INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2014, VOL. 60, NO. 2, PP. 193–198
Manuscript received March 10, 2014; revised June, 2014. DOI: 10.2478/eletel-2014-0024

A –5 dBm 400MHz OOK Transmitter for Wireless Medical Application

M. Yousefi, Z. D. Koozehkanani, H. Jangi, N. Nasirzadeh, and J. Sobhi

***Abstract*—A 400 MHz high efficiency transmitter for wireless medical application is presented in this paper. Transmitter architecture with high-energy efficiencies is proposed to achieve high data rate with low power consumption. In the on-off keying transmitters, the oscillator and power amplifier are turned off when the transmitter sends 0 data. The proposed class-e power amplifier has high efficiency for low level output power. The proposed on-off keying transmitter consumes 1.52 mw at -5 dBm output by 40 Mbps data rate and energy consumption 38 pJ/bit. The proposed transmitter has been designed in 0.18µm CMOS technology.**

***Keywords*—transmitter, power amplifier, on-off keying, low power**

I. Introduction

Wireless body sensor network provides wireless connectivity among sensors that used for exhibition signals vital of body and personal serves. Vital signal monitoring, diagnose assistant, and the drug delivery are medical application of WBAN [1, 4]. Personal computer, cell phone, WLAN and internet network are personal serves that used to connect with medical center and WBAN. Fig. 1 illustrates a typical scenario of WBAN application.

In typical WBAN applications, the distance between node and gateway node is less than 3m, and the output power for transmitter (TX) is less than 1mw. Sensor node is composed of sensing section, ADC, digital processor and transceiver. Sensor node must be small to limit the required source energy, while the transceiver consumes extra energy. As a result, the design of an RF transceiver is challenge for the WBSN sensor node.

In most reported papers, Figure of merit for transmitter is that how much energy is consumed for sending one bit by assuming that error did not occur in transition data. That is,

$$FOM = P_{DC} / datarate \qquad (1)$$

Where, P_{DC} is consuming power of transmitter. In order to maximize the lifetime, Data rate and dc power must be respectively high and low. High data rate wireless is required for application like capsule endoscopy or multichannel biosensor recording. OOK and frequency shift keying (FSK) are mostly modulation in the RF transceiver sensor node.

M. Yousefi, Z. D. Koozehkanani, H. Jangi, N. Nasirzadeh, and J. Sobhi are with the Faculty of Electrical and Computer Engineering, University of Tabriz, Iran.

OOK modulation has the advantage over FSK modulation because it is suitable for simple super-regenerative [4]–[6] and envelope detection [7] architecture. The extraordinary gain and simplicity of super-regeneration promise low cost and low power consumption. Owing to mitigated sensitivity and selectivity requirements of receiver, envelope detector with just RF amplification and without power-hungry local oscillator (LO) can be the simplest. Receiver architecture and leads to the best energy-efficient receiver architecture.

Transmitter is composed of two major building blocks: the oscillator and the power amplifier (PA). The PA is the main contributor to the overall power consumption of transmitters. High efficiency power amplifiers must provide the required power for signal transmission. One widely used high efficiency structure is class-e power amplifier.

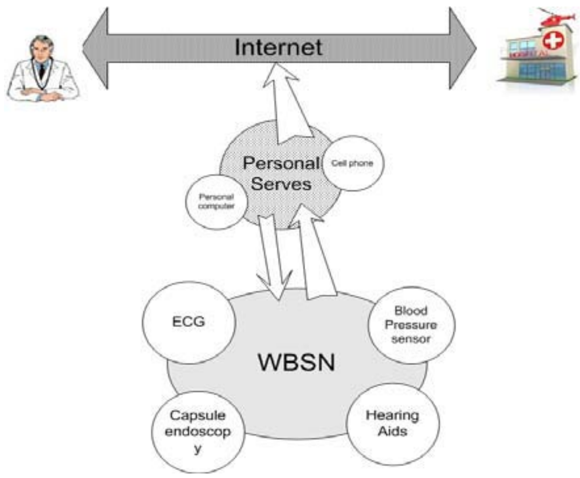

Fig. 1. A typical scenario of WBSN application.

Class-e PA is a nonlinear switching type PA that can ideally achieve 100% efficiency. This high efficiency has spurred many research interests on the design and analysis of class-e PAs [8]–[15] The existing works of class-e PA mostly focus on designs optimized at high output level, ranging from 23 to 33 dBm [9]–[15]. High efficiency and low level output power design of power amplifier (PA) is a requirement for optimization of the energy efficiency of the transmitter, which is one the key building blocks of sensor nodes in wireless sensor networks. For most short distance communication standards, such as Bluetooth and ZigBee, the output power ranges from 0 to 10 dBm [16], [17] and in wireless body sensor networks it is even under 0dBm [18]– [21]. The conventional class-e power Amplifier introduced by Sokal [8] can produce large power levels with good efficiency but in applications requiring low level output power such as wireless body sensor networks, the efficiency of this PA is not sufficient.

The power amplifier presented in [22] has the potential to transmit at low output power levels with proper efficiency. An advantage of this structure is that it can be fully integrated meaning that all required elements could be on chip. It has even higher efficiency at lower frequencies. Another issue in wireless sensor networks is the carrier frequency. According to IEEE802.11.4.6 standard, the allocated frequency range for MICS is from 401 MHz up to 406 MHz [23]. In the Fig. 2, power added efficiency (PAE) versus output power level for different types of class-e power amplifiers is shown. An approximate line crossing simulation points shows that efficiency decreases as the output power level decreases. In the proposed amplifier, using a modified class-e structure it is able to deliver low output power with appropriate efficiency at 400 MHz. In the proposed Transmitter used class-e PA that works with 400 MHz and -5 dBm output power and properly efficiency. Information of PA is presented in subsection I. B.

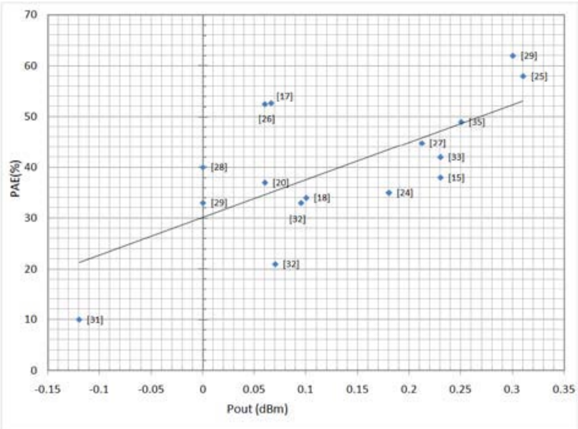

Fig. 2. Efficiency of power amplifier versus output power level

In this paper, transmitter architecture with high energy efficiencies is proposed to achieve high data rate with low power consumption. This paper is organized as follows. Section II describes the basic operation transmitter architecture used. Results are presented in Section III. Finally, the conclusions are presented in Section IV.

II. TRANSMITTER STRUCTURE

The transmitter (TX) block diagram is shown in Fig. 3. In this design, OOK modulation scheme is utilized, in which binary “1” is represented by a pulse and binary “0” by no pulse transmission. The TX adopts simple circuitry structure to save power. It is composed of two major building blocks: the oscillator and the PA. The OOK TX can be easily realized by turning on or off the PA and digital controlled oscillator (DCO) according to message data. The structure of PA and DCO is presented in the following I.A and I.B subsections. In proposed transmitter when DCO is turned off, the PA is turned off, too.

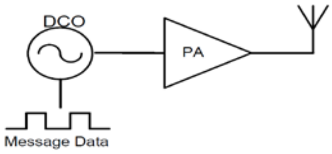

Fig. 3. Block diagram of transmitter.

A. Digital Controlled Oscillator (DCO)

Oscillators are blocks that play a key role in wireless communication network. In conventional high data rate OOK transmitters, oscillator and power amplifier turn off when the transmitter sends “0” data. However, all of components of the transmitter must be switched on and off with data rate frequency. The required time of ON/OFF duration of all the blocks determines the maximum data rate frequency. The required time for ON/OFF duration of oscillator is higher than the other blocks of TX.

In the proposed TX, LC complementary oscillator is used that its circuitry is shown in Fig. 4. It consists of the digital signals that are adopted to control The C bank has 5 transistor switches with capacitors and generates thirty two overlapped discrete tuning curves to increase the desired frequency tuning range. Simulation results show that the tuning range is about 400-406 MHz with a 200 KHz/step. The minimum capacitor of C bank is 60 fF.

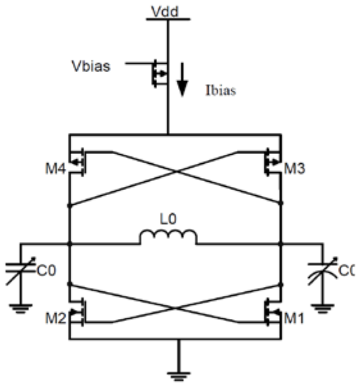

Fig. 4. The circuit of DCO.

As the following, the equation indicates the amplitude voltage is proportional with parallel resistance and bias current.

$$V_{amp} = \frac{4}{\pi} R_p I_{bias} \tag{2}$$

The Rp is equivalent resistance that is determined with quality factor of inductor. In the complementary oscillator, having high swing voltage required that bias current or parallel resistance to be high. It should be reminded that high bias current will increase power consuming and large parallel resistance requires for inductor. Unfortunately, the integrated inductor inherently has low quality and Rp could not be high. Since the oscillator must be having enough output voltage for driving of PA. So, for have high swing output in the oscillator dc current must be increased.

In the designed complementary oscillator, bias current is 1.8 mA and 13.7 nH inductor with Q=10. The swing voltage is 0.4 volt that is sufficient for driving modulator. The designed DCO has -150 dBc/Hz (100KHz offset) frequency phase noise and 0.4 volt swing.

B. Power Amplifier

The proposed class-e PA is shown in Fig. 5. The L_0 and L_1 inductors are spiral inductor. The inductor L_1 is chosen as DC feed. The capacitor C_3 provides alternative current path for higher harmonics. The inductor L_1, C_3 and the capacitor C_4 form an impedance matching network which transforms the antenna resistance to Req at the desired output frequency (ω_o). The inductor L_1

Unlike conventional structures, the harmonic rejection is now provided by both L_1 and C also helps reducing higher harmonics current component.

This allows smaller L_1 to be chosen for on-chip integration. It should be pointed out that the proposed architecture has merged the harmonic rejection and impedance matching into a network consisting of L_1, C_2, C_3 and C_4

This circuit is designed to operate with a supply 0.4 V and -5 dBm output power and 400 MHz by changing power supply, output power can be change. With this characteristic of PA, the transmitter will capable be saving energy. . For this architecture, the drain parasitic capacitance of switching transistor can be incorporated into C_1, whereas the pad parasitic can be merged with C_4. Therefore, the circuit shown in Fig. 4 can be a compact representation of the actual implemented PA with all parasitic taken into considerations.

Table I summarizes a comparison between several class-e power amplifiers. Power amplifier [22] has 55% efficiency at 0 dBm output power and operates at 2400 MHz among the amplifiers of Table I, the proposed amplifier has 33% efficiency at -2 dBm output power, the possibility for full integration and operating at 400 MHz

C. Modulation of Transmitter

The switching of transmitter is carried out by modulator; for this proposes, the TX uses a controlled current source. When the transmitter sends “0” message data, Ibias is 0 and 1 data Ibias is 1.8 mA. In other words, modulator turns the transmitter on or off.

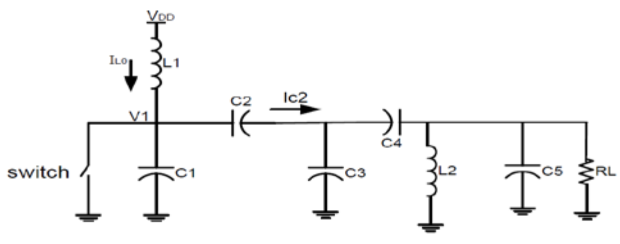

Fig. 5. The schematic of power amplifier.

TABLE I
COMPARISON TABLE OF CLASS-E PAS

Ref.	Freq. (GHz)	Pout(dBm)	PAE (%)	Vdd(V)	Tech.
[28]	2.4	9.54	33	1.2	0.18∝m
[19]	2.4	0	55	0.5	0.13∝m
[7]	1.8	33	31	3.3	0.18∝m
[20]	2.2	18	35	1.6	0.18∝m
[31]	1.4	25	49	1.5	0.25∝m
[27]	0.4	-12	10	1	0.18∝m
Prop. PA	0.4	-2	33	0.5	0.18∝m

III. RESULTS

The proposed transmitter shown in Fig. 6, has been designed in 0.18 μm CMOS process. Minimum output swing of DCO working at 400 MHz is 0.4 V. Fig. 7 shows the waveforms of output modulated signal with 1010 message data and 40 Mbps data rate. The DCO consumes 1.8 mA from a 1 V power supply when sending “1”.

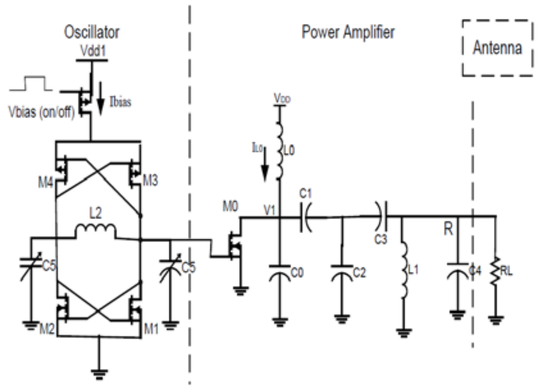

Fig. 6. Circuitry of the proposed transmitter.

To change the output power level, power supply voltage of the PA can be altered. As Fig. 8 shows by changing the supply voltage from 0.35 V to 0.55 V, the output power level varies from -6 to -2 dBm and TX efficiency varies from 10 to 14%. If power supply voltage of the DCO is changed from 0.95 to 1.05 V as shown in Fig. 9, output frequency varies from 408.7 MHz to 401.6 MHz and output power varies from -5.9 to -4.6 dBm.

The phase noise of the transmitter versus power supply voltage of the DCO has been shown in Fig. 10. Phase noise is -150 dBc/Hz beyond 100 KHz offset in 1 V power supply. The output power level of the transmitter is -5 dBm at 50 ohms load. A performance comparison with other reported low power transmitters has been provided in Table IV. FOM for the proposed transmitter is 38 pJ/bit. The proposed transmitter performs favourable compared to the others.

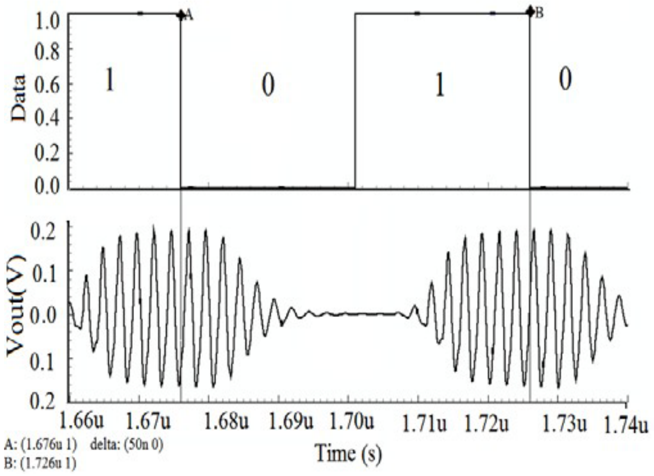

Fig. 7. Waveform of output modulated signal with 1010 data message and 40 Mbps data rate.

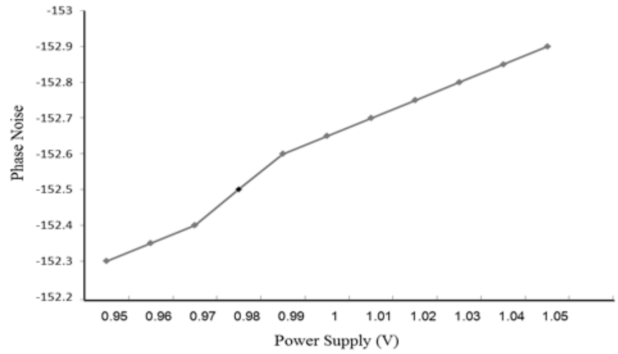

Fig. 10. Phase Noise of transmitter.

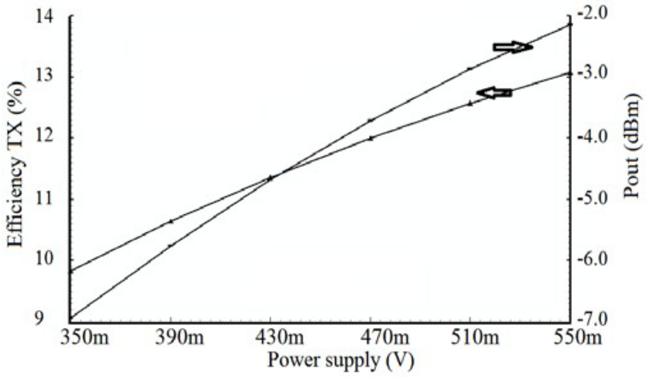

Fig. 8. Efficiency and Pout of proposed transmitter versus power supply of PA.

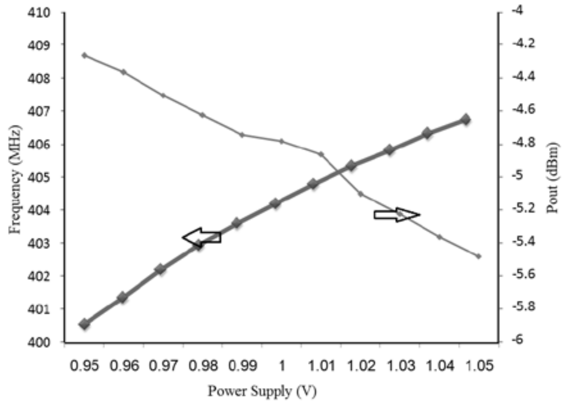

Fig. 9. Frequency and Pout versus power supply of DCO.

TABLE II
WIDTH OF TRANSISTORS, SIZING OF CAPACITORS AND INDUCTORS OF PROPOSED TRANSMITTER

Index	Inductors (nH)	Capacitors (pF)	Width of transistors (µm)
0	10.5	4.2	360
1	9.2	9	480
2	13.7	12.9	480
3	------	40	1440
4	------	4	1440
5	------	14.8	------

TABLE III
SUMMARIZES OF CHARACTERISTIC OF PROPOSED TX

Parameters		Value
Power supply	Oscillator	1v
	PA	0.4v
Technology		0.18 µm
Modulation		OOK
Fall Time		7ns
Rise Time		9ns
Maximum Data Rate		40Mb/s
Carrier Frequency		400 MHz
Power consumption		1.52mW
Output Power(mW)		0.32 (-5 dBm)
FOM(pJ/bit)		38

.

TABLE IV
PERFORMANCE COMPARISON OF TXS

Reference	[37]	[36]	[38]	[39]	This work
$F_{carrier}$	2.4	0.44	0.433	2.4	0.4
Technology(μm)	0.13	0.35	0.35	0.18	0.18
Data Rate (Mbps)	0.3	40	10	4/0.5	40
Modulation	FSK	OOK	OOK	OOK/FSK	OOK
Phase Noise	-106	-103	-125	NA	-150
Power Supply (v)	0.6	3	1	1.8	1-0.4
Pdc(mW)	1	2.58	0.52	2	1.52
Output Power(mW)	0.3	0.951	0.06	5.85/11.7	0.32
FOM (pJ/bit)	11111	64.5	51.8	500/10500	38

IV. CONCLUSION

A highly efficient OOK transmitter has been proposed for wireless medical application. The transmitter chip has been designed in 0.18-μm CMOS process. The oscillator and class-e power amplifier compose OOK transmitter with 40 Mbps data rate and 38 pJ/bit FOM. The output power of proposed transmitter is -5 dBm. The proposed transmitter requires two different supply voltages; the PA uses a power supply value about 0.4 V while modulator and oscillator blocks work under 1 V power supply. The proposed high efficiency transmitter is well suited for high data rate monitoring of biomedical signals.

REFERENCES

[1] A. W. Wong, D. McDonagh, G. Kathiresan, O. Omeni, O. El-Jamaly, T. K. Chan, P. Paddan, and A. Burdett, “A 1 V, micropower system-on chip for vital-sign monitoring in wireless body sensor networks”, in Proc. IEEE Int. Solid-State Circuits Conf. San Francisco, 2008, pp. 138–139.

[2] Y. J. Yang, Y. J. Huang, H. H. Liao, T.Wang, P. L. Huang, C.-W. Lin, Y.-H.Wang, and S. shi Lu, “A release-on-demand wireless CMOS drug delivery soc based on electro thermal activation technique”, in Proc. IEEE Int. Solid-State Circuits Conf. San Francisco, 2009, pp. 288–289.

[3] M. Vidojkovic1 et al., “A 2.4GHz ULP OOK Single-Chip Transceiver for Healthcare Applications”, in Proc. IEEE Int. Solid-State Circuits Conf. San Francisco, 2011, pp. 458-460.

[4] Brian P. Otis, Y.H. Chee, and Jan M. Rabaey, “A 400μW-RX 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks”, in proc IEEE Int. Solid-State Circuits Conf, San Francisco, 2005, vol. 1, pp. 396–606.

[5] J.-Y. Chen, M. Flynn, and J. Hayes, “A fully integrated auto-calibrated super-regenerative receiver in 0.13 mCMOS,”IEEE J. Solid-State Circuits, vol. 42, no. 9, pp. 1976–1985, Sep. 2007.

[6] J. Bohorquez, A. Chandrakasan, and J. Dawson, “A 350 WCMOS MSK transmitter and 400 W OOK super-regenerative receiver for medical implant communications,” IEEE J. Solid-State Circuits, vol. 44, no. 4, pp. 1248–1259, Apr. 2009.

[7] D. Daly and A. Chandrakasan, “An energy-efficient OOK transceiver for wireless sensor networks,” IEEE J. Solid-State Circuits, vol. 42, no. 5, pp. 1003–1011, May 2007.

[8] N. O. Sokal, “Class-E RF Power Amplifiers”, QEX, no. 204, pp. 9-20. Jan/Feb. 2001.

[9] M. Acar, A. J. Annema, B. Nauta, “Analytical design equations for class-E power amplifiers”, IEEE Trans Circuits Syst. vol. 54, no. 12, pp: 2706–2717, Dec. 2007.

[10] S. Jin, B. Park, K. Moon, M. Kwon, and B. Kim, “Linearization of CMOS Cascode Power Amplifiers Through Adaptive Bias Control”, Microwave Theory and Techniques, IEEE Tran. on , vol.61, no.12, pp.4534,4543, Dec. 2013

[11] M. Apostolidou, M. P. V. Heijden, D. M. W. Leenaerts, J. Sonsky, A. Heringa, I. Volokhine, “A 65 nm CMOS 30 dBm class-E RF power amplifier with 60% PAE and 40% PAE at 16 dB back-off”, IEEE J. Solid-State Circuits, vol. 44, pp. 1372–1379, May 2009.

[12] R. Brama, L. Larcher, A. Mazzanti, and F. Svelto, “A 30.5 dBm 48% PAE CMOS class-E PA with integrated balun for RF applications”, IEEE J. Solid-State Circuits, vol. 43, pp.1755–1762, Agu. 2008.

[13] K. L. R. Mertens, M. S. J. Steyaert, “A 700-MHz 1-W fully differential CMOS class-E power amplifier”, IEEE J. Solid-State Circuits, vol.37, pp. 137–141, Feb. 2002.

[14] K. C. Tsai, P. R. Gray, “A 1.9-GHz 1-W CMOS class-E power amplifier for wireless communications”, IEEE J. Solid-State Circuits, vol.34, pp. 962–970, Jul.1999.

[15] M. Yousefi, Z. D. Koozehkanani, J. Sobhi and H. Jangi, “A 1.8 GHz Power Amplifier Class-E with Good Average Power Added Efficiency”, Circuits and Systems, vol.4, pp. 504-509, Dec. 2013.

[16] P. Reynaert and M. Steyaert, RF Power Amplifiers for Mobile Communications. New York, Springer, 2006.

[17] G. Retz, et al. “A highly integrated low-power 2.4 GHz transceiver using a direct-conversion diversity receiver in 0.18 m CMOS for IEEE802.15.4 WPAN”, in: Proc. IEEE ISSCC. San Francisco, CA. 2009, pp. 414-415,415a.

[18] Y. S. Eo, H. J. Yu, S. S. Song, Y. Y. Ko, J. Y. Kim, “A fully integrated 2.4 GHz low IF CMOS transceiver for 802.15.4 ZigBee applications”, In. Proc. 4TSolid-State Circuits Conference4T IEEE ASSCC07, Jeju, 2007, pp. 164–167.

[19] J. Bae, L. Yan, H. Yoo, “A Low Energy Injection-Locked FSK Transceiver With Frequency-to-Amplitude Conversion for Body Sensor Application”, IEEE J. Solid-State Circuits, vol. 46, pp. 928-937, 2011.

[20] B. Cook, A. Berny, A. Molnar, S. Lanzisera, K. Pister, “Low-power 2.4 GHz transceiver with passive RX front-end and 400 mV supply”, IEEE J Solid-State Circuits; vol. 41, pp. 2757–2766, 2006.

[21] J. Bae, N. Cho, H. J. Yoo, “A 490 mW fully MICS compatible FSK transceiver for implantable devices”, In. Proc. Symposium on VLSI Circuits, 2009, pp. 36–37.

[22] J. Tan, C. H. Heng, Y. Lian, “Design of Efficient Class-E Power Amplifiers for Short-Distance Communications”, IEEE Tran. ON circuit and systems, vol.59, pp. 2210-2220, 2012.

[23] IEEE P802.15.6/ IEEE standard, May 2010.

[24] D. Sira, P. Thomsen, and T. Larsena “Output Power Control in Class-E Power Amplifiers”, IEEE Microwave And Wireless Components Letters, vol. 20, no. 4, pp. 232–234, Apr 2010

[25] R. Brama,. L. Larcher, A. Mazzanti, F. Svelto, “A 1.7-GHz 31dBm differential CMOS Class-E Power Amplifier with 58% PAE”, in Proc. Custom Integrated Circuits Conf. 2007, San Jose, pp. 551-554.

[26] J. Cai and Z. Li, “A 1-V, 800-MHz CMOS class-E power amplifier with power Wireless Communications & Signal Processing (WCSP)”, in Proc. 2013 Int. Conf., 2013, pp. 1-4.

[27] A. O. Ameen, and K. M. Sharaf, “A 1.75 GHz CMOS Class E RF Power Amplifier and oscillator”, Microelectronics 2007 ICM 2007 Int. Conf., 2007, pp. 235 – 238.

[28] K. L. R. Mertens, and M. S. J. Steyaert, “A 700-MHz 1-W fully differential CMOS class-E power amplifier”, IEEE J. of Solid-State Circuits, vol. 37, pp. 137-141.

[29] Q. Zhang, P. Feng, Z. Geng, X. Yan, and N. Wu, “A 2.4-GHz Energy-Efficient Transmitter for Wireless Medical Applications”, Trans. on Biomedical Circuits and Systems IEEE, vol. 5, pp. 39–47, Feb 2011.

[30] X. Huang, E. Harpe, P. ; X. Wang, and G. Dolmans, “A 0dBm 10Mbps 2.4GHz ultra-low power ASK/OOK transmitter with digital pulse-shaping”, Radio Frequency Integrated Circuits Symposium, Anaheim, CA, 2010, pp. 263 – 266.

[31] M. R. N-Ahmadi, at et, “A 2mW 400MHz RF transceiver SoC in 0.18um CMOS technology for wireless medical applications”, Radio Frequency Integrated Circuits Sym., 2008, pp. 285 – 288.

[32] M. M. El-Desouki, M. J. Deen, M. Haddara, and M. Yaser, “A low-power CMOS class-E power amplifier for biotelemetry applications”, in Proc. Microwave Conference, 2005, European, vol. 1.

[33] T. Sowlati, and D.M. W. Leenaerts, "A 2.4-GHz 0.18-μm CMOS self-biased cascode power amplifier", Solid-State Circuits, IEEE J. of RFIC Virtual J. IEEE, vol. 38, pp. 1318–1324, Aug 2003.
[34] D. Sira, P. Thomsen and T. Larsen, "A cascode modulated class-E power amplifier for wireless communications", Microelectronics J., vol. 42, pp 141–147, Jan 2011.
[35] A. Shirvani, D. K. Su, and B. A. Wooley, "A CMOS RF power amplifier with parallel amplification for efficient power control", IEEE J. of Solid-State Circuits, vol. 37, pp. 684–693, Jun 2002.
[36] D. C. Daly and A. P. Chandrakasan, "An energy-efficient OOK transceiver for wireless sensor networks," IEEE J. Solid-State Circuits, vol. 42, pp. 1003–1011, May 2007.
[37] Ben W. Cook et,"An Ultra low Power 2.4GHz RF Transceiver for Wireless Sensor Network in 0.13 μm CMOS with 400mw supply and an Integrated Passive RX front-End," in IEEE ISSCC dig. Tech. Papers, pp. 1460-1469, Feb. 2006.
[38] M. Kumarasamy Raja and Yong Ping Xu, " A 52 pJ/bit OOK Transmitter with adaptable data rate," in Proc Solid-State Circuits Conf., 2008. IEEE Asian, Fukuoka, Japan 3-5 Nov 2008, pp. 341 –344.
[39] Z. Qi, K. Xiaofei and W. Nanjian, "An ultra-low-power RF transceiver for WBANs in medical applications," Journal of Semiconductors, vol. 32, June 2011.