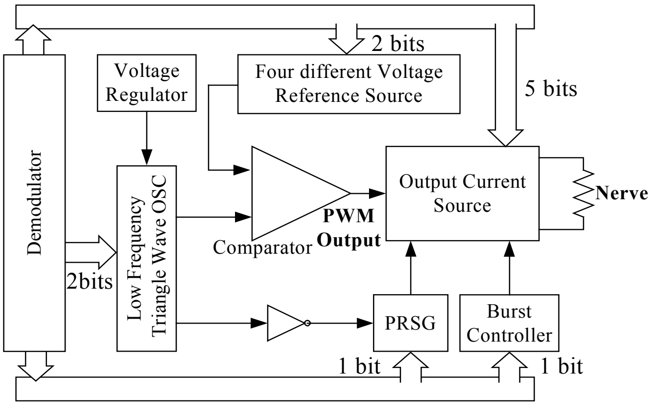

Figure 3. Block diagram of the proposed novel microstimulator.

The proposed control circuitry of an implantable microstimulator

A low-frequency triangular wave oscillator has been developed in this work. After comparing its output signals with some voltage reference via a comparator, a rectangular periodic pulse would be formed. There could be sixteen stimulus waveforms generated by combining four voltage reference levels and four frequencies of triangular wave, respectively. In output current source, there would be 32 current intensities produced by a set of 5-bit codes. Additionally, this system also includes burst mode and random mode stimuli for other special clinical applications.

1) The micro-power operational amplifier

In order to satisfy the low-power requirement of microstimulator in biomedical applications, low supply voltage and low static current operations are design concern. The major circuitry of amplifier used in voltage regulator has been designed and operated in the weak inversion [10-11]. The operating current of MOSFET in weak inversion region has been designed to less than 1uA; it's suitable for implantable biomedical systems or electrical devices restricted with batteries capacity [10].

2) Output current source

Because the charge accumulation caused by the monophasic current easily injures human nerves, nerves stimulators generally adopt biphasic current to provide the balance of positive and negative charge, and simultaneously avoid bringing irreversible oxidation-reduction reaction occurred in electrodes. The H-bridge circuit in this study has been used to make current source delivering stimulus current from diverse directions alternately. Besides, the current sources of traditional microstimulators need to ensure three cascade transistors working in the saturation region are indicated from previous studies [12-14], and they can't work normally when the power supply descends; moreover, they are unsuitable for low voltage or single battery operation. We propose a current source shown in Figure 4 to improve the problems mentioned previously.

In this design, we make the lengths and widths of transistors M_4~M_0 scaled from 16 to 1 respectively, and use the

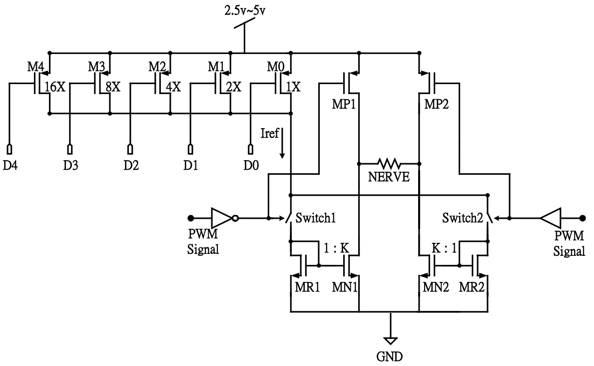

Figure 4. The proposed novel output current source of microstimulators

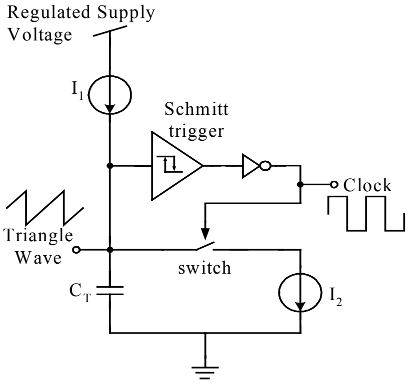

Figure 5. The low-frequency triangular wave oscillator

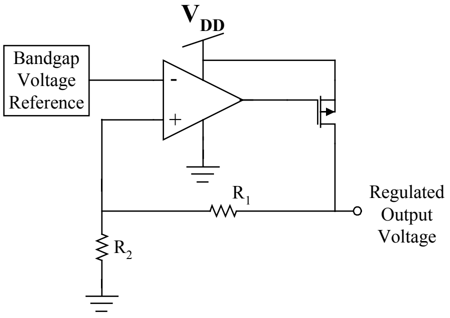

Figure 6. The voltage regulator

programmable digital inputs D_4~D_0 to choose 31 sets of reference currents (I_{ref}) with different intensities. Then, the control signal turns on either one set of the switch (Switch1 or 2) and the transistor (MP1 or MP2) at the same time. Therefore, the H-bridge circuit appears only one path at the ON state of M_{P1}-NERVE-M_{N2} or M_{P2}-NERVE-M_{N1}. Via exchanging the high or low level of control signal, it can change the ON path of the H-bridge circuit, and generate the stimulus currents in alternative directions on nerve cells. Simultaneously, after the reference current ((I_{ref}) flowing into the current mirror which is make up of M_{R1}, M_{N1} or M_{R2}, M_{N2}, it could duplicate the stimulus current according to the multiple K of the current mirror. Because the current source in the ON path has less transistor used than the conventional output current source mentioned in other micro stimulator. Thus, the output current can be manipulated normally in low supply voltage. And its power can be expressed as the following equation：

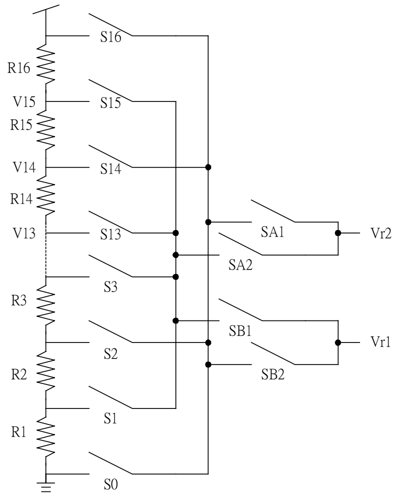

Figure 7. The voltage reference generator

$$Power \leq VDD \times I_{ref}(1+K) \tag{1}$$

where K is the multiple of the current amplifier.

3) Low-frequency triangular-wave oscillators and voltage regulators

A low-frequency oscillator is shown in Figure 5. When the current I_1 charges the capacitor C_T to the high level of Schmitt trigger, the output of Schmitt trigger is LOW, and then drives the switch to be ON through an inverter to form a discharging path that make I_1 and C_T discharge via I_2. When the capacitor discharges to the low level of Schmitt trigger, the output of Schmitt trigger is HIGH, and via an inverter the switch turns off and the capacitor charges subsequently. Thus, we can get a triangular wave on the capacitor node and a synchronous rectangular wave on the Clock terminal [15]. In the condition of I_2=$2I_1$, the frequency of this oscillator is:

$$f = \frac{I_1}{2C_T V_H} \tag{2}$$

V_H is the Hi-Lo voltage difference of Schmitt trigger. This oscillator provides four frequencies: 50 Hz, 100 Hz, 150 Hz and 200 Hz. A temperature-independent bias current and constant oscillating frequency has been implemented by a bandgap reference and a regulator shown in Figure 6 [16].

4) Voltage reference generator and pulse width modulation circuit

In this study, the pulse width modulation waveform is formed by the comparison of a triangular wave and a voltage reference; utilizing the analog multiplexer composed of a resistances chain and switches can accomplish the function of output voltage reference shown in Figure 7. Figure 8 demonstrates the stimulation result of a triangular wave with four dc reference signals respectively. Figure 9 shows the stimulus result of the pulse width modulation verse the intensity of the stimulus current in the 100 Hz stimulus frequency.

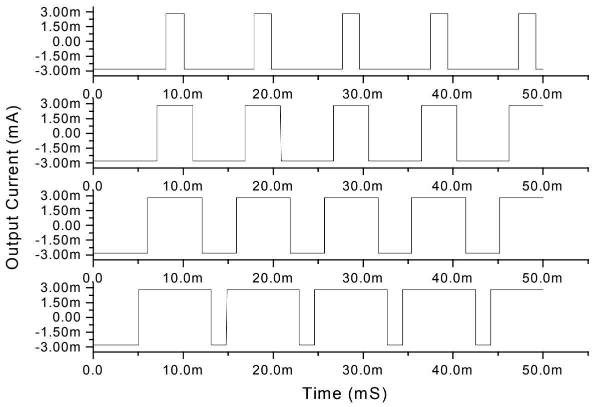

Figure 9. The output stimulus current in PWM

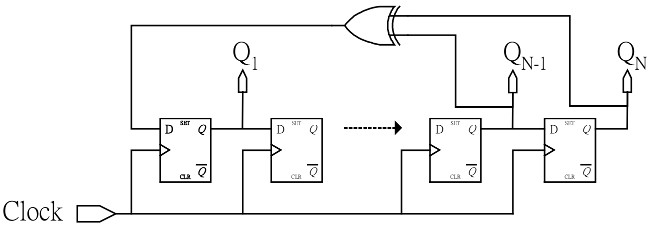

Figure 10. The pseudo random number generator

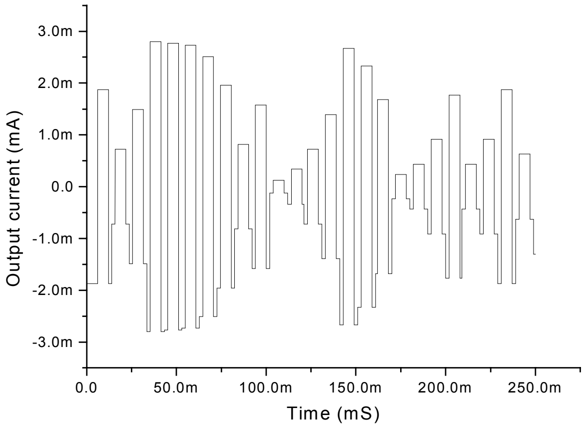

Figure 11. The random stimulus waveform

5) Random mode and burst mode

In order to get the random stimulation function, a pseudo random number generator [17] has been adopted. The pseudo random number generator is a serial in and parallel out register, and the last two output bits feed back to the input as shown in Figure 10. Taking 3 bits for example, the output is 7-3-1-4-2-5-6-7….etc. If total bits are N, the total random number would be:

$$\text{Total random number} = 2^N \tag{3}$$

Figure 11 shows the random stimulus result. Additionally, in order to imitate the burst stimulations for massage therapy applications, we can utilize a counter to count the number of rectangular waves from the oscillator output. In the fixed amount of rectangular waves, the currents are delivered, while in the next amount of rectangular waves, the currents are blocked, so that the burst function could be performed. The burst mode circuitry is shown as Figure 12. Figure 13 shows the simulation results of burst stimulus waveform in 100 Hz.

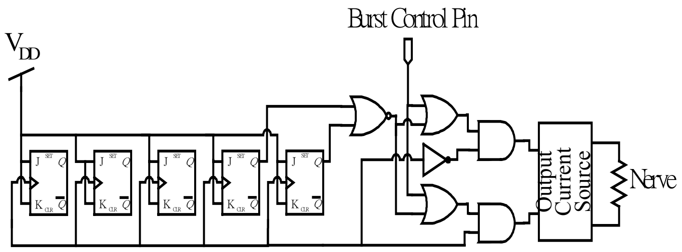

Figure 12. The control circuit in burst mode

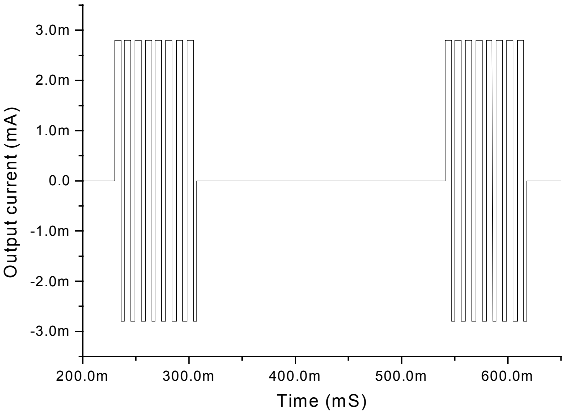

Figure 13. The stimulus waveform in burst mode

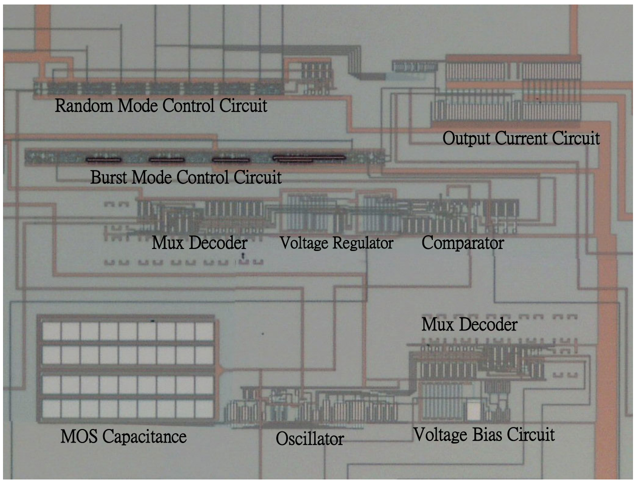

Figure 14. Microphotograph of the microstimulator chip

Measurement Results

The circuits of this study were verified by HSPICE simulator and fabricated in TSMC 0.35 μm CMOS process, and the microphotograph of the designed microstimulator is shown in Figure 14 and the core layout is about 800 x 600 μm^2. The measurements were performed using a 1k load resistor and 100 Hz oscillation frequency. The output was viewed with a Tektronix TDS-3032 300-MHz digital sampling oscilloscope.

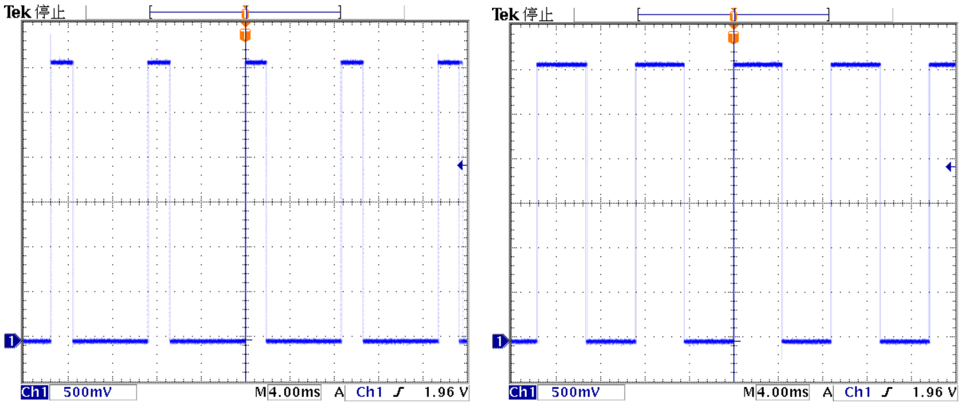

Figure 15. (a) The stimulus output signal, duty cycle is 24%, pulse width is 2.21ms (b) duty cycle is 50%, pulse width is 4.63ms

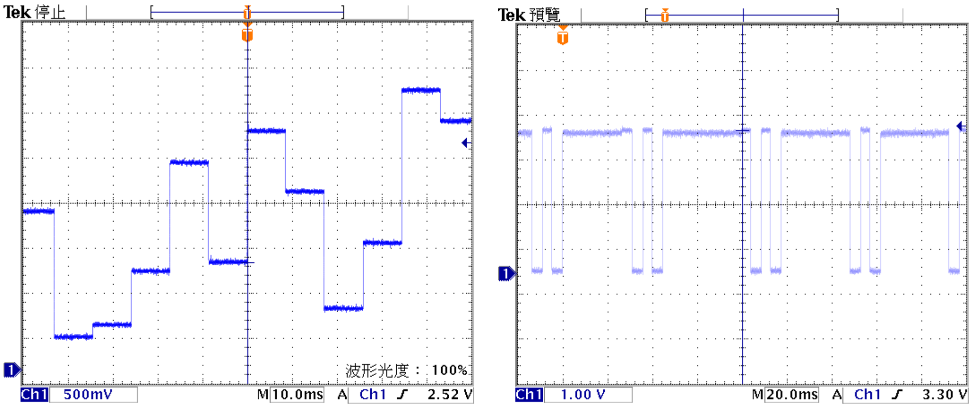

Figure 16. (a) The stimulus waveform in random mode (b) The stimulus waveform in burst mode

Table 1. Summary of measurement results

Parameter	Value
Power Supply	3.3v
Maximum Power Consumption	9.8mW
Output Current Amplitude	0~2.8mA, 5-bits programmable
Stimulation Frequency	50, 100,150 and 200Hz, 2-bits programmable
Stimulation Duration	0.11mS ~ 15.6mS, modulated by 4 frequencies and 4 different voltage levels.
R Load	500 ohm ~ 1000 ohm
Random mode	Available
Burst mode	Available
Program Language for Stimulation Controller	Not necessary

Figure 15 (a) and (b) shows the signal measured directly across the load resistor. The measurement results are 24%, and 50% respectively. The measurements results of stimulus waveform in random mode are shown as Figure 16 (a) and the stimulation intensity can change randomly are proved. Measurement results of stimulus waveform in burst mode are shown in Figure 16 (b), the waveforms are consistent with HSPICE simulation, and illustrate this design has quit feasibility in different stimulation modes.

Summary and Conclusion

A new implantable microstimulator chip using pulse width modulation skills has been designed and fabricated in a 0.35μm CMOS technology. To achieve low power consumption, critical MOSFETs in the operational amplifier were operated in the weak inversion region. The performance of the proposed stimulator is summarized in Table 1. The stimulus pulse generated by PWM can collocate with four different frequencies including 50Hz, 100Hz, 150Hz, and 200Hz to be selected. The output current source can provide different current intensity from 0 to 2.8 mA in 3.3V working voltage with the 5 bits control code. Besides the stimulus waveform in regular mode, this circuit also provides the stimulus waveform in burst and random mode. Experimental results show great promise for the proposed microstimulator to be used in future clinical applications.

Acknowledgments

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