A 20Mbps sub-0.1nJ/b Transmitter for Capsule Endoscope Application

Byeong Seol Kim[1] and Joon Sung Bae[a]
Department of Electrical Engineering, Kangwon National University
E-mail : [1]kimbs@kangwon.ac.kr

Abstract **– In this paper presents a high-speed and low-power transmitter for capsule endoscope application in CMOS 65nm process. The transmitter consists of a FSK modulator for high speed, low power modulation and a class-E Power Amplifier that can effectively transfer power to the antenna. The modulator has to secure sufficient loop bandwidth for high speed operation. Therefore, we implemented the fast FSK modulator using two frequency synthesizers (PLL). The frequency band used is the 420-440MHz band, which is a frequency that can minimize loss, and two frequency synthesizers are switched to 20Mbps. The power amplifier using series resonance at the output network, with frequency selective characteristics, a class-E switching power amplifier with 87% power efficiency at the output power of -16dBm. 1V was used for the supply voltage, and the DC power consumption was 1.7mW. The phase noise of the FSK modulator is -85dBc at 420MHz. The fabricated chip occupied a core area of 0.3mm*0.36mm, achieving sub-0.1nJ/b energy efficiency.**

Keywords**—Class-E switching power amplifier, FSK modulator, FSK Transmitter, Implantable Medical Devices (IMD)**

I. INTRODUCTION

Recently, a wireless capsule endoscope is emerging as an alternative to the cable-attached endoscope by providing an effective and non-painful diagnostic method. The capsule should have a small form factor under the battery with little capability. Moreover, given that transferring colored VGA, 4-fps images require a 20Mb/s data rate, the energy-efficient wireless transmitter is the critical enabler for the application. The non-coherent frequency shift keying (FSK) modulation is optimized for the energy-efficiency since its constant amplitude with zero-crossing data permits the use of an efficient nonlinear PA without any spectral regrowth found in phase-shift keying (PSK) [1] and on-off keying OOK [2] modulations. Previously, the signal generation for FSK has been mainly from the phase-locked oscillator [3-4], open-loop oscillator [5], and injection-locked oscillator [6], which suffers from limited loop bandwidth or large power consumption due to the I/Q signal generations with an upconverting mixer (Fig. 1a), frequency drift issue (Fig. 1b) over the process variation, and calibration overheads, respectively. Therefore, achieving up to 20Mb/s data rate with low power consumption and low system cost is still a significant challenge.

In this paper, we have implemented a high-speed 420-440MHz FSK transmitter which consists of 1) a fast switching FSK modulator with two phase-locked oscillators and 2) an energy-efficiency Class-E power amplifier (PA) with configurable switching transistors. As a result, the transmitter has high energy-efficient, it consumes 1.7mW at -16 dBm output power with a data rate of 20Mb/s, corresponding to the energy consumption of 0.085nJ per bit. Compared with previous work using similar frequency bands [6], it improved energy-efficiency by more than four times.

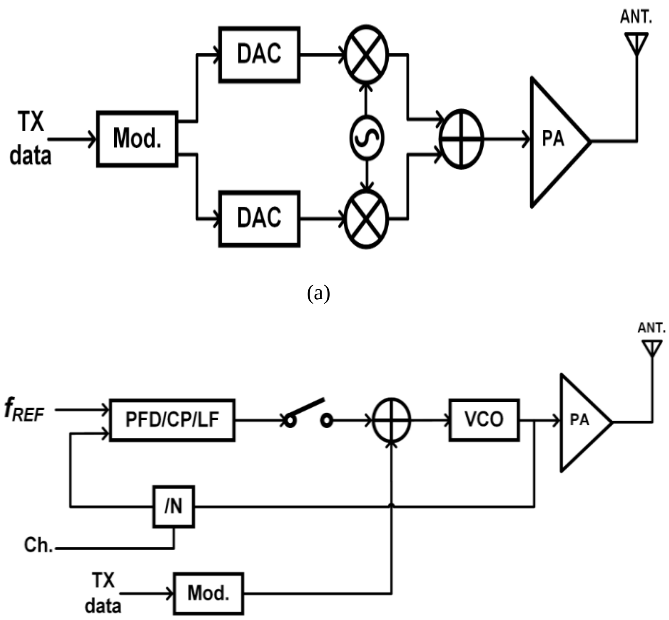

Fig. 1 *Previous works; (a)* FSK transmitter with an upconverting mixers *(b)* Open loop FSK transmitter

a. Corresponding author; baej@kangwon.ac.kr

Manuscript Received Jul 12, 2021, Revised Sep. 23, 2021, Accepted Sep. 29, 2021

II. CIRCUIT IMPLEMENTATION

A. Overall Architecture

Fig. 2 shows the overall architecture of the proposed FSK transmitter, which consists of a high-speed FSK modulator and energy-efficient Class-E PA. The modulator utilizes two independent phase-locked loops (PLLs) based frequency sources followed by a switching multiplexer. Provided that the PLL is realized with a low power ring voltage-controlled oscillator (VCO), the data rate is not limited by the loop dynamics, minimizing the frequency switching time without degradation of the modulation speed. Since the FSK is performed by direct-switching with little delay, the target data rate of 20Mb/s can be easily obtained with two PLLs, each of which can be controlled under 1mW. The output phases of the two integer PLLs using a common reference are well aligned at the reference clock's rising edge, resulting in phase continuity at the modulator. In addition, the fast charge switching charge pump with cascode biasing and a retiming flip-flop is used to mitigate the current mismatch in the charge pumps and the logic delay of the frequency divider, minimizing the timing mismatch between two PLLs. The timing mismatch between PLLs is less than 50ps.

B. Class-E Power Amplifier

Fig. 3 shows the class-E PA circuitry composed of the reconfigurable switches, off-chip Choke inductor, and matching LC tank. The driving current from input switches is transferred to the Choke inductor. After the input switches off, stored current in the inductor continues flowing through the resonance tank to block unwanted harmonics from reaching the antenna. Since the input switch only turns on when the drain to source voltage is almost zero, little power is dissipated in the input devices. The soft switching capacitor is added to improve the switching efficiency to reduce drain voltage before the drain current is drawn. Assuming the off-chip inductor's quality factor in resonance

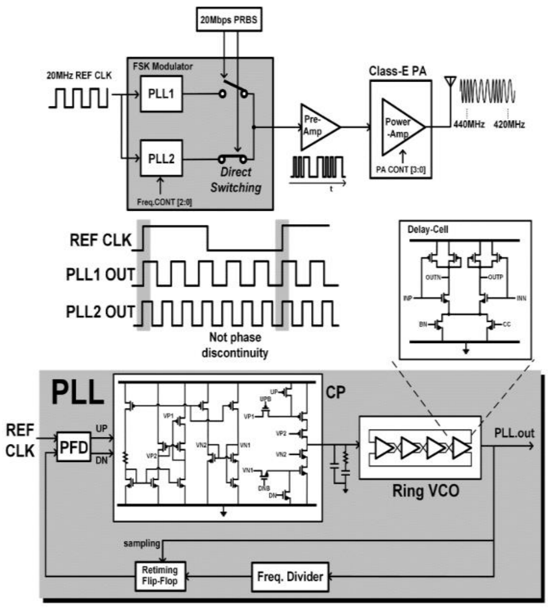

Fig. 2 Overall architecture

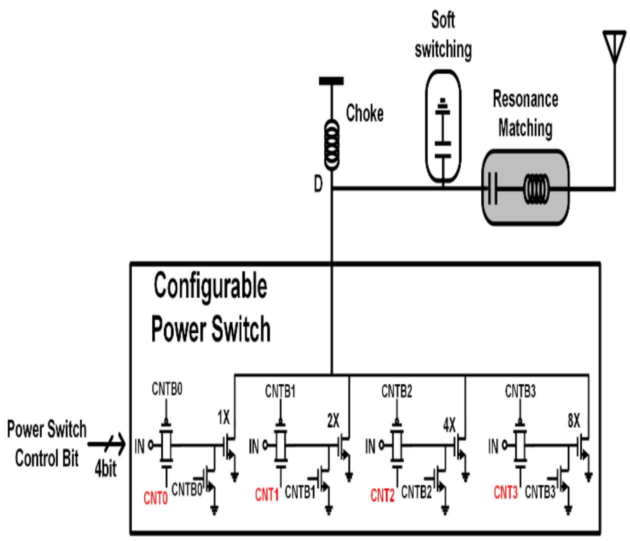

Fig. 3 Class-E PA

matching is large enough, the capacitance (Csoft) for soft switching is obtained using equation (1), where R is the antenna impedance. The output power can be expressed in equation (2) as well. The resonance matching LC tank is composed of 8.6nH inductance and 17pF capacitance, and soft switching capacitance is set to 1.7pF. It can combine with a miniaturization antenna [8] for capsule endoscopy applications.

$$C_{soft}\omega R = \frac{8}{\pi(\pi^2+4)} \tag{1}$$

$$P_{DC} = P_o = \frac{{V_{DC}}^2}{R} * \frac{8}{(\pi^2+4)} \tag{2}$$

III. IMPLEMENTATION RESULTS

The capsule endoscope transmitter has been fabricated in 65nm CMOS technology, and its chip microphotograph is shown in Fig. 4. The total chip area, including the pads, is 0.9mm * 1.3mm, while the active area is 0.3mm * 0.36mm. All circuit measurements are performed with a 1V supply voltage.

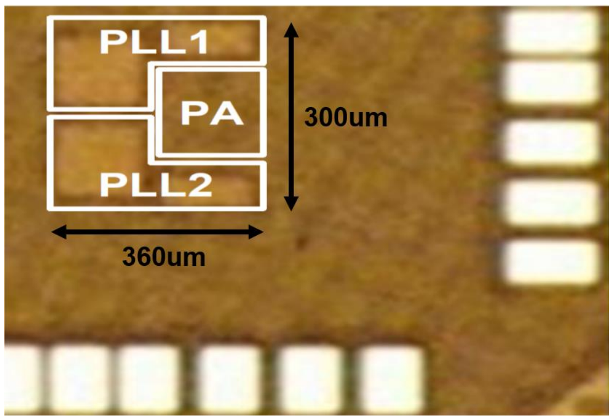

Fig. 4 Chip microphotograph.

Fig. 5 shows the output spectrum of the single PLL at 420MHz. Its phase noise is measured at -85 dB/c @ 1MHz, and the reference spur is measured at -47dBc. The output power is set to -16dBm through the reconfigurable switches in the PA.

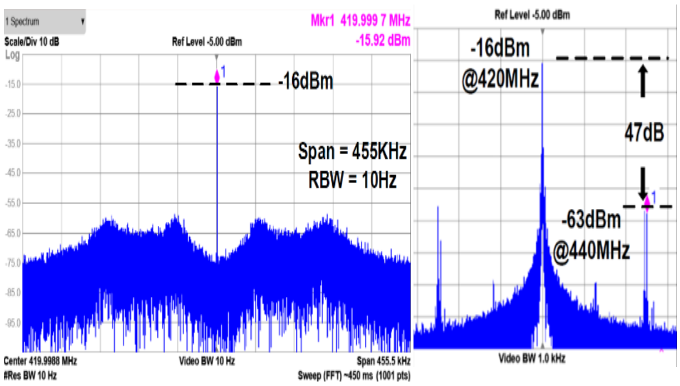

Fig. 5 Phase noise and reference spur

Fig. 6 shows the output spectrum of 20Mb/s BFSK transmitted signal with a frequency deviation of 20MHz, which has a modulation index of 1. The common reference clock of 20MHz is used, showing the phase continuity of the FSK signal at the switching moment thanks to the fast switching charge pump and the retiming flip-flop.

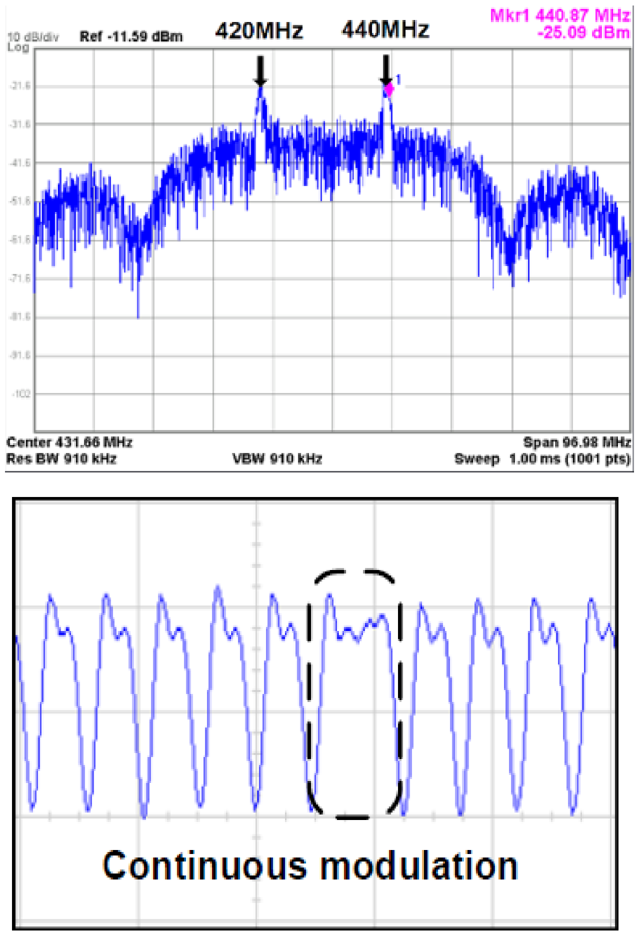

Fig. 6 Measured FSK spectrum and time domain waveform at the switching moment.

Fig. 7 plots the output power and power efficiency of the Class-E PA concerning the control code of the reconfigurable switches from 0 to 15. The output power can be configurable from -35 dBm to -16 dBm, which corresponds to the power efficiency from 30% to 87%. Table 1 compares the proposed transmitter with other 400MHz transmitters. We have achieved the 20Mb/s data rate through the direct switching FSK modulator consuming 1.7mW with a high energy efficiency of 0.085nJ/b, still under the die area of 0.11mm^2, showing a promising solution for use in capsule endoscope application.

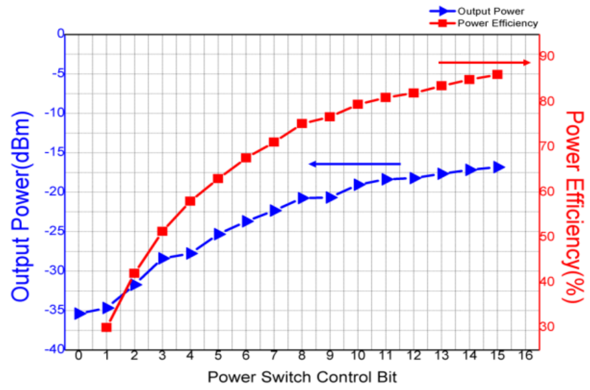

Fig. 7 Output power and power efficiency according to PA control signal.

IV. CONCLUSIONS

This paper implemented a low-power, high-speed transmitter for a capsule endoscope application with 65nm CMOS technology. The 20Mb/s data rate is obtained by adopting high speed switching FSK modulator with two independent low power PLLs. Moreover, the Class-E amplifier is exploited to efficiently transfer the FSK signal into the antenna with a soft switching capacitor. At the output power of the -16dBm, the PA achieves 87% of power efficiency. With the 1V supply voltage, the transmitter consumes 1.7mW with sub-0.1nJ/b energy efficiency.

TABLE I. Comparison with other transmitters.

Parameters	[1]	[3]	[4]	[6]	This Work
Technology	65nm CMOS	90nm CMOS	180nm CMOS	130nm CMOS	65nm CMOS
Frequency (MHz)	400-450	429	400	401-428	420-440
Data Rate (Mb/s)	10	0.2	3	11	20
Modulation Method	OQPSK	FSK	MSK	QPSK	BFSK
Output Power (dBm)	-15	-8.2	0	-13	-16
DC power (mW)	2.97	0.39	3.9	4.08	1.7
Die Area(mm^2)	1.5	1	13.3	0.643	0.11
Energy Efficiency (nJ/b)	0.28	1.95	1.3	0.37	0.085

ACKNOWLEDGMENT

This work was supported by the Technology Innovation Program (20012355, Fully implantable closed loop Brain to X for voice communication) funded By the Ministry of Trade, Industry & Energy (MOTIE, Korea).

REFERENCES

[1] Jiang, H., Weng, Z., Li, Y., Dong, J., Rhee, W., &Wang, Z. : '10 Mbps 0.3 nJ/bit OQPSK transceiver IC for 400–450 MHz medical telemetry', *Electronics Letters*, 2016, *52*(22), 1830–1832.

[2] Chang, G., Maity, S., Chatterjee, B., &Sen, S. : 'Design Considerations of a Sub-50 Mu-W Receiver Front-end for Implantable Devices in MedRadio Band', *Proceedings of the IEEE International Conference on VLSI Design*, *2018-Janua*, 329–334.

[3] Chun-Yuan Chiu, Zhen-Cheng Zhang., &Tsung-Hsien Lin. : 'A 0.6-V 200-kbps 429-MHz Ultra-low-power FSK Transceiver in 90-nm CMOS', *IEEE Asian Solid-State Circuits Conference November 6-8, 2017/Seoul, Korea, 193-196.*

[4] Hanjun Jiang, Fuie Li, Xinkai Chen, Yanqing Ning, Xu Zhang, Bin Zhang, … Zhihua Wang. : 'A SoC with 3.9mW 3Mbps UHF transmitter and 240uW MCU for Capsule Endoscope with Bidirectional Communication', *IEEE Asian Solid-State Circuits Conference November , 2010, 8-10.*

[5] De Beaupré, V. C., Zaïd, L., Rahajandraibe, W., & Bas, G. : 'A fully integrated 2.45-GHz frequency synthesizer and FSK modulator', *Proceedings of the IEEE International Conference on Electronics, Circuits, and Systems*, 2006, 1208–1211.

[6] Teng, K. H., & Heng, C. H., 'A 370-pJ/b Multichannel BFSK/QPSK Transmitter Using Injection-Locked Fractional-N Synthesizer for Wireless Biotelemetry Devices', *IEEE Journal of Solid-State Circuits*, 2017, *52*(3), 867–880.

[7] Ibrahim, M. A. A., & Onabajo, M. , 'A Low-Power BFSK Transmitter Architecture for Biomedical Applications' *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2020, *67*(5), 1527–1540.

[8] S. Hashem & J. Rashed-Mohassel, 'Miniaturization Of Dual Band Implantable Antennas' *MICRO AND OPTICAL TECHNOLOGY LETTERS*, 2017, 59(1), 36–40.

Byeong Seol Kim received the B.S. and M.S. degrees in electrical and electronics engineering from Kangwon National University, Chuncheon, Korea, in 2019 and 2021, respectively. His research interest includes RF circuits and linear RF transmitters for wireless communications. And wireless power transfer for biomedical devices.

Joon Sung Bae (M′14) received the B.S. degree from the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2007, and the M.S. and Ph.D. degrees in electrical engineering from KAIST, in 2009 and 2013, respectively. His Ph.D. dissertation concerned circuits and systems for wireless body area network. He was an Analog Circuit Designer with IMEC, Leuven, Belgium, where he investigated ultra-lowpower biomedical circuits. Since 2017, he has been with the Department of Electrical and Electronics Engineering, Kangwon National University, Chuncheon, South Korea, where he is currently an Assistant Professor. His current research interests include energy-efficient mixed-signal circuits and systems for the Internet of Things, biomedical sensors, and body area networks. Dr. Bae is currently a Technical Program Committee Member of the International Solid-State Circuits Conference. He was a recipient of Asian Solid-State Circuits Conference Best Design Awards in 2011 and 2014.