A Low Power CMOS Chirp-Spread-Spectrum OOK Transmitter for In-Body Communication

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Abstract— **In this paper, the design of a transmitter for in-body communication's applications is described. The proposed transmitter uses On-Off keying (OOK) modulation method to achieve high efficiency for a long battery lifetime. And the current-combining Class-C power amplifier also helps the efficiency enhancement. And the transmitter is robust to interference using Chirp Spread Spectrum (CSS). CSS is realized by Voltage Controlled Oscillator (VCO) as the carrier frequency is swept by saw-tooth wave. The sweeping range is ±10 % around 500MHz. The simulation performed in standard CMOS 0.13-µm process shows that the overall DC power consumption is 2.1mW and the efficiency of power amplifier alone is 71%. The transmitter is simulated at 20Mbps data rate.**

Keywords - in-body communiation; chirp spread spectrum; current- reusing; current- combining; CMOS power amplifier;

I. INTRODUCTION

Research on RF technology for in-body communication is one of the most active areas today, as it can realize more convenient monitor on patients' condition, more accurate diagnosis, and examine new definite treatments. For examples, a wireless capsule endoscope can transfer the images captured inside the body to an instrument outside, and a wireless sensor device put inside the body can check patients' health condition, and much more biomedical applications are available and in ready for more improved performance. Accordingly, analyses of the propagation models for RF communication inside human body also became an important issue, because to find the optimum operating frequency band is a critical matter to minimize the loss through human body [1-5].

In a previous study [5], the transmit loss depending on frequency was considered and the proper frequency was determined to be 500MHz. And the system used an on-off keying (OOK) modulation method which is efficient in power consumption and the structure of which is relatively simple, so proper for low power systems. However it is weak with outer interference and has the bad bit-error rate (BER) characteristic. Furthermore the frequency used in the system is overlapped by TV broadcast bands, so the system may suffer from the severe interference. As a solution, chirp spread spectrum (CSS) combined with OOK is proposed which is called as CSS-OOK [6]. In this paper a transmitter for an inner body device is designed using CSS-OOK and its performance is simulated. In the next study, the BER performance will be able to show the validity of the system compared with a conventional OOK system.

TABLE I. SPECIFICATION TARGET

Frequency Band	425 ~ 575MHz
Supply Voltage	2.8 ~ 3.2V (3V)
Transmit Power	0dBm
Data rate	20Mbps

Table 1 shows the specifications of the design. The band around the same frequency is used according to the result of the previous work but it is wider than before to make CSS. The supply voltage is assumed to be 3 V though it is initially 3.2V but decreases to 2.8V because of the battery discharge. As shown, the transmit power should be limited as 0dBm since excessive power can be harmful to human body due to the strong EM field.

One of the important issues in designing the wireless devices is to minimize the DC power consumption for a longer battery lifetime. Specifically in transmitters, power amplifier (PA) consumes most of the total DC power. Therefore improvement of PA's efficiency directly enhances the whole efficiency. The other required specification is that PA should support the wide frequency range for the realization of CSS. In this work, the highly efficient and wideband PA is designed with current-reusing and current-combining structure.

In Section II, the overall architecture of the transmitter is shown, and each composing block is described in detail. And then, Section III presents the performance of the circuit simulated in Advanced Design System by Agilent Technologies.

II. TRANSMITTER ARCHITECTURE

The whole transmitter's block diagram is shown in Fig. 1. It consists of low-drop-out (LDO), saw-tooth wave generator (SWG), voltage controlled oscillator (VCO), driver stage and PA. Each circuit is explained in the follow.

A. *Low-drop-out circuit*

As time passes by, the battery voltage gradually gets lower. It is a fatal problem because VDD of the circuit directly

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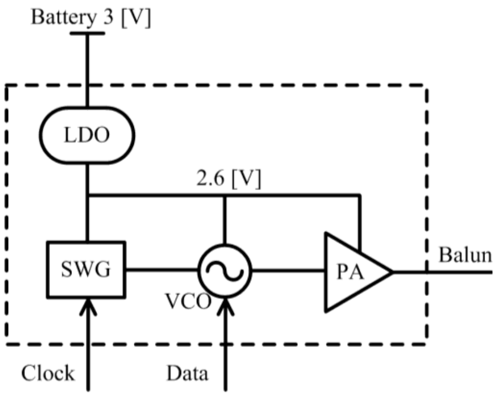


Figure 1. Transmitter's Overall Architecture

changes the operating frequency. Therefore, in order to supply a constant and stable VDD, a simple low-drop-out (LDO) voltage regulator is included. It is in a feedback structure which compares the output voltage with a reference.

B. Saw-tooth wave generator

Saw-tooth wave generator makes the linear and inclined saw-tooth waves that will be an input to the controlling node of the oscillator. It uses the clock signal that has the same bit rate with the processing data. Therefore it simultaneously begins the sweep with the start of the ON states of data.

C. Voltage controlled oscillator

VCO is made as a ring oscillator that consists of two inverters and one NAND gate. The NAND gate is used to realize the OOK modulation by inputting the binary data and the output signal node, as shown in Fig. 2. And the frequency can be controlled by the current tale M2 and the current mirror circuit. By varying the gate voltage of M0, the frequency is controlled. Saw-tooth wave is fed to the control node, sweeps the frequency and makes VCO generate CSS.

The VCO cannot avoid the change of center frequency due to a variance in the fabrication process. To solve the problem, M0 is made of four differently sized PMOSs in parallel connection. By selecting and combining the gates flexibly, the right frequency can be adjusted even with the process variation.

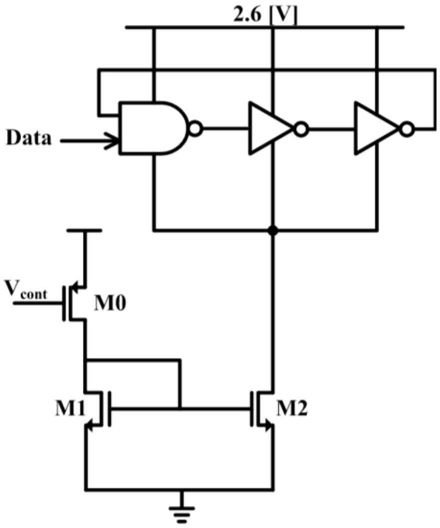


Figure 2. Simplified schematic of the VCO

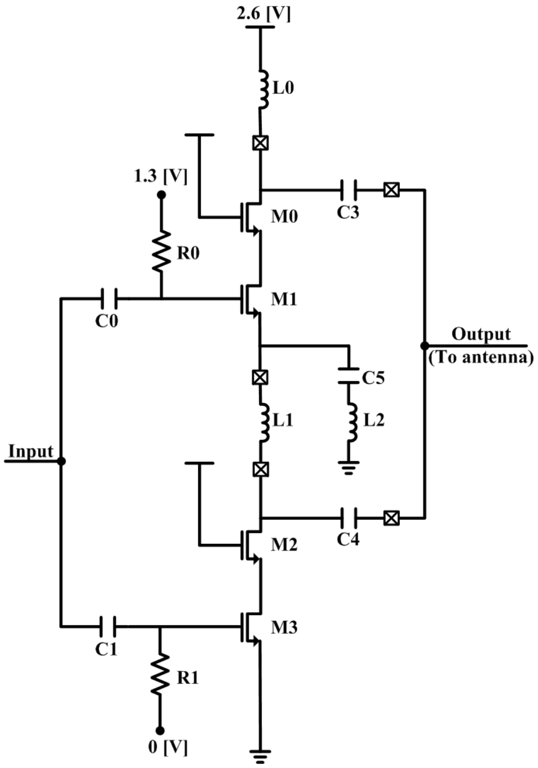


Figure 3. Schematic of current combing PA

D. Power amplifier

The supply voltage of 2.6 V is relatively high for PA whose targeted output power is 1mW. This is one of the obstacles to get the high drain efficiency of PA, since it means a high transform ratio of matching network. The much larger optimum impedance of output than the load makes matching network lose more power and degrades the efficiency. To solve this problem, current-reusing and current-combing power amplifier structure is employed. Fig. 3 shows the schematic which is using a shunt inductor and a series capacitor as the matching network.

Current-reusing structure itself helps the efficiency enhancement. Further, it divides the amplitude of output voltage swing into the half of the basic structure. And as a current-combining structure, two amplifiers share the output voltage [7]. As a result, each amplifier's drain impedance becomes a quarter of the simple conventional amplifier's. This reduces the loss of the matching network. Also, it lowers the Q factor of the network and makes the bandwidth wide. It is a suitable characteristic for CSS.

And the PA is designed to operate in class-C. Since the circuit is using OOK modulation, the PA's linearity is not a priority. Instead, nonlinear but high-efficient PA like switching PAs is preferable. Also, as the PA should not

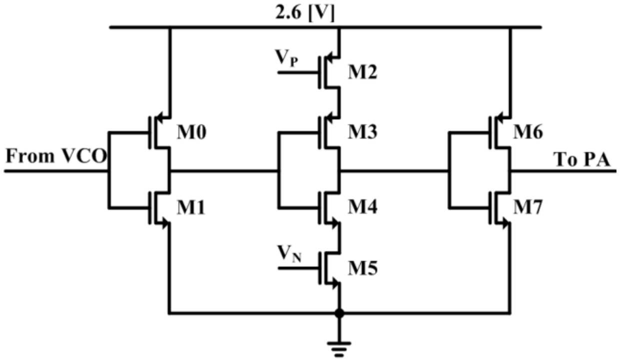


Figure 4. Schematic of the driver stage

consume DC power in OFF states (when data bit is “0”), class-A, B, or AB has no advantage in efficiency without any switching circuit. Furthermore, since the transmitter module has limited area to be equipped in a small device, the number of off-chip elements should be minimized. Therefore, switching PAs which need both a series resonance and an impedance matching network are not appropriate in this application, while class-C PA is sufficient with a simple matching network. Class-C is rarely used where the high power is required though its efficiency is superior to other linear PA classes, because its maximum output power is much lower than others [8]. But in this application high output is not needed, so class-C is suitable in many ways.

To make PA operate as class-C, the conduction angle of input needs to be below 180 degrees. It is realized by adjusting the width of NMOS and PMOS of drive amplifiers which are located between VCO and PA (Fig. 4). If the node named V_P that is originally set to 0V is connected to a higher bias voltage, the charging time of the drain node of M3 is increased. Then the conduction angle of inputs to PA gets wider. Reversely, it gets narrow with the bias voltage on node V_N lower than VDD.

PA is designed with the load impedance of 200ohm instead of the conventional value of 50ohm, since it is much more helpful for the reduction of the transform ratio, along with the structure proposed above. Actually, the load impedance is determined by using a balun the input port impedance of which is 200ohm. The balun converts the output signal to a differential pair to feed an ultra-wideband antenna.

III. SIMULATION RESULTS

This section shows the performance of the transmitter designed by standard 0.13-μm CMOS process model. The whole circuit is post-layout-simulated in time domain with 20Mbps random binary signal as the data input.

The output voltage waveform of VCO in CSS-OOK modulation is shown in Fig. 5. On and off operation according to the input data is clearly seen.

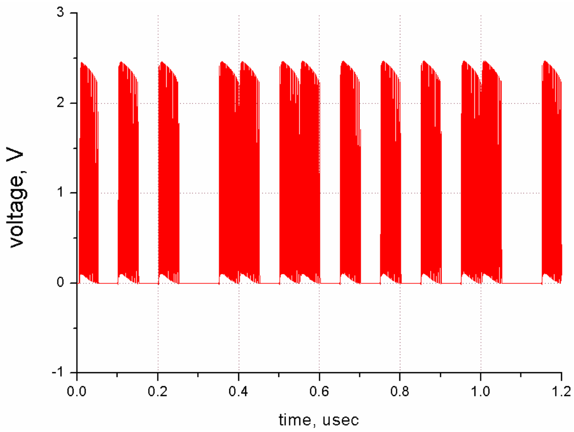


Figure 5. Output of CSS-OOK VCO in time domain

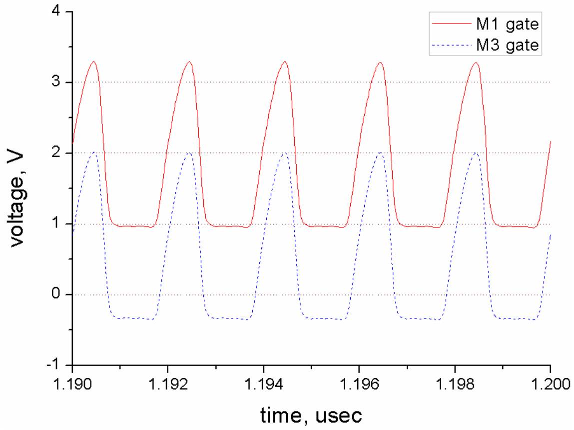


Figure 6. PA input signal (gate voltage) waveforms

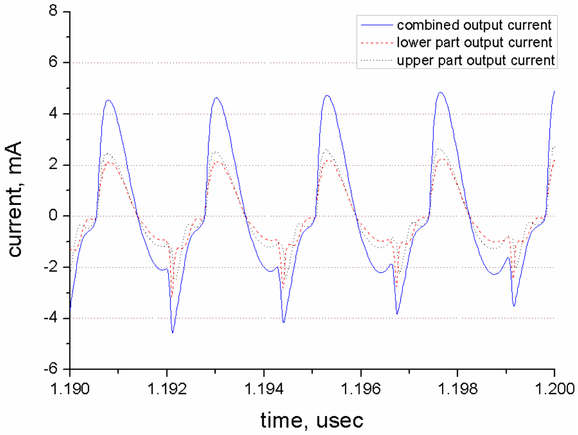
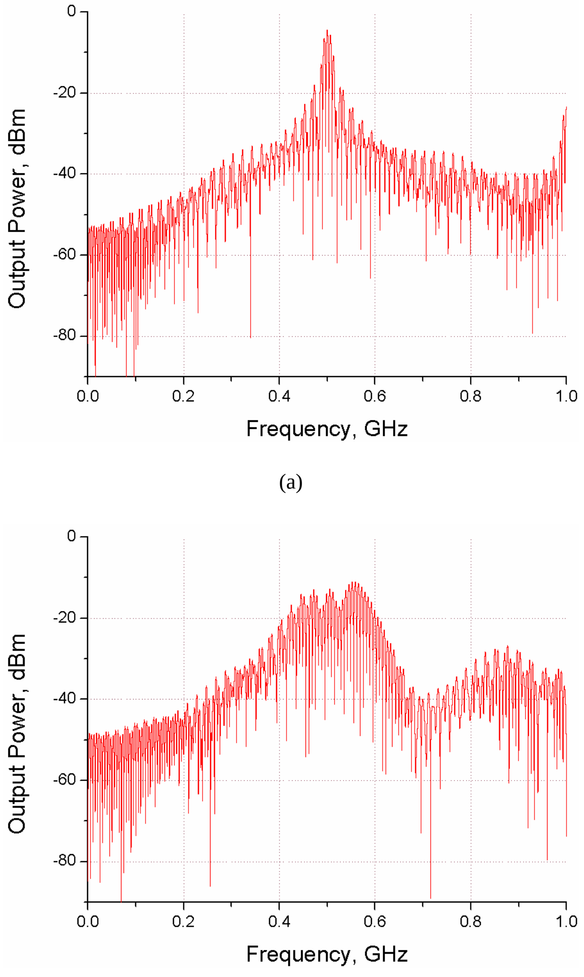


Figure 7. PA output current waveforms

Next, the input and output of PA is drawn in Fig. 6 and 7 each. As explained above, the PA input waveform is shaped in driver stage. Considering the threshold voltage is around 0.4V, the conduction angle is definitely below 180 degrees. The waves are biased to 0V and 1.3V each then fed to inputs of PA respectively. The solid line in Fig. 6 is the input at the gate node of M3 in Fig. 3, and the dashed one is of M1. And Fig. 7 shows the output current waveforms. As already described in the last section, the output current from upper and lower part (at the drain node of M0 and M2 in Fig. 3 respectively) are combined into the dashed line. As shown, the current waveforms have peaks and are not sinusoidal. It is due to harmonic frequencies resulted from having no harmonic



(a)

(b)

Figure 8. PA output power in frequency domain with (a) Non CSS (b) CSS

control circuit. But the distortion is unavoidable to minimize the number of passive components which take much of the chip area and increase power loss.

Finally, PA's output in frequency domain is shown in Fig. 8. Fig. 8a is with DC voltage at VCO's control node, while Fig. 8b with saw-tooth wave sweeping the frequency. Actually, CSS-OOK and simple OOK is achieved by turning on and off the SWG. PA's efficiency in both cases is over 70%. The total efficiency includes LDO in calculation. The output power is obtained by averaging the power of frequency channel between 400 and 600MHz. The performance of both cases is summarized in Table II.

The simulation result of CSS-OOK modulation is not better than that of simple OOK, since the PA's efficiency degrades as the operating frequency drifts apart from the center frequency where the performance is optimized. However the difference is small enough not to affect the comparison of the two methods' characteristics on interference.

TABLE II. SIMULATION RESULTS

Modulation Type	**Non CSS**	**CSS**
Process	Standard 0.13-µm CMOS	
Data rate	20Mbps	
Frequency	500MHz	425-575MHz
Power Consumption	2.1mW	2.5mW
Average Output Power	-1.3dBm	-0.8dBm
Total Efficiency	35.1%	33.3%
PA Efficiency	74.1%	72.0%

IV. CONCLUSION

A low power transmitter architecture that is robust to interference is proposed for in-body communication and designed and simulated in UMC 0.13-µm CMOS process. Its high efficiency is achieved by a current-combining class-C power amplifier that is suitable for low power applications. What remains now is the verification of CSS-OOK's better characteristic on interference than OOK's with the fabricated system circuits.

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