All-MOS ASK Demodulator for Low-Frequency Applications

Tzung-Je Lee, *Student Member, IEEE,* Ching-Li Lee, Yan-Jhih Ciou, Chi-Chun Huang, and Chua-Chin Wang†, *Senior Member, IEEE*

***Abstract*— A miniature ASK demodulator without any passive elements, i.e., R or C, for low-frequency applications is presented in the paper. The noise margin of the envelope detector in the proposed ASK demodulator is enlarged such that any Schmitt trigger or current limiting resistor is no longer needed. It results in the number of transistors required for the ASK demodulator circuit is reduced to 12, while the area is merely 0.003025 mm^2 using 0.35 μm 2P4M CMOS process. The power consumption is found to be 1.01 mW by physical measurement on silicon. The data rate is measured to be 250 kbps for 2 MHz carrier frequency and 27% modulation index.**

***Index Terms*— ASK demodulator, low-frequency ISM band, noise margin, envelope detector, wireless network.**

I. Introduction

VFC Because of rapid development of IC and MEMS (micro-electro-mechanical systems) technologies, implantable and portable electronic biomedical devices become feasible. Particularly, the implantable devices have been developed to diagnose or cure the patients' diseases, e.g., the bladder stimulation for passing urine control [1], the neuron electrical micro-stimulation to alleviate paralysis and atrophy [2], and the cortical neural prosthesis for deep brain stimulation which is helpful for the disabilities of Parkinson's disease [3].

In order to avoid the infection on the wound due to the wired connection, wireless transmission is much preferred for the communication between the implantable devices and the external control module. ASK modulation methodology has been selected for the telemetry in lots of previous works because of its simplicity [4]- [9]. Besides, the low-frequency ISM band (2.0 or 13.56 MHz) are widely used due to the low absorption rate of live tissues. More importantly, the area of the implantable electrical devices must be as small as possible to reduce the discomfort of the patient who is implanted with the device. However, the prior ASK demodulators contain large capacitors for demodulation in low-frequency bands such that the system size is large, e.g., a 10 pF capacitor in both of Liu's [4] and Baru's [5] designs. Therefore, a C-less (without capacitor) ASK demodulator was reported [7] to reduce the area of the implantable system. However, the bias-based envelope detector in the C-less ASK demodulator generates an envelope signal with small amplitude. Hence, a Schmitt trigger is required in the C-less ASK demodulator to ensure correct demodulation in the noisy environment. This paper, thus, modifies such a C-less ASK demodulator to retain its advantage of no capacitor and further remove the Schmitt trigger by improving the noise margin of the envelope detector. What even better is that there will be no resistor in the proposed ASK demodulator design. The area of the chip is then reduced to be merely 0.003025 mm^2.

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The authors are with the Department of Electrical Engineering, National Sun Yat-Sen University, Kaohsiung, 80424, Taiwan. (e-mail: ccwang@ee.nsysu.edu.tw)

† the contact author.

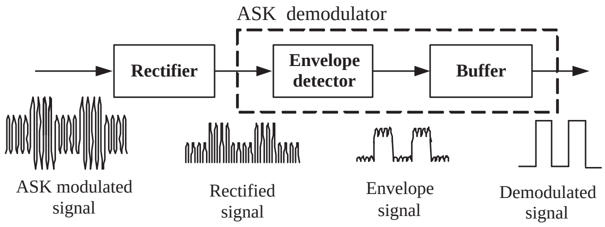

Fig. 1. Block diagram for ASK demodulation.

II. All-MOS ASK Demodulator

The wireless implantable devices usually use coupling coils to transmit power and data from an external coil to an internal coil. The received signal on the internal coil is then sent to a power regulator to produce a stable supply voltage for the implantable electrical device and the demodulator for data demodulation. When the ASK demodulation is used, the implantable device needs a rectifier to obtain the half-wave signal before the ASK demodulator, as shown in Fig. 1. Notably, the proposed design is implemented by a typical 0.35 μm 2P4M CMOS process with VDD = 3.3 V.

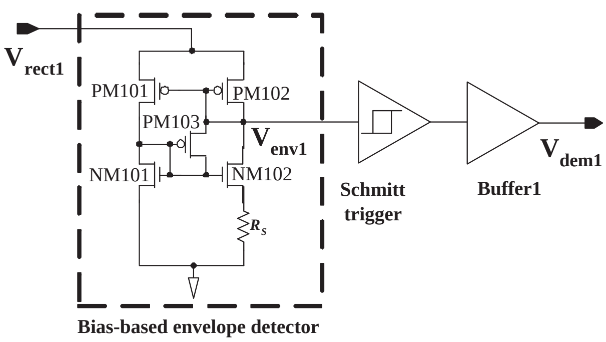

Fig. 2. Schematic of the bias-based C-less ASK demodulator.

A. Prior Bias-based C-less ASK demodulator

Fig. 2 shows the prior C-less ASK demodulator which contains no capacitors [7]. It senses the rectified signal, V_{rect1}, and generates the demodulated signal, V_{dem1}. The output of such a bias-based envelope detector varies severely dependent on the low frequency components of the rectified signal, V_{rect1}. Thus, it could be used to sense the envelope of the ASK-modulated signal. The generated envelope signal, V_{env1}, is an AC vibration on a DC voltage according to the digital level of the ASK modulated signal. However, due to the inherent feature of stability of the bias schematic, the amplitude of V_{env1} is quite small. Because the induced signal on the internal coils will be corrupted easily owing to the displacement and angle between the external and internal coils, a Schmitt trigger must be added to sense the small V_{env1}. Therefore, the noise margin of the bias-based ASK demodulator can be enhanced. Notably, PM103 works during start-up only.

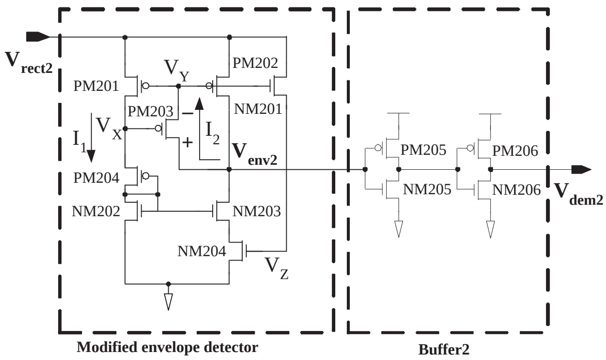

Fig. 3. Schematic of the proposed ASK demodulator.

B. Circuitry of the proposed all-MOS ASK demodulator

This paper, by contrast, proposes a modified ASK demodulator which contains no Schmitt trigger, as shown in Fig. 3. In order to achieve the purpose of removing the Schmitt trigger, the noise margin of the envelope detector must be enhanced. That is, the amplitude of the envelope signal V_{env2} should be enlarged. With V_{env2} biased at 2.13 V for logic 1 of ASK modulated signal, PM202 is designed to be turned off for logic 0 of ASK modulated signal. It results in V_{env2} can be discharged to 0 V when logic 0 is received. Therefore, the amplitude of V_{env2} is enlarged and the Schmitt trigger is no longer needed.

1) Start-up : In a bias circuit, a steady DC voltage or DC current should be generated. However, the bias circuit might operate at the state without current flowing because all MOSs are turned off initially. Thus, a start-up circuit is required to provide a current through the bias circuit to carry out the demodulation function.

There are two possible scenarios when the proposed circuit is initialized:

<*i.*> When V_{rect2} is low (2.5 V) initially, PM201 and PM202 will be off such that V_{env2} is at 0 V if $V_Y > V_{rect2}$ - $V_{th,PM201}$. If $V_Y < V_{rect2}$ - $V_{th,PM201}$, PM201 and PM202 will be turned on such that V_{env2} is biased at 1.7 V initially. Because V_X is at 0.6 V initially, V_Y will be pulled to the voltage close to 1.7 V by PM203. Then, PM201 and PM202 will be turned off. It results in V_{env2} to be discharged to 0 V.

<*ii.*> When V_{rect2} is initially high (3.3 V), PM201 and PM202 will be turned on for $V_Y < V_{rect2}$ - $V_{th,PM201}$. Then, V_{env2} can be biased at the desired voltage of 2.13 V. If $V_Y > V_{rect2}$ - $V_{th(PM201)}$ initially, PM201 and PM202 are off such that V_{env2} is biased at 0 V initially. V_Y will then be discharged to the voltage of $V_X + V_{th,PM203}$ and PM201 and PM203 will be turned on. Thus, V_{env2} will be pulled to 2.13 V.

Therefore, PM203 is deemed as the self-start-up circuit, which biases the envelope detector to the desired operating voltage initially in these two scenarios.

Besides, the channel resistance of PM203 and the gate parasitic capacitors of PM201, PM202, and NM201 behave as an LPF (low pass filter), with the 3-dB frequency of

$$f_{3dB,Y} = \frac{1}{R_{on} \cdot C_Y} = \frac{1}{\beta_{PM203} \cdot V_{OD} \cdot C_Y}, \qquad (1)$$

where β_{PM203} is the transconductance parameter, V_{OD} is the over drive voltage of PM203, and C_Y is the parasitic capacitor at node Y. The LPF can suppress the high frequency carrier of the ASK-modulated signal. Thus, the AC disturbance of V_Y is reduced such that V_Y can be treated as a control signal for PM201 and PM202. Similarly, V_Z is also a filtered voltage resulted from the LPF composed of NM201 and NM204 to control the channel resistance of NM204.

2) Normal operation: After the demodulation is started up as described in the above, it enters the normal operation, which also has two possible scenarios: V_{rect2} is low or V_{rect2} is high.

<*i.*> V_{rect2} = low (received ASK signal is low): When the low voltage level of ASK-modulated signal is received, V_{rect2} is at 2.5 V. PM201 and PM202 will be turned off because V_Y is biased at 1.88 V for V_{rect2} at 3.3 V. Thus, V_{env2} is discharged to 0 V by NM203 and NM204. With V_X at 0.95 V and V_{rect2} = 2.5 V, PM203 will be turned on to discharge V_Y to the voltage close to $V_X + V_{th,PM203}$ ($\approx$ 0.95 + 1 = 1.95 V). That is, if

$$V_{rect2,low}(DC) - |V_{th(PM202)}| < V_{Y,low}(DC), \qquad (2)$$

where

$$V_{Y,low}(DC) \approx V_{X,low}(DC) + |V_{th(PM203)}|, \qquad (3)$$

PM201 and PM202 will be kept off for logic 0 of ASK-modulated signal such that

$$V_{env2,low}(DC) \approx 0. \qquad (4)$$

Notably, the suffix “low” in the voltage symbols indicate that the voltages are obtained when V_{rect2} is at the low state. Moreover, “DC” in the parentheses denotes the DC component of the voltage.

<*ii.*> V_{rect2} = high (received ASK signal is high): When the high voltage level (logic 1) of ASK modulated signal is

received, V_{rect2} is at 3.3 V. Because V_Y is biased at 1.88 V for V_{rect2} at 2.5 V, PM201 and PM202 will be turned on for $V_{th(PM201)} = V_{th(PM202)} = 1$ V when V_{rect2} changes from 2.5 V to 3.3 V. Thus, V_{env2} is pulled to its high level voltage from 0 V. Because V_X is at 1.15 V for $V_{rect2} = 3.3$ V, V_Y will be charged by I_2 through PM203. The increased V_Y will reduce the charging current from PM201 and PM202. Thus, the high voltage level of V_{env2} will be biased at 2.13 V, which can be expressed by Eqn. (5) for $V_{th(PM203)} = 1$ V.

$$V_{env2,high}(DC) \approx V_X(DC) + |V_{th(PM203)}|, \quad (5)$$

where the suffix "high" in $V_{env2,high}$ means that the voltage is obtained at the high state of V_{rect2}. Besides, NM204 possesses an aspect ratio smaller than 1 to reduce the quiescent current.

3) Buffer : In order to drive large capacitive loads and to avoid the loading effect to the envelope detector, a buffer which can drive a 10 pF load at 20 kbps bit rate is added. Moreover, the switch point of the buffer must be set to the value between the peak and valley of V_{env2} such that the state of V_{env2} can be sliced correctly.

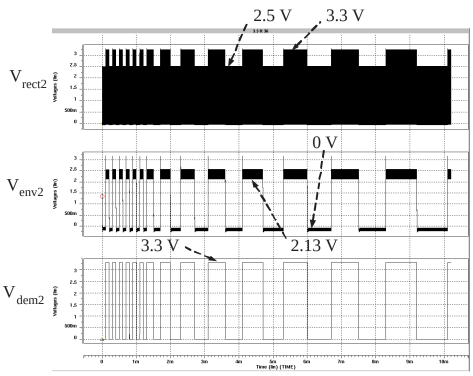

Fig. 4. Post-layout simulation result of the proposed ASK demodulator at [VDD=3.3 V, TT model, 36°C].

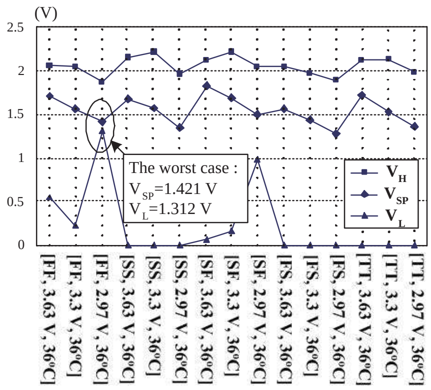

Fig. 5. Simulation results of V_H, V_L, and V_{SP} in different PVT corners.

III. Simulation and Measurement Results

The proposed ASK demodulator is carried out using TSMC (Taiwan Semiconductor Manufacturing Company) 0.35 μm 2P4M CMOS process. Fig. 4 shows a transient post-layout simulation of the proposed ASK demodulator. The demodulated output of the proposed demodulator, V_{dem2}, is generated from the rectified signal, V_{rect2}. The output of the envelope detector, V_{env2}, swings between 2.13 V and 0 V such that the following buffer can detect the voltage level of V_{env2} easily. Fig. 5 shows high level (V_H), low level (V_L) of V_{env2}, and the switch point (V_{SP}) of the buffer in different PVT (process, supply voltage, and temperature) corners. Notably, the temperature is simulated at 36^{o}C to comply with the human's normal temperature. Moreover, V_H denotes the smallest value at the peak of V_{env2}; V_L denotes the largest value at the valley of V_{env2}. Fig. 5 shows that all of the V_{SP} voltages fall between V_H and V_L. Thus, V_{env2} can be correctly sliced by Buffer2 in these corners. Notably, V_L is not biased at 0 V in all of these corners. Moreover, V_L is pulled high in FF and SF corners. That is caused by the small threshold voltages of PMOS ($V_{th(PMOS)}$) which will be produced in SF and FF corners. According to Eqn. (2) and (3), small $V_{th(PMOS)}$ might turn on PM201 and PM202 when V_{rect2} is low. It is why V_L will be pulled to 1.312 V in the worst case (FF, 2.97 V, 36^{o}C).

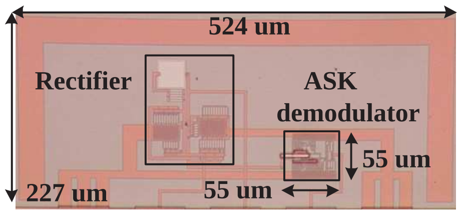

Fig. 6. Die photo of the proposed ASK demodulator.

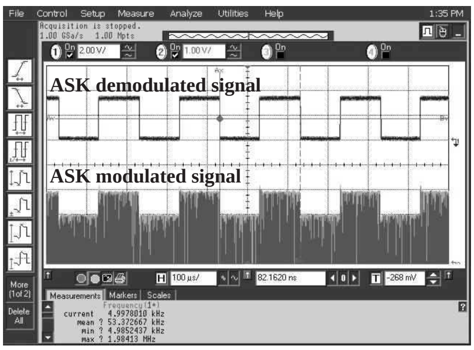

Fig. 7. Measured waveform of the proposed ASK demodulator with 10 kbps data rate when the modulation index is 27%.

Fig. 6 shows the die photo of the proposed all-MOS ASK demodulator, which occupies merely 0.003025 mm^2. Fig. 7 shows the measured waveform of the ASK modulated and ASK demodulated signals when data rate is 10 kbps and the modulation index is 27%. Moreover, Fig. 8 shows the proposed ASK demodulator can even recover the modulated signal correctly when the data rate is up to 250 kbps for 27% modulation index. Table I reveals the performance comparison with prior works. The proposed demodulator is the only design which contains no resistors and capacitors. Moreover, the area of the proposed design is smaller than these prior works.

TABLE I
COMPARISON WITH PRIOR ASK DEMODULATORS

Design	Cap. No.	Res. No.	MOS No.	Area (mm^2)	Carrier (MHz)	Data Rate (kbps)	MI	FOM	Year
[4]	1	-	14	0.3	10	1000	30%	3.33	2000
[6]	3	-	13	-	4	70	35%	0.5	2003
[7]	0	1	16	0.01274	2	10	18.75%	0.27	2004
[8]	1	1	> 30	-	-	250	-	-	2004
[9]	1	3	19	-	10	800	100%	0.8	2000
[10]	10	3	> 26	0.22	10	200	10%	2	2000
[11]	1	-	> 58	-	13.56	-	-	-	2005
[12]	3	3	> 43	0.18	1	18	100%	0.18	2006
Ours	0	0	12	0.003025	2	250	27%	3.583	2007

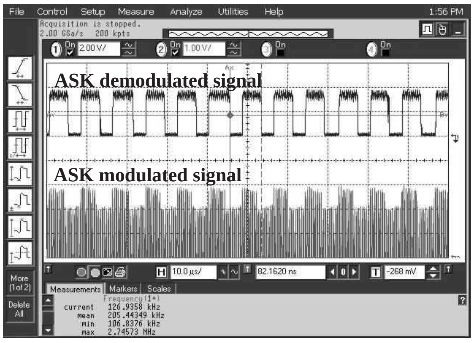

Fig. 8. Measured waveform of the proposed ASK demodulator with 250 kbps data rate when the modulation index is 27%.

Besides, the carrier frequency, maximum data rate, and the corresponding modulation index are shown in Table I. Because the fast data rate for the ASK demodulator can be achieved easily when fast carrier frequency and large modulation index are used. Thus, we define a simple figure of merit (FOM = $\frac{\text{data rate}}{(\text{carrier frequency})\cdot(\text{modulation index})}$) to normalize the data rate such that the data rate could be compared fairly. It shows that the proposed design has the best FOM compared to all of the prior works.

IV. CONCLUSION

Miniaturization is a critical specification of the implantable electrical devices. Lots of prior ASK demodulators employed capacitors such that the area was too large. We have presented a novel all-MOS ASK demodulator. By improving the noise margin of the bias-based envelope detector, the Schmitt trigger is then no longer needed. It, thus, reduces the size of the proposed ASK demodulator. The proposed design employs merely 12 MOSs and occupies 0.003025 mm^2. The average power consumption is 1.01 mW by physical measurement.

V. ACKNOWLEDGMENT

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