

C-less and R-less Low-Frequency ASK Demodulator for Wireless Implantable Devices[§]

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Abstract—A miniature ASK demodulator without any passive elements, i.e., R or C, for implantable devices 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 mm² using 0.35 μ m 2P4M CMOS process. The power consumption is found to be 1.01 mW by physical measurement on silicon.

Keywords: ASK demodulator, implantable device, noise margin, envelope detector, wireless network

I. INTRODUCTION

Because of rapid development of IC and MEMS (micro-electro-mechanical systems) technologies, implantable electronic devices become feasible. The implantable devices were 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]. 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 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 design. The area of the chip is then reduced to be merely 0.003025 mm².

II. C-LESS AND R-LESS 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.

A. 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.

B. Circuitry of the proposed 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. The proposed ASK demodulator employs a MOS,

[§] This research was partially supported by National Science Council under grant NHRI-EX95-9319EI and NSC 94-2213-E-110-053.

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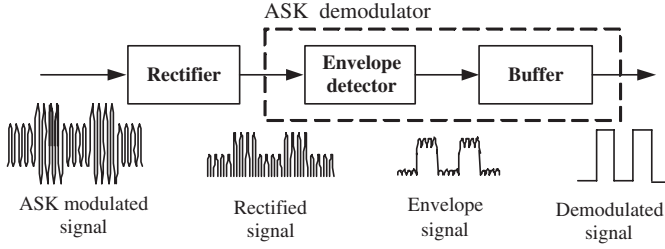


Fig. 1. Block diagram for ASK demodulation.

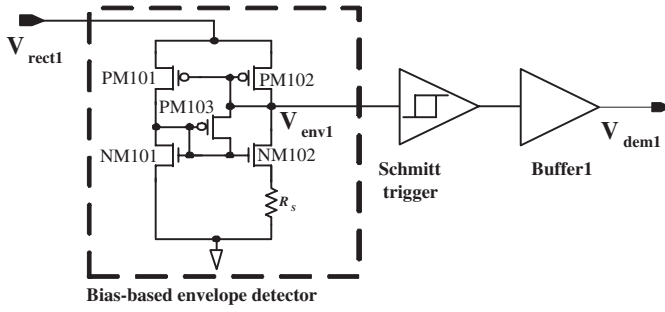


Fig. 2. Schematic of the bias-based C-less ASK demodulator.

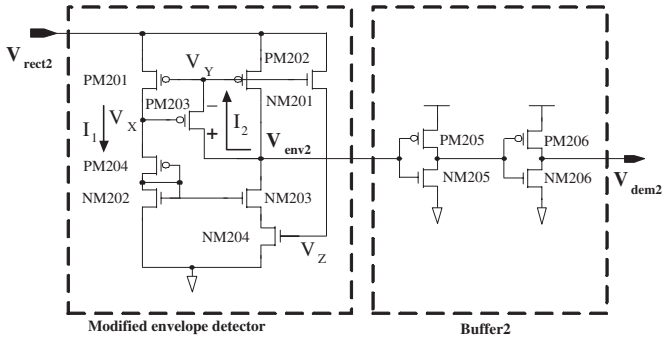


Fig. 3. Schematic of the proposed ASK demodulator.

NM204, to replace the resistor, R_s , in the bias-based C-less ASK demodulator. Since the gate drive of NM204, V_Z , is coupled to the drain of NM201, it is also deemed as a voltage-controlled resistor. Besides, the charging path would be opened when low level of ASK modulated signal appears. It results in that V_{env2} could be pulled as low as possible. Thus, the amplitude of V_{env2} is enlarged and the noise margin of the envelope detector is increased as well. Therefore, the Schmitt trigger is no longer needed.

1) *Start-up* : In a general bias circuit, all MOSs of the bias might be turned off initially such that the bias itself is turned off. Thus, a start-up circuit is usually included to guarantee that the circuit can work correctly after the supply voltage is applied. In the proposed ASK demodulator, when V_{rect2} is low, PM201 and PM202 will be off initially. Thus, no start-up problem will occur at the low state of V_{rect2} . On the other hand, for the high state of V_{rect2} , if V_Y is in a low voltage level initially, PM201 and PM202 can be turned on. If V_Y is initially high such that PM201 and PM202 are off. It results in

V_X to be a low voltage to turn on PM203. Thus, V_Y would be discharged through PM203 to be a lower level such that PM201 and PM202 could be turned on. Thus, PM203 plays the role of self-start-up.

Besides, the channel resistance of PM203 and the gate parasitic capacitors of PM201, PM202, and NM201 behave as an LPF (low pass filter) to 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) *High voltage level of ASK-modulated signals* : When the high-level (mark level) ASK-modulated signal is present, PM201 and PM202 are turned on such that V_{env2} is pulled high. In the meantime, PM203 is also on to charge the node V_Y from the node V_{env2} . (In this case, the node V_{env2} is treated as the source of PM203 while V_Y is the drain.) The increased V_Y causes the current, I_1 through PM204 and NM202, to be reduced. It pulls V_X down further. Thus, the channel in PM203 will be enhanced such that PM203 might continue turned-on even though V_{env2} is also dropping due to I_2 . However, V_{env2} drops faster than V_X . Therefore, V_{env2} is finally steady at the moment when PMOS turns off. Thus,

$$V_{env2,high}(DC) = V_X(DC) + |V_{th}(PM203)|, \quad (1)$$

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

3) *Low voltage level of ASK-modulated signals* : When V_{rect2} switches to the low level (space level), V_Y is too high to turn on PM201 and PM202. Thus, V_{env2} is pulled down through NM203 and NM204. Besides, the sum of the threshold voltages of NM202, PM204, and PM203 are designed to be not less than V_Y such that PM203 is off when the ASK voltage level is low, as shown in (3). Therefore, V_Y could not be discharged through PM203. (In this case, the node V_Y is treated as the source of PM203 while V_{env2} is the drain.) That is, if

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

where

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

then PM201 and PM202 are kept off at the low state of ASK-modulated signals. Because NM204 behaves as a voltage-controlled resistor, its resistance could be small enough to be neglected as long as V_Z is high enough. Therefore, V_{env2} could be pulled down to be very close to ground. It implies that

$$V_{env2,low}(DC) = 0, \quad (4)$$

Notably, the suffix “low” in the voltage symbols indicate that the voltages are obtained when V_{rect2} is at the low

state. Besides, $V_{X,low}$ would be approximately clamped at $V_{th}(NM202)$ by the diode-connected NM202 and the gate capacitor NM203.

4) *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 kb/s 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.

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 corners. Notably, the temperature is simulated at 36°C to comply with the human's normal temperature. Notably, V_H has the smallest value at the peak of V_{env2} ; V_L shows the largest value at the valley of V_{env2} . It 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. Unfortunately, V_L is not at 0 V in all of these corners, which is pulled high in FF and SF corners. It is resulted from the small threshold voltages of PMOS ($V_{th}(PMOS)$) in SF and FF corners. According to (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°C). Although the function still works correctly in this corner, extra power consumption is generated. The simulated average power consumption in the worst case is 0.208 mW given a 10 pF load.

Table I shows the comparison of the core area and the overall number of the MOSs with several prior works. It is revealed that the proposed ASK demodulator has the smallest area. Fig. 6 shows the die photo of the proposed ASK demodulator, which occupies merely 0.003025 mm^2 . Fig. 7 shows the measured waveform. The input signal is a 20 kb/s bit rate square wave which is modulated by a 2 MHz sine wave. The demodulated output signal is a 20 kb/s square wave. Table II summaries the simulation and measurement results of the proposed design. Notably, the average power consumption of the measurement is larger than that of the simulation because the input signal is not an ideal ASK modulation signal. Especially, the output of the demodulator results the appearance of the sever switch at the logic transition of the ASK modulation signal, as shown in Fig. 7. However, in order to avoid erroneous signal demodulation, a tolerance design can be done following the ASK demodulator.

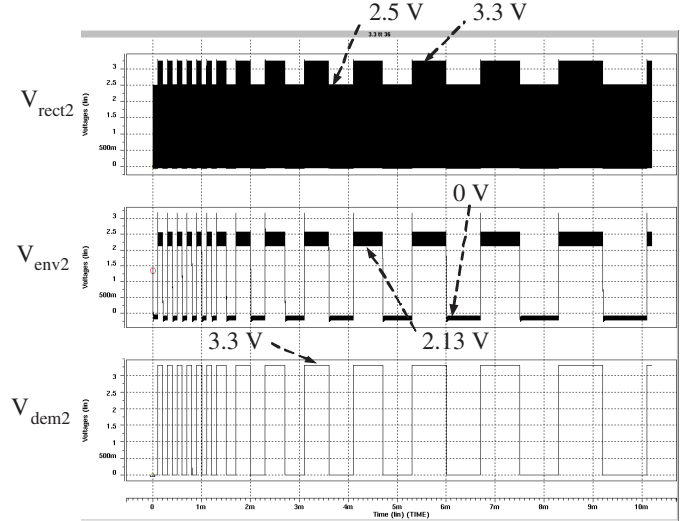


Fig. 4. Post-layout simulation result of the proposed ASK demodulator at [VDD=3.3 V, TT model, 36°C].

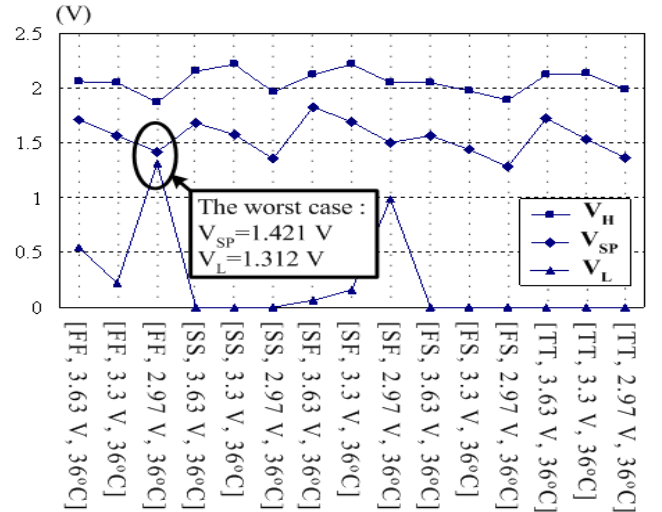


Fig. 5. Simulation results in different corners.

IV. CONCLUSION

Miniaturization is a critical specification of the implantable electrical devices. Lots of prior ASK demodulators employed

TABLE I
COMPARISON WITH SEVERAL PRIOR WORKS

Design	Capacitor	Quantity of MOSs	Core area (mm^2)
[4]	10 pF	14	0.3
[5]	10 pF	13	0.29
[6]	2 capacitors	10	0.32
[7]	0	16	0.0127
[8]	1 capacitor	> 30	N/A
[9]	1 capacitor	19	N/A
[10]	8 capacitors	> 26	0.22
Ours	0	12	0.003025

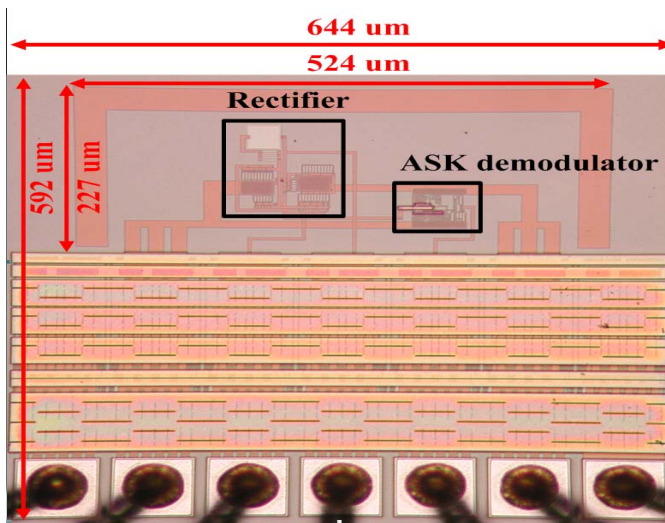


Fig. 6. Die photo of the proposed ASK demodulator.

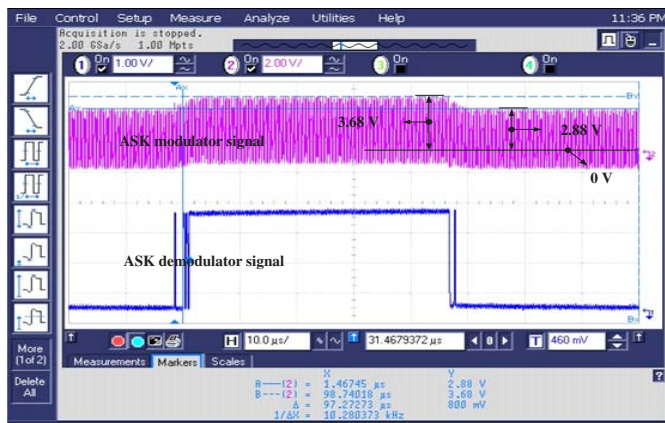


Fig. 7. Measured waveform of the proposed ASK demodulator.

TABLE II
SIMULATION AND PHYSICAL MEASUREMENT RESULTS

	Simulation	Measurement
Bit rate (@ modulation index=16%)	20 kb/s	
Carrier freq.	2 MHz	
Logic high of modulated signal	3.2~3.4 V	3.68 V
Logic low of modulated signal	2.5~2.7 V	2.88 V
Duty cycle of output	50.5~52%	48.57%
Logic high of demodulated signal	3.3 V	3.16 V
Logic low of demodulated signal	0 V	0.04 V
Average power consumption	0.208 mW	1.01 mW

capacitors such that the area was too large. We have presented a novel C-less and R-less 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

The authors would like to express their deepest gratefulness to CIC (Chip Implementation Center) of NARL (National Applied Research Laboratories), Taiwan, for their thoughtful chip fabrication service. The authors also like to thank "Aim for Top University Plan" project of NSYSU and Ministry of Education, Taiwan, for partially supporting the research.

REFERENCES

- [1] J. S. Walter, J. S. Wheeler, W. Cai, W. W. King, and R. D. Wurster, "Evaluation of a suture electrode for direct bladder stimulation in a lower motor neuron lesioned animal model," *IEEE Trans. on Rehabilitation Engineering*, vol. 7, no. 2, pp. 159-166, June 1999.
- [2] G. E. Loeb, F. J. R. Richmond, D. Olney, T. Cameron, A. C. Dupont, K. Hood, R. A. Peck, P. R. Troyk, and H. Schulman, "BIONTM. Bionic neurons for functional and therapeutic electrical stimulation," *20th IEEE Engineering in Medicine and Biology Society*, vol. 5, pp. 2305-2309, Nov. 1998.
- [3] R. E. Isaacs, D. J. Weber, and A. B. Schwartz, "Work toward real-time control of a cortical neural prosthesis," *IEEE Trans. on Rehabilitation Engineering*, vol. 8, no. 2, pp. 196-198, June 2000.
- [4] W. Liu, K. Vichienchom, M. Clements, S. C. DeMarco, C. Hughes, E. McGucken, M. S. Humayun, E. De Juan, J. D. Weiland, and R. Greenberg, "A neuro-stimulus chip with telemetry unit for retinal prosthetic device," *IEEE J. of Solid-State Circuits*, vol. 35, no. 10, pp. 1487-1497, Oct. 2000.
- [5] M. Barú, H. Valdenegro, C. Rossi, and F. Silveira, "An ASK demodulator in CMOS technology," in *Proc. IV Iberchip Workshop*, pp. 37-42, 1998.
- [6] H. Yu, and K. Najafi, "Low-power interface circuit for bio-implantable microsystems," *2003 IEEE Inter. Solid-States Circuits Conf.*, vol. 1, pp. 194-203, Feb. 2003.
- [7] C.-C. Wang, Y.-H. Hsueh, U. F. Chio, and Y.-T. Hsiao, "A C-less ASK demodulator for implantable neural interfacing chips," in *Proc. 2004 IEEE Inter. Symp. on Circuits and Systems., ISCAS 2004*, vol. 4, no. 4, pp. 57-60, May 2004.
- [8] A. Djemouai, and M. Sawan, "New CMOS current-mode amplitude shift keying demodulator (ASKD) dedicated for implantable electronic devices," in *Proc. 2004 IEEE Inter. Symp. on Circuits and Systems., ISCAS 2004*, vol. 1, no. 1, pp. 441-444, 2004.
- [9] R. Harjani, O. Birkenes, and J. Kim, "An IF stage design for an ASK-based wireless telemetry system," in *Proc. 2000 IEEE Inter. Symp. on Circuits and Systems., ISCAS 2000*, vol. 1, pp. 52-55, 2000.
- [10] G. Gudnason, "A low-power ASK demodulator for inductively coupled implantable electronics," *IEEE Inter. Solid-States Circuits Conf.*, pp. 385-388, 2000.