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A 2.4GHz Low Power ASK Transmitter for Wireless Capsule Endoscope Applications*

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Abstract: A 2.4GHz ASK transmitter suitable for a low power wireless capsule endoscope system is presented. A mixer-based frequency up-conversion transmitter architecture is employed to achieve a high data rate. A pseudo-differential stacked class-A power amplifier using the current reuse technique is proposed to save power. The transmitter mainly includes two parts: a 20MHz ASK modulator based on a constant amplitude phase lock loop (PLL) and a direct up-conversion RF circuit. This design, implemented in a TSMC 0.25μm CMOS process, achieves a -23.217dBm output power with a data rate of 1Mbps and dissipates 3.17mA of current with a single 2.5V power supply.

Key words: wireless capsule endoscope; amplitude shift keying; PLL; transmitter; CMOS
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1 Introduction

Wireless communication techniques have been advancing rapidly in the past two decades. Many high performance wireless systems, such as cellular telephones, GPS systems, and WLAN systems[1~5], have been developed. Recently, much more medical equipments using wireless communication techniques have been exploited to monitor human health[6,7], such as wireless capsule endoscope systems. Many researchers and corporations have researched the capsule endoscope because of its great market demand.

Traditional endoscopic examination of the small intestine is limited by the intestine's significant length and distance from accessible orifices. Wireless capsule endoscopy has been developed to facilitate the examination of this inaccessible portion of the gastrointestinal tract. In May 2000, Iddan *et al.*[8] reported on wireless capsule endoscopy systems and the results of animal trials in Nature. Then they conducted trials in the human body, leading to the U. S. Food and Drug Administration approval of the device for clinical use in 2001. Recently, a successful research of wireless capsule endoscopy has been reported in many countries, but practicable products are limited to the 'M2A' (Given Imaging, Atlanta, GA).

In wireless capsule endoscope systems, the main constraints of the wireless transceiver are very different from those of conventional wireless applications. First, the communication is highly asymmetrical since the data flow is mostly from inside to outside of human body. Second, a high data transmission rate of several Mbps must be reached to achieve high quality medical images. Last and most important, low power transceivers are typically required since small, low-capacity batteries are used. Due to the foregoing characteristics, achieving a low power, high data rate transmitter has been a challenge to implementing wireless capsule endoscope systems.

In addition to the requirements of low power consumption and a high, reliable data rate, a high integration level is also an issue for the small size of the capsule. Hence, various levels of the system design hierarchy, from the modulation technique and circuit architecture to the selection of the carrier frequency, must be explored to maximize the li-

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fetime of the battery and to minimize the size of the capsule endoscope system.

In low power transmitters, the constant amplitude FSK modulation technique is generally used to achieve higher power efficiency using a nonlinear power amplifier[9]. However, in wireless capsule endoscope systems using the FSK modulation technique, the smaller capsule requires a higher carrier frequency, and a power-hungry frequency synthesizer is required to generate the desired frequency used in FSK modulation. In this paper, the ASK modulation technique is used because of its weak frequency dependency. A simple RF LC oscillator with an off-chip, high-Q inductor is used as the carrier frequency generation circuit, and in order to achieve higher power efficiency with a linear power amplifier, a pseudo-differential stacked class-A power amplifier is proposed.

2　Transmitter architecture

In traditional ASK transmitter architecture, an RF oscillator starts or stops under the control of the transmitted baseband data to implement the ASK modulation. In a low power ASK transmitter, the startup time of the RF oscillator is long, which seriously restricts the data rate of the ASK system. Therefore traditional ASK transmitters are often used in low data rate wireless systems. However, in a wireless capsule endoscope system, the requirements of high quality medical images force us to exploit a new transmitter architecture to achieve a high transmitted-data rate. Hence, we base our proposed high data rate ASK transmitter for wireless capsule endoscope applications on a mixer-based frequency up-conversion transmitter architecture, as shown in Fig. 1. This ASK transmitter can be divided into two parts, including a 20MHz ASK modulator and a direct up-conversion RF circuit. First, a low frequency PLL with well-defined output amplitude is employed to generate the 20MHz carrier frequency. Then, under the control of the baseband data (Tx_Data) and the modulation mode selection (Mod_Sel), 20MHz ASK modulation signals can be achieved through the modulation control circuits. The up-conversion RF circuit up-converts the low frequency ASK signal to the 2.4GHz ISM band, and then a micro-antenna transmits the modulation signal outside of human body. A temperature-independent, high supply rejection reference is designed to provide reference currents and voltages for the ASK transmitter. In order to achieve a smaller capsule, almost all the building blocks are integrated except for a high-Q off-chip inductor.

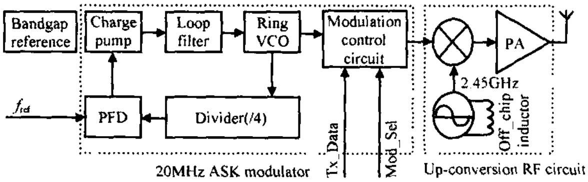

Fig. 1　ASK Transmitter Architecture

3　Building blocks

3.1　Low frequency phase lock loop

A simple integer-N PLL is used to generate the low frequency carrier. It includes a divide-by-4 asynchronous divider, a constant amplitude ring VCO, a rail-to-rail charge pump, a zero dead zone PFD, and a second-order loop filter (as shown in Fig. 1). When the PLL is locked to the reference frequency f_{ref}, in the output of ring VCO, an accurate frequency of $4f_{ref}$ is achieved which acts as the low frequency carrier.

In the low frequency carrier generation circuit, the key block is the ring VCO with well-defined output amplitude. In general, according to the circuit switching behavior, ring VCOs can be categorized into two types: fixed and full swings. The full swing ring VCO is not suitable for wireless capsule endoscope systems because of its high dynamic power consumption. Thus in this design, a fixed swing ring VCO using the replica bias technique is employed[10]. This VCO includes three delay stages, and each delay cell is realized with a source-coupled circuit with pMOS differential input devices and nMOS triode-region load devices. The benefits of using a fully differential delay cell are its good power supply rejection and process variation immunity. A schematic diagram of the replica bias delay cell is shown in Fig. 2. The replica bias circuits include a feedback amplifier A, a voltage-controlled pMOS current transistor MI1, a source follower MS1 and a triode-region transistor M5. MI2 and M1～M4 constitute the unit delay stage. The building block "VTI" is a high linearity voltage-to-current converter. The extra capacitor C_d is added to the output nodes to achieve the desired delay for the given application. If the loop gain is sufficiently large, the drain voltage of M5 $V_P \approx V_{ref}$, and then the small V_{ref} will force M5 to perform as a linear resistor. Once M3 and M4 are identical to M5, and I_2 is identical to I_1, the on-resistance of M3 and M4 is equal to that of M5, and then the output nodes voltage V_X and V_Y vary from 0 to V_{ref} as M1 and M2 steer the tail current I_2 to one side or the other. Hence, using the replica bias technique, a well-defined output amplitude is achieved that is equal to the reference voltage V_{ref}. With the invariable output amplitude and load capacitor C_d, the delay of the unit delay stage t_{delay} can be approximated as

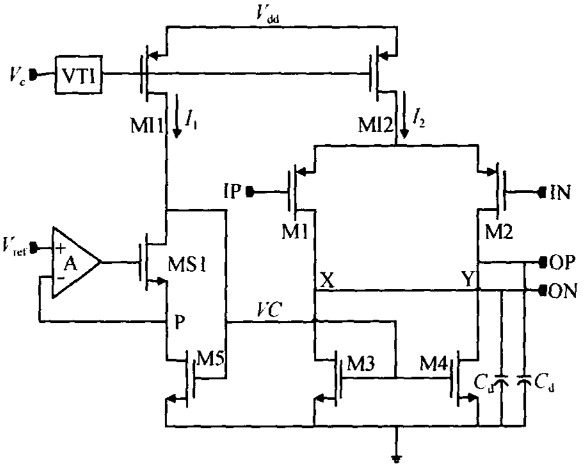

Fig. 2 Replica bias delay cell

$$t_{delay} = \frac{C_d V_{ref}}{I_2} \quad (1)$$

Equation (1) indicates that t_{delay} is a monotonically decreasing function of the tail current I_2. As mentioned earlier, VTI will ensure that I_2 is proportional to the control voltage V_c. Therefore, t_{delay} is inversely proportional to V_c, and it ensures the linear monotonicity between the frequency of the ring VCO and the control voltage V_c.

3.2 Modulation control circuits

Modulation control circuits are the interface between the low frequency PLL and the RF up-conversion circuits. A schematic diagram is depicted in Fig. 3. Mod_Sel is used to select the modulation mode. When Mod_Sel is '0', S1 and S2 are "ON" while S3 and S4 are "OFF". The modulation control circuits will be bypassed, and the input signal directly appears in the output nodes. When Mod_Sel is '1', the modulation control circuits perform as an ASK modulator. If the transmitted data Tx_Data = 1, and S1 and S2 are "ON" while S3 and S4 are "OFF", then the low frequency carrier directly transfers to the output. If Tx_Data = 0, and S1 and S2 are "OFF" while S3 and S4 are "ON", then the output voltage is equal to the common-mode level of the input node, which ensures a fast transition time when Tx_Data change from '0' to '1'.

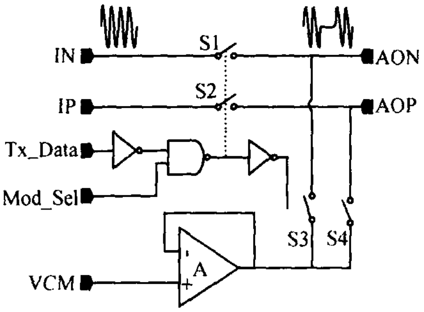

Fig. 3 Modulation control circuit

3.2.1 Up-conversion RF circuits

The up-conversion RF circuit consists of three parts, as shown in Fig. 1: an oscillator with a high-Q, off-chip inductor, an up-conversion mixer with an inductor load, and a pseudo-differential stacked Class-A PA. The low frequency ASK signal is first up-converted to the 2.4GHz frequency band through the up-conversion mixer. Then the stacked PA amplifies and transmits the modulated signal. Since the ASK modulation signal is insensitive to frequency variation, an open-loop oscillator with coarse tuning is used for LO generation for low power consumption applications.

3.2.2 Pseudo-differential stacked PA

As mentioned earlier, low power consumption and high power efficiency are crucial factors in the design of a wireless capsule endoscope system. The PA, as an important part of wireless capsule endoscopy, consumes about 40%~50% of the power of the total system. In a traditional PA, to achieve enough drive capability, a driver and an output stage are used. This circuit has the drawback of high power consumption because there are two current paths from the supply.

However, in a wireless capsule endoscope system, the maximum output power is less than

0dBm, which allows the current-reuse technique to be used in the design of the PA. This combines the two current paths into a single current path, thereby reducing the power consumption and enormously increasing the power efficiency of the total system. A schematic diagram of the proposed stacked PA is shown in Fig. 4. M1, M2, L_1, and C_1 constitute the first-stage amplifier, which is stacked on the output stage, which consists of M3, M4, L_2, and C_2. The capacitor C_3 couples the output of the first-stage to the input of the output stage. The current of the output stage is reused by the first-stage amplifier, which saves power. The voltage node X provides an ac ground which prevents interference between the two amplifier stages. In this design, the node X is biased around $V_{dd}/2$, which protects the device from excess drain-gate voltage. MB1～MB4 and S1 &S2 constitute the current bias circuit. Pow_Con is used to control the output power. When Pow_Con = '1', then S2 is 'ON' and the lower current I_{low} infuses the bias circuit, so the low output power will be transmitted. When Pow Con = '0', the higher current I_{high} is infused and the high output power will be transmitted. Compared with the traditional PA, our proposed pseudo-differential PA has higher power efficiency, and the simulation power consumption is about half that of a traditional PA with the same output power.

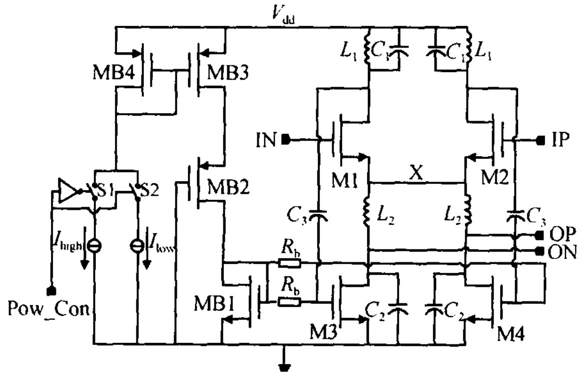

Fig. 4　Pseudo-differential stacked Class-A PA

4　Results

To verify the performance of the ASK transmitter designed here, the proposed circuit was fabricated in a TSMC 2P6M 0.25μm CMOS process. Figure 5 shows a microphotograph of the ASK transmitter. The die size is 1170μm ×3097μm. Except for one discrete inductor, all the components are integrated in the IC. For measurement convenience, the PA output is directly connected to a 50 load that acts as the antenna.

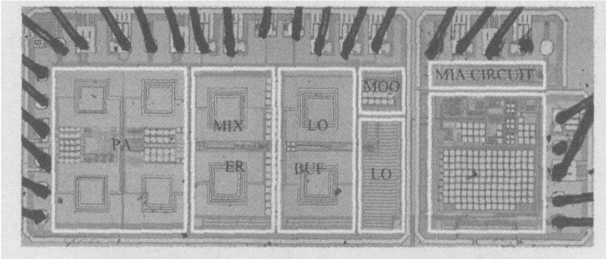

Fig. 5　Microphotograph of ASK transmitter

The measured signal peak-to-peak amplitude of the low frequency PLL is shown in Fig. 6. The maximum signal amplitude is 119mV when the PLL is locked at 19.5MHz, and the minimum signal amplitude is 84.5mV when the PLL is locked at 12MHz. The measured PLL can be locked between 6.5 and 36MHz. Figure 7 shows the measured 20MHz ASK signal with a 1Mbps input data rate.

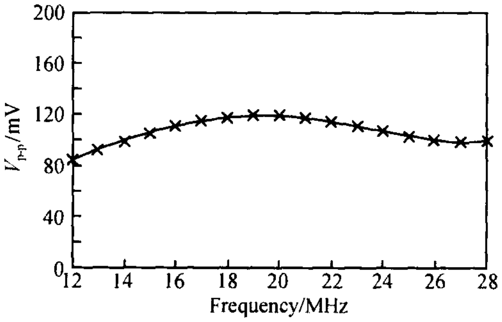

Fig. 6　Measured signal amplitude of PLL

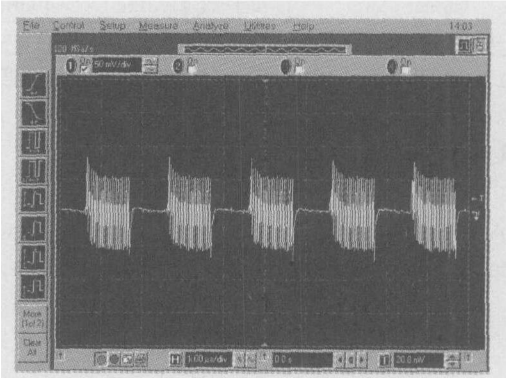

Fig. 7　20MHz ASK signal with 1Mbps input data

Connecting the PA output to a vector signal analyzer, the modulated ASK signal and the demodulated signal can be measured. The ASK modulation signal spectrum with a 1Mbps data rate is shown in Fig. 8 (a), and the output power is -23.217dBm with a 2.4GHz center frequency. Figure 8(b) shows the demodulated signal where the input data rate is 1Mbps, and the current consumption is roughly 3.17mA with a 2.5V power supply.

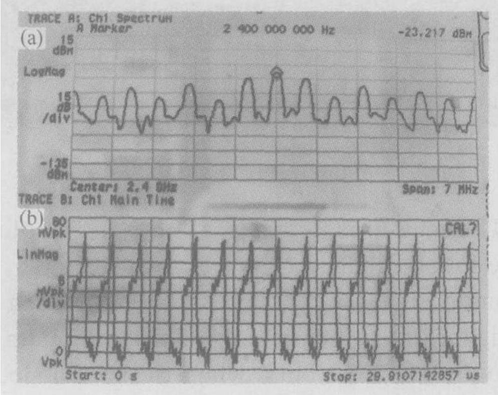

Fig. 8 (a) Modulated output ASK spectrum; (b) ASK demodulation

Table 1 summarizes the measurements of the proposed ASK transmitter and Ref. [11]. The proposed transmitter has a higher data rate, higher integration level, higher carrier frequency, and lower energy consumption per bit.

Table 1 Performance comparison

Design features	This Work	Ref. [11]
Supply voltage	2.5V	0.9V
Data rate	1Mbps	100kbps
Carrier frequency	2.4GHz	433MHz
Current consumption	3.17mA	1.9mA
Energy consumption	7.925nJ/bit	17nJ/bit
Output power	-23.217dBm	-10dBm
Technology(CMOS)	0.25μm	0.25μm
Chip area	3.62mm^2	4.8mm^2

5 Conclusion

A fully integrated ASK transmitter for wireless capsule endoscope applications is presented. A low frequency carrier with a well-defined amplitude is implemented using the replica bias technique. A pseudo-differential class-A PA with the current reuse technique is used to save power. The transmitter operates at a frequency of 2.4GHz and is realized using the up-conversion technique. With a 1Mbps data transmission rate, an output power of -23.217dBm can be achieved, and only 3.17mA current is dissipated with a 2.5V power supply.

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一种应用于无线内窥镜的2.4GHz低功耗ASK发射机*

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摘要: 提出了一种应用于无线内窥镜系统的2.4GHz低功耗ASK发射机.为了获得高的数据传输速率,采用了基于混频器的直接上变换发射机结构.为了节省功耗,提出了一种基于电流复用技术的伪差分堆栈结构的A类功放.低功耗发射机由两部分组成:基于恒幅度锁相环(PLL)的20MHz的ASK基带调制器和直接上变换的射频电路.该设计已经采用TSMC 0.25μm CMOS工艺实现并进行了验证.测试结果表明,发射数据速率为1Mbps时,发射机的输出功率为-23.217dBm.采用单2.5V的电源供电下,低功耗发射机消耗的电流约为3.17mA.

关键词: 无线内窥镜; 幅度键控; 锁相环; 发射机; CMOS

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