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An ASK Data Demodulator Circuit for Implantable Medical Devices Supporting a Minimum Modulation Depth of 0.034%*

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Abstract— **Amplitude shift keying (ASK) data demodulation method has been widely used for simultaneous wireless data and power transfer in implantable medical devices (IMDs). Small amplitude modulation depth (MD) is usually preferred as it helps promote energy harvesting efficiency. This paper presents an ASK data demodulator that has good immunity to disturbances and can demodulate ultra-low MD ASK signal. A three-stage amplifying structure (3SAS) is proposed, in which the common-mode level of each amplifier is set between the high and low levels of its input signal envelope to prevent amplifier gain saturation and maximize the amplification of the envelope difference. Two envelope detectors (EDs) are used before and after the 3SAS respectively. The first one is to obtain a coarse envelope for 3SAS input and the second one is to further suppress the residual carrier interference and get a fine envelope. The proposed demodulator is implemented in 0.18-μm high-voltage Bipolar-CMOS-DMOS (BCD) technology. The detectable MD is measured as low as 0.034%, showing that the proposed demodulator can work smoothly and robustly in some extreme cases of simultaneous data and power transferring.**

Clinical Relevance— **The ASK data demodulator proposed in this paper supports ultra-low modulation depth. This reduces the bit error rate of the data link and keeps a highly power conversion efficiency for wireless power and data transfer in implantable medical devices.**

I. INTRODUCTION

Recently, various types of implantable medical devices (IMDs) are increasingly used to improve the quality of healthcare facilities as they have a major impact on diagnosis, treatment, monitoring, and prevention of disease or illness [1-4]. To avoid infection in treatment and restriction on mobility, these medical devices should be fully-implantable without any wire penetrating the skin [5]. IMDs should be able to obtain power to avoid the need for battery replacement and can support communication with external devices. Nowadays, many IMDs receive power and exchange data wirelessly through a single pair of coils simultaneously to minimize the size of the implant. To create detectable variations on the secondary coil and complete data transmission, the conventional carrier modulation schemes are commonly implemented using frequency-shift keying (FSK), phase-shift keying (PSK) or amplitude-shift keying (ASK). Among them, FSK and PSK are more difficult to implement and usually consume high power [6]. ASK has become a generally preferred solution for wireless data transfer since it is a good candidate for low power consumption and low complexity design.

However, ASK is sensitive to noise and all kinds of disturbances that may affect the modulation depth (MD) of the ASK signal in the data demodulation [6]. For good immunity to disturbances, the MD of the ASK signal is required to be higher, but this will reduce efficiency of energy harvesting for both wireless power and data transfer. Ye et al. [7] found that the power conversion efficiency of the wireless power transfer will be degraded if the MD of the ASK signal increases. What's more, a low detectable MD can maintain low-power consumption for data communication. Therefore, it is necessary to design an ASK data demodulator that can process the low MD ASK signal.

To demodulate AM signal with low MD, some researchers [8-11] have designed various ASK data demodulation circuit based on the traditional demodulator. However, these improvements can only detect the amplitude modulation (AM) signal with a minimum MD of 2%. Ye et al. [12] designed an envelope detector (ED)-based receiver with a shift limiter for signal demodulation, and the detectable MD is as low as 0.1%. Although it can detect lower MDs, the circuit is complex and is only suitable for wireless data transfer systems operating at low voltages (<1.8V). To demodulate ASK signals under low MDs and different operating voltages, we proposed a simple ASK data demodulator. It expands amplitude difference of the ASK signal by introducing a three-stage amplifying structure (3SAS). To suppress carrier interference, the inverting input voltage of each amplifier is set according to the noninverting input signal of each amplifier. Before amplification, an ED is used to control the amplitude of the ASK signal under different operating voltages and generate a coarse envelope of the signal. The method proposed by us can demodulate an ASK signal with a minimum MD of 0.034%.

The rest of this paper is organized as follows. Section II illustrates the method of the proposed ASK data demodulation. Section III describes the detailed circuit of the proposed ASK data demodulator including EDs, amplifiers and a hysteresis comparator. Section IV shows the results and analyses of the experiment. The conclusion is drawn in Section V.

II. DEMODULATING METHODS

Under low MDs, the difference between the high and low levels of the AM signal is too small to be detected. An amplifier is used in the traditional ASK data demodulator

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to amplify the difference. But when the MD is extremely low (<1%), either the strong carrier saturates the amplifier or the signal on the carrier drowns in the noise [12]. By setting the inverting input voltage of the amplifier, the linear range of the amplifier is moved to the higher amplitude of the carrier. To further amplify the MD, a 3SAS is adopted, and the inverting input voltage of each amplifier is adjusted to suppress the carrier gradually. If the MD of the ASK signal is directly amplified, we need to move the linear range of the amplifier according to different carrier amplitudes. It's necessary to preprocess the ASK signal to control its amplitude. Therefore, we proposed a wireless data transfer structure as shown in Fig. 1. The data transmission completed by the ASK relies on the wireless power transfer link of the IMDs. In the process of wireless power transfer, the external transmitter generates an AC signal through the DC to AC converter. The coil outside the body is the primary coil and is denoted as L_P, the coil inside the body is the secondary coil and is denoted as L_S. The coupling coefficient between the two coils is denoted as k. The AC signal is generated in the body through induction between the coupling coils. After AC to DC conversion, the power receiver provides a DC voltage for the load. The secondary coil L_S, the power receiver, and the ASK data demodulator are implanted in the body. The information is modulated onto the carrier, and the ASK signal recorded as V_{LC} is received on the internal resonant network through the coupling coils. By demodulating the V_{LC} with an ASK data demodulator, the AM signal can be recovered and the information can be received in implantable systems. As shown in the ASK demodulator in Fig. 1, the data demodulation proposed in this paper first adjusts the amplitude and generates the envelope of V_{LC} through ED1. The output of the ED1 is recorded as V_{env1} and it is amplified by a 3SAS which is denoted as AMPs to expand the dynamic range. After amplification, the envelope of the AMPs block's output signal recorded as V_{amp3} is extracted by ED2, and the output of the ED2 is recorded as V_{env2}. Finally, to avoid the misjudgment of the comparator caused by the glitch on V_{env2}, a hysteresis comparator is used to complete the signal comparison.

Fig. 2 shows the theoretical waveform of every signal in the proposed ASK data demodulator in this design. It takes a low MD as an example. It is observed that the difference between the high and low levels of V_{LC} is very small, as shown by the red dashed line of V_{LC}. V_{env1} and V_{env2} represent the output signal of ED1 and ED2 respectively. When the MD is too low, the high-frequency component from the carrier has a great influence on V_{env1}. By regulating the linear range of the amplifier, the dynamic change can be expanded and the carrier can be suppressed. V_{amp1}, V_{amp2} and V_{amp3} represent the output of each amplifier in the 3SAS. After amplifying the signal step by step, the difference between the high and low levels of V_{amp1}, V_{amp2} and V_{amp3} is more and more obvious. In this way, it's easy to detect the envelope of V_{amp3} through ED2. What's more, the high-frequency component from the carrier can be suppressed again through ED2. In the data transmission, the bit error rate (BER) decreases as the signal-noise ratio increases. To reduce it, a low pass filter is used to filter out high frequency noise during envelop detection, and the bandwidth of amplifier is reduced to attenuate the interference outside the signal band. The method can effectively reduce the interference caused by high carrier amplitude in wireless data transfer under low MDs.

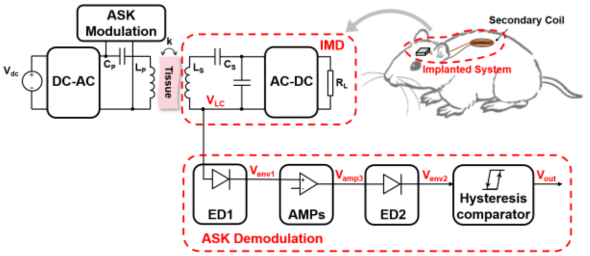

Figure 1. Schematic diagram of wireless data transmission system.

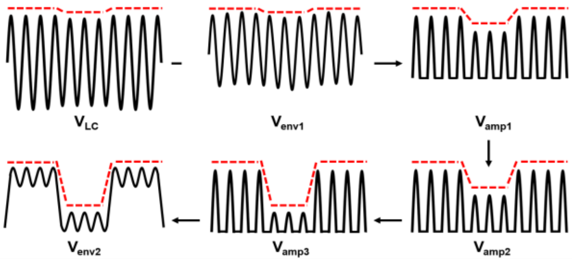

Figure 2. Schematic diagram of the signal amplification.

III. CIRCUIT IMPLEMENTATION

The schematic of the ASK data demodulator proposed by us is shown in Fig. 3. The demodulator consists of two EDs, a 3SAS and a hysteresis comparator. These blocks are implemented in the same voltage domain and all operate with a supply voltage of 5 V. The CMOS technology we use provides high-voltage diode that can handle the high amplitude ASK signals.

A. Analysis of the ED

The ED is essentially a filter, which filters the carrier frequency and leaves the frequency component of the modulated signal. It is able to extract the envelope of the input signal by charging a capacitor when the amplitude of the input signal is raises and discharging through a resistor when it falls. The circuit schematics of ED1 and ED2 are shown in Fig. 3. ED1 is composed of passive components such as capacitors and resistors, while ED2 uses transistors to form diode, capacitor and resistors to save area. To handle different ASK signals caused by various carrier amplitudes, ED1 uses a voltage divider to control the bias voltage of the envelope signal.

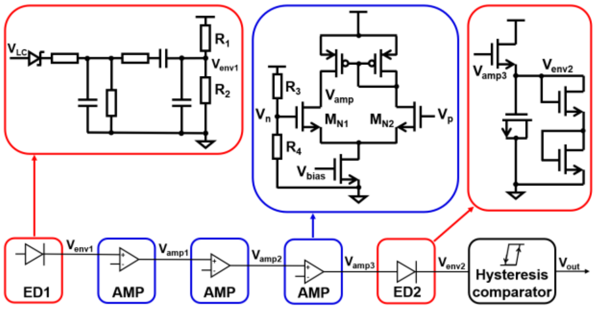

Figure 3. The schematic of the ASK data demodulator.

B. Analysis of the 3SAS

Fig. 3 also depicts the schematic of the 3SAS. It is composed of three amplifiers of the same structure. The amplifier we use is a two-stage differential amplifier with a gain of more than 40 dB, and the inverting input voltage of the amplifier is set according to the noninverting input signal to prevent amplifier gain saturation. The NMOS transistors M_{N1} and M_{N2} are the differential inputs of the amplifier. The gain of the amplifier depends on the transconductance of the CMOS and the output impedance of the structure. The 3SAS is used to amplify the dynamic range of the envelope signal to improve the resolution and reduce the interference.

C. Analysis of the Hysteresis Comparator

The schematic of the hysteresis comparator is depicted in Fig. 4. The hysteresis comparator includes a preamplifier, a positive feedback stage and an output driver. The NMOS transistors M_{N1} and M_{N2} are the differential inputs of the preamplifier. The preamplifier amplifies the input signal, improves the resolution of the comparator, and isolates the input signal from the kickback noise from the positive feedback to ensure circuit performance. The positive feedback stage is used to distinguish the difference of the input signal and realize the hysteresis effect. By setting the W/L of M_{N3}, M_{N6} and M_{N4}, M_{N5} to be different, the hysteresis can be achieved. The NMOS transistors M_{N7}, M_{N8} and PMOS transistors M_{P1}, M_{P2} constitute the output driver, and it is used to realize wave shaping.

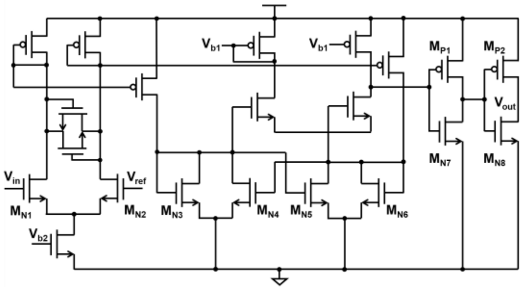

Figure 4. The schematic of the hysteresis comparator. V_{in}, V_{ref} are the input and reference voltage of the hysteresis comparator.

IV. EXPERIMENTAL RESULTS

To verify the feasibility of the method proposed in section II. This paper uses Cadence Virtuoso to draw the schematics which are shown in section III and build the experimental simulation environment. The wireless power transfer structure, signal modulation, and ASK data demodulator are implemented in a 0.18-micron (μm) high-voltage Bipolar-CMOS-DMOS (BCD) technology. In the simulation process, the carrier frequency is set to 120 kHz, the frequency of the modulated signal is 2 kHz, and their duty cycles are both 50%. In the experiment, the performances of the ASK data demodulator under different MDs are obtained by changing the coupling coefficient of the coils which is recorded as k. The waveforms of V_{LC} when k is set to 0.1 and 0.5 are shown in Fig. 5. The blue waveform represents the V_{LC} waveform when k = 0.5, and the difference between the high and low levels of V_{LC} is 236.79 mV. The red waveform represents the V_{LC} waveform when k = 0.1, and the amplitude difference is only 10.23 mV. By calculating, the MD of the ASK signal corresponding to the coupling coefficient of 0.1 and 0.5 is 0.034% and 0.799%, respectively.

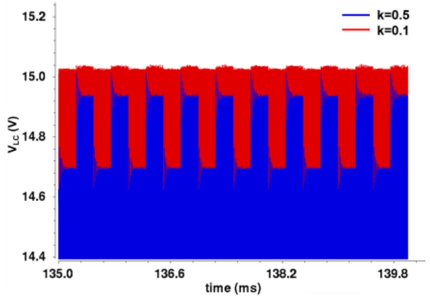

Figure 5. The waveform of V_{LC}.

Fig. 6 shows the amplitude-frequency characteristic curve of ED1 and depicts the waveforms of V_{env1} under different coupling situations. By observing the curve in Fig. 6(a), the signal is attenuated by 1.85 dB and 45.07 dB at 2 kHz and 120 kHz, respectively. In Fig. 6(b), the red and blue waveforms represent V_{env1} with coupling coefficients of 0.1 and 0.5, respectively. After envelope detecting, V_{env1} can fluctuate around a fixed DC bias voltage of 2.5 V, which is convenient for subsequent processing with a general amplifying structure. When k = 0.5, the dynamic range of V_{env1} is 140.70 mV. When k = 0.1, the dynamic range of V_{env1} is only 3.55 mV. When the MD is too low, signal demodulation can't be completed because the dynamic range of the signal may deviate from the reference voltage of the comparator. By adding a 3SAS after the envelope detection, V_{env1} is amplified, and the carrier interference is suppressed. The waveform of each signal under a low MD of 0.034% is shown in Fig. 7.

The detailed voltage information of each waveform in Fig. 7 is recorded in Table I. The dynamic range of V_{env1} is 3.55 mV. After one-stage amplification of V_{env1}, the dynamic range of V_{amp1} is 371.39 mV. The gain of the two-stage differential amplifier is above 40 dB, and the dynamic range of V_{env1} has been amplified by more than 100 times after the first stage of amplification. Although the output signal of the amplifier is half-clipped at one side, the other side of it can be amplified. It is found that the high and low-level transitions of V_{amp2} are smooth. It is easy to produce glitches during the secondary

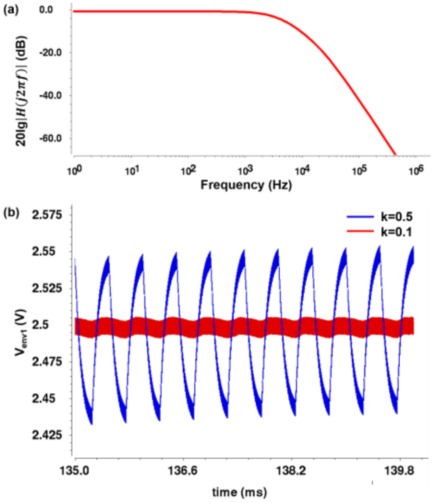

Figure 6. (a) The amplitude-frequency characteristic of ED1. (b) The waveform of V_{env1}.

envelope detection and lead to misjudgments when comparing. Therefore, it is amplified for the third time to obtain an orange waveform V_{amp3}. The waveform of V_{amp3} is more regular and the envelope of it can be easily detected to complete signal demodulation through the hysteresis comparator.

The result of data demodulation is shown in Fig. 8. The green waveform is a 2 kHz modulated signal, which was applied to a 120 kHz carrier signal in the experiment to obtain the AM signal. The red waveform is V_{LC}. It's observed that the amplitude changes of V_{LC} are consistent in the modulated signal. The blue waveform represents the demodulated signal. It can be observed that the demodulated signal can correctly reflect the amplitude change of V_{LC}. Through the method proposed in this paper, the AM signal under the lowest MD of 0.034% can be successfully demodulated.

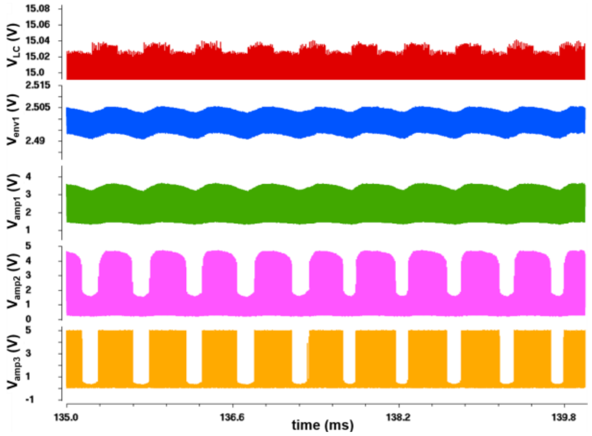

Figure 7. Schematic diagram of the amplified signal waveform.

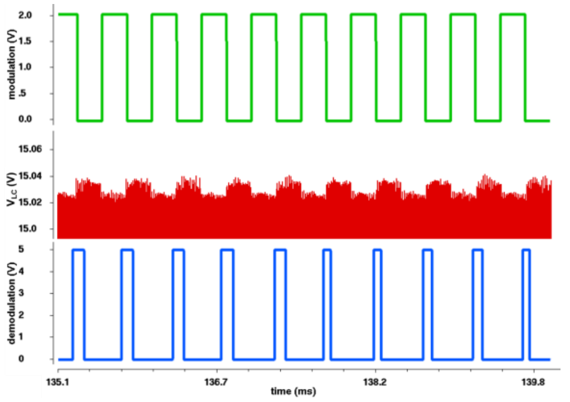

Figure 8. Schematic diagram of signal demodulation waveform.

TABLE I. VOLTAGE OF EACH SIGNAL

	Dynamic Range of Voltage		
	$V_{max}{}^a$ (V)	$V_{min}{}^b$ (V)	V_{max} - V_{min} (V)
V_{LC}	15.035	15.025	0.010
V_{env1}	2.505	2.502	0.003
V_{amp1}	3.624	3.253	0.371
V_{amp2}	4.672	1.582	3.090
V_{amp3}	4.995	0.141	4.854
V_{env2}	2.944	1.999	0.945

a. Maximum voltage; b. Minimum voltage

V. CONCLUSION

In this paper, the ASK data demodulator consists of two EDs, a three-stage amplifying structure and a hysteresis comparator, which is easier to be implemented than PSK and FSK. The demodulator can support a minimum modulation depth of 0.034%. The amplifying structure is presented to prevent amplifier gain saturation and expand the dynamic range of envelope. ED1 is used to detect the envelope and reduce the amplitude of the ASK signal to handle the situation of the high amplitude carrier. ED2 is used to get a fine envelope. The ASK data demodulator can demodulate signals in some extreme communication cases in implantable medical devices and is a good candidate for low power consumption in wireless power and data transfer. Besides, the ASK data demodulator circuit doesn't introduce too many capacitors and can simplify the system complexity.

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