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A Low-Power Noncoherent BPSK Demodulator for Implantable Medical Devices

B. Beheshti and M. Jalali
Electrical and Computer Engineering Department
Shahed University
Tehran, Iran
bbeheshti@ieee.org

Abstract—**A fully-integrated non-coherent BPSK demodulator intended for implantable medical devices is presented. Places of every 180 degrees phase transitions in BPSK modulated signals are recognized using active high-pass filters as negative and positive sharp pulses with adequate amplitude. In order to recover the initial base-band data, the sharp pulses are converted to digital level pulses using an op-amp based Schmitt trigger circuit. For a data rate of 1 Mbps and carrier frequency of 1 MHz, the proposed demodulator achieved a 100% data rate to carrier frequency ratio. Designed in a 0.18 µm standard CMOS technology, it consumes only 49 µA from a 1.8 V supply.**

I. INTRODUCTION

In recent decades, relation between engineering and medical sciences such as cooperation in field of implantable devices and microchips in vivo lionize a lot. These devices can be used for therapy of disabilities such as blindness and deafness [1] and also study and treatment of nervous system and its disorders such as epilepsy, paralysis and Parkinson's disease. As shown in Fig.1, the implant systems receive their power from external controller and have bidirectional data transmission with external world. This communication is provided by wireless technology [2]. Inductive link is the simplest specimen of this technology. The implanted part should gain its power by rectifying the carrier of induced signal, extract the data from received signal and prepare it for stimulation part and also send back information to external world.

In the cases where the implant interfaces with nervous system [3], this device should be capable of providing high data rate [2], [4]. In addition, this device should consume low power and work with a low frequency carrier [5]. There are many methods for transferring a digital data to an implant module, but the three more important of them are Binary Amplitude Shift Keying (BASK) [6], [7], Binary Frequency Shift Keying (BFSK) [8], [9] and Binary Phase Shift Keying modulation (BPSK) [2], [10]. BASK is one of the simplest methods, but since this modulation works by amplitude variation of carrier, a small noise can influence it easily. This causes wrong interpreting of the incoming data, thus increasing the bit error rate (BER) [1], [11]. Moreover, the transmitted power efficiency as well as data transmission rate is nominally low [10], [12]. BFSK and BPSK are more proper modulation schemes, but BFSK uses two carrier frequencies [5], so it is useful for wideband applications that causes poor bandwidths efficiency [8] and increases system complexity. In contrast to BFSK, BPSK has a fixed carrier frequency [11] making it useful for narrowband applications. In addition, it has a relatively high power transferring efficiency and achieves lower bit error rate (BER) among other methods [2].

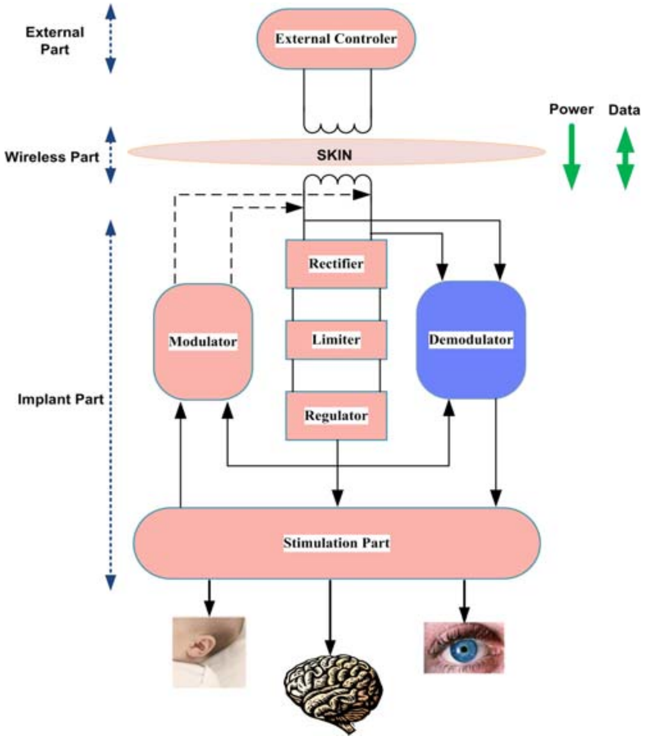


Figure 1. Power and data telemetery for implantable biomedical devices

BPSK demodulators can be divided into two categories; coherent and non-coherent detectors. Coherent detectors [13] are based on phase locked loops (PLL) and usually yield better bit error rate (BER). In the other hand, non-coherent detectors usually try to detect phase discontinuities in the carrier signal. Non-coherent detectors are simpler to design and consume less power.

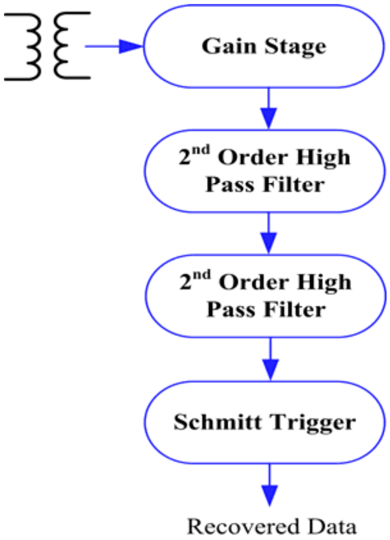


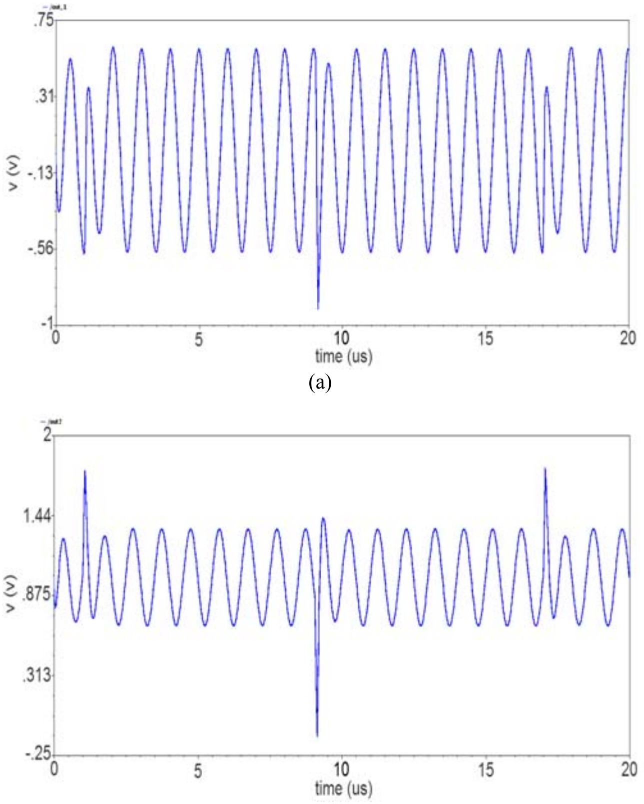
Figure 2. Block diagram of the proposed BPSK demodulator

II. PROPOSED BPSK DEMODULATOR

The block diagram of the proposed demodulator is shown in Fig.2. First the BPSK signal enters to a gain stage circuit where its strength is controlled. Then this signal is fed to a two subsequent 2nd order high pass filter circuit. The places of phase transition (bit transition) in BPSK signal are determined with this circuit by generating positive and negative sharp pulses. These pulses are in fact like impulses. Also, this circuit amplifies the amplitude of these impulses making them recognizable for Schmitt trigger circuit. In the next sections, the operation and circuit details of the presented demodulator are described.

A. *Gain stage*

In implantable microchips, depending on application, the distance between transmitter and receiver coils may vary, causing considerable variation in induced signal strength. In order to guarantee the circuit operability a gain stage circuit should precedes the demodulator. In this design, the gain stage is implemented implicitly within subsequent active high-pass filters.



(a)

(b)

Figure 3. Derivetives of a BPSK signal; (a) 2nd (b) 4th order derivitives.

B. *2nd Order High Pass Filter*

By multiplication of a sinusoidal carrier into a bi-polar bit stream, which switches instantaneously between +1 and -1, a modulated BPSK signal will be generated. Of course, in reality, the transitions in the bit stream are not extremely steep and each transition can be modeled [14] by a hyperbolic tangent (tanh) as

$$bpsk(t) = \sin(\omega t).\tanh(\alpha t) \tag{1}$$

where a single transition at t=0s is assumed. In this modeling 2α roughly specifies the switching time required by $\tanh\alpha t$. A high pass filter as a differentiator can detect the phase discontinuities. However, in the BPSK signal there is no discontinuity and a first order differentiation which is defined as

$$\frac{dbpsk(t)}{dt} = \omega\cos(\omega t)\cdot\tanh(\alpha t) + \alpha\sin(\omega t)\cdot\mathrm{sech}^2(\alpha t) \tag{2}$$

produces a zero at t=0s. So, at least a second order differentiation is needed for specifying these bit transitions. It can be shown that

$$\left.\frac{dbpsk^2(t)}{dt^2}\right|_{t=0} = 2\alpha\omega \tag{3}$$

But, as shown in Fig. 3(a) the amplitude of these impulses is not adequate enough to being detected in next stage. So, we used another second order differentiation stage to solve this problem as we have

$$\left.\frac{dbpsk^4(t)}{dt4}\right|_{t=0} = -\alpha\omega(\omega^2 + 3\alpha\omega^2 + 8\alpha^2) \tag{4}$$

which has a higher value prone to be well recognized by a threshold detector (Fig. 3(b)).

A simple RC passive high pass filter can be used as a differentiator. However, this simple circuit doesn't amplify incoming signal and thus requiring explicit amplification stage. Active high pass filter, on the other hand, can solve this

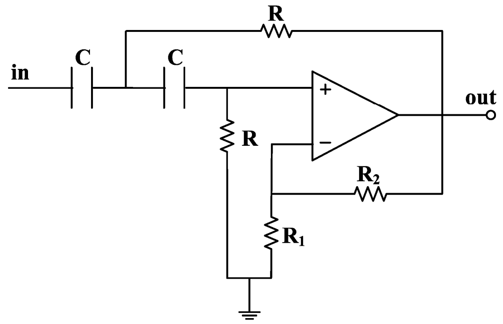


Figure 4. 2nd order active high pass filter circuit

problem if provides sufficient gain. So as shown in Fig. 4, in the proposed demodulator a pair of 2nd order high pass filter was used.

C. Schmitt Ttigger

The voltage at the output of the active high pass filters has negative and positive impulses over a DC voltage and a small feed through of the carrier. A technique is needed to convert these impulses to standard digital level pulses without being affected by the DC level voltage and carrier terms. In other words, a windowing mechanism is required to reject intermediate voltage levels, just detecting positive and negative impulses. The hysteresis window of a Schmitt trigger circuit can be a perfect solution for this problem. Thus, we have used a standard CMOS Schmitt trigger circuit with adjusted hysteresis edges to convert the impulses and restoring the data edges perfectly.

Figure 5 depicts the circuit schematic of the op-amp based embedded Schmitt trigger circuit. In this circuit when V_{in} is low V_{out} is high and M_1 bypasses R_3. Thus the upper edge of hysteresis window denoted by v_{in+} in Fig .5(b) is

$$v_{in+} = \left(1+\frac{R_1}{R_2}\right)V_{ref} \tag{5}$$

while for the lower edge of the hysteresis window, v_{in-}, we have

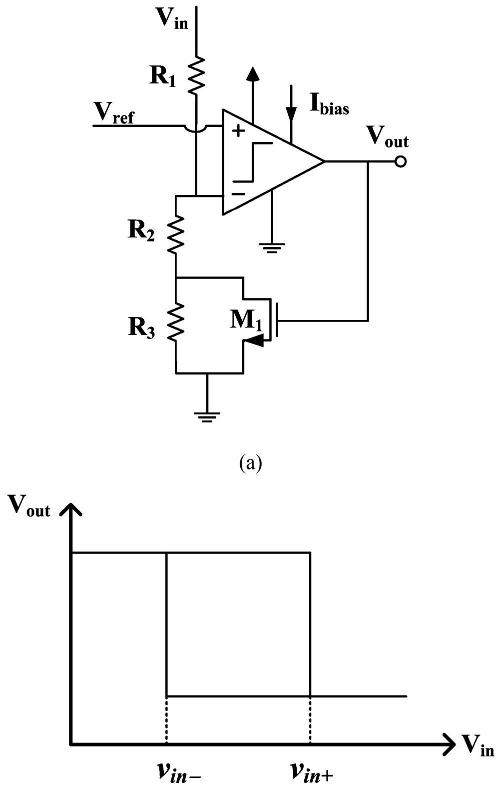
$$v_{in-} = \left(1+\frac{R_1}{R_2+R_3}\right)V_{ref} \tag{6}$$

As a result the hysteresis window can be properly adjusted, which is less sensitive to PVT variations of course if V_{ref} is.

III. SIMULATION RESULTS

The proposed demodulator has been designed and simulated in a standard 0.18-μm CMOS technology. The response of the circuit to a BPSK modulated signal is shown in Fig. 6. According to this figure, the circuit can achieve a data-rate-to-carrier-frequency-ratio of about 100%. For a data-rate of 1Mbps and a carrier frequency of 1MHz, the demodulator only consumes 49μA under a 1.8V power supply. A “Figure of Merit” (FOM) has been developed to fairly compare this work with recently published literatures as:

$$\text{FOM} = \frac{\text{Data rate}}{\text{Power} \times \text{Carrier frequency}} \tag{7}$$



(a)

(b)

Figure 5. Op-amp based Schmitt trigger circuit (a) schematic diagram, (b) hysteresis window.

Table I summarizes the comparison. Due to a high data-rate-to-carrier-frequency-ratio and relatively low power consumption, the FOM of this work is very high in comparison to the other works.

Table I Comparison of recent BPSK demodulators

Reference	Carrier Frequency (MHZ)	Data Rate (MHZ)	Data Rate to Carrier Frequency Ratio	Power Consumption (μW)	FOM
[2]	8	8	100%	148	6.75
[2]	4	4	100%	93	10.75
[5]	10	10	100%	232	4.31
[10]	10	1.12	11.2%	610	0.18
[11]	10	10	100%	119	8.40
[15]	4	0.8	20%	59	4.00
This Work	1	1	100%	88.2	11.3

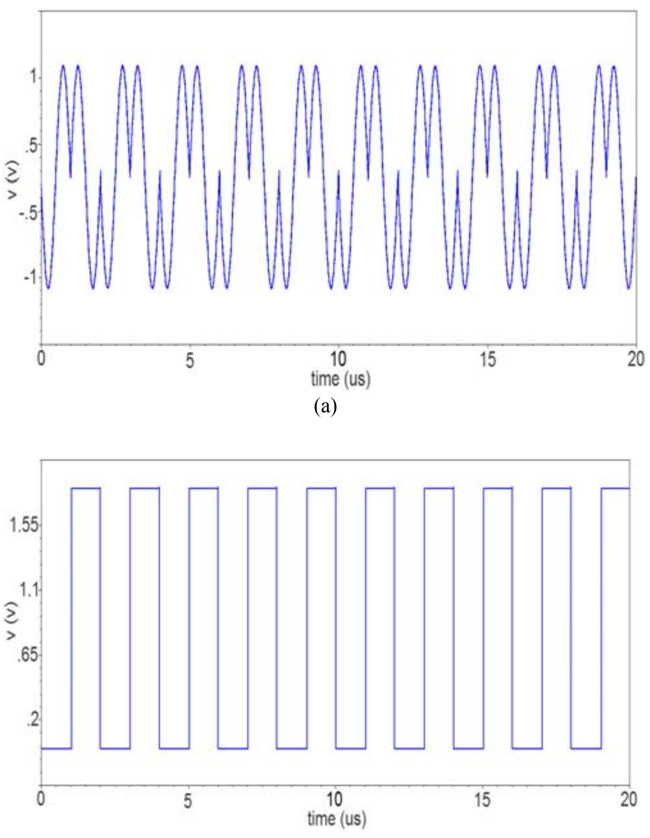


Figure 6. Response of the circuit to a BPSK modulated signal; (a) BPSK signal at the antenna side and (b) recoverd data at the output of the demodulator.

IV. CONCLUSUON

A new low-power and high-speed fully-integrated non-coherent BPSK demodulator is presented. The proposed demodulator recognizes the data based on detecting places of phase transitions in modulated signal using active high-pass filters. Then an op-amp based Schmitt trigger circuit assigns each phase transition to a rising or falling edge in recovered data, thus recovering the original base-band data.

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mjalali@shahed.ac.ir

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