500 MHz OOK Transmitter With 22 pj/bit, 38.4% Efficiency Using RF Current Combining

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***Abstract*—A 500 MHz On-Off Keying (OOK) transmitter integrated with a high-efficiency wideband power amplifier (PA) is designed for low-power/high-data rate applications. The PA biased in Class C region, employs a bias current-reused and an RF current-combining structure to achieve a high-efficiency and high-data rate. The transmitter is fabricated using a 0.13 μm CMOS process. The chip size is 0.6 mm^2 and the measured drain efficiency of the PA reaches 59.5% at 500 MHz with 1.62 dBm output power while consuming only 2.52 mW dc power from a 3 V power supply. The efficiency of the transmitter is 38.4% and the energy usage is 22 pJ/bit at a data rate of 100 Mbps with -0.75 dBm average output power.**

***Index Terms*—Capsule endoscopy, CMOS power amplifier (PA), current combining, current reuse, high efficiency, OOK modulation.**

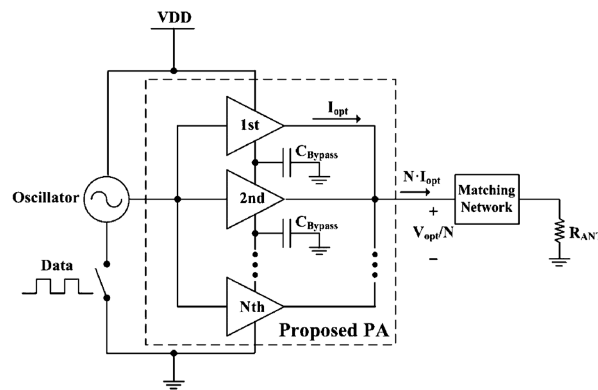

Fig. 1. Block diagram of the OOK transmitter with proposed PA.

I. Introduction

In short-range wireless communication, especially when using capsule endoscopy systems, a high-speed and high-efficiency transceiver is required to transmit high-resolution images for accurate diagnoses and to extend the battery life of the device [1]. Thus, a high efficiency transmitter is essential for increasing the total transceiver efficiency due to its large dc power consumption. Simultaneously, the transmitter should have enough bandwidth for a high-data- transmission rate.

An On-Off Keying (OOK) transmitter is one candidate for solving these issues in low-power applications, such as Medical Implant Communication Services (MICS) and, Wireless Sensor Networks (WSN), because of the transmitter's low-power consumption and high-data rate [1]–[5].

In order to design a high-efficiency transmitter, [1] used a class-B PA that has a gate bias switch to turn off the PA during Off-state and [2] used Film Bulk Acoustic Resonators (FBAR). Other studies, [3] adopted the type of current-reused LC-oscillator employed in RF-carrier generation despite a limitation of data rate and [5] employed a complementary voltage-controlled oscillator.

In this study, we design the OOK transmitter integrated with the high-efficiency wideband PA proposed [6], [7] in detail and show the measurement results of the fabricated chip. The proposed PA that operates in Class C employs a bias current-reused and RF current-combining structure, which decreases the optimum-load impedance so that the loss of matching circuit is reduced and the bandwidth of the PA is widened. Also, the current-reused type is suitable for low-power applications [3]. Therefore, the transmitter's bandwidth and efficiency are maximized.

The operating frequency and the target output power are set to 500 MHz and 0 dBm respectively from previous work [1]. The fabricated PA shows a maximum drain efficiency of 59.5% at 500 MHz with 1.62 dBm output power, while the measured efficiency of the transmitter is 44.9% during On-state. The efficiency of transmitter is 38.4% and the energy usage is 22 pJ/bit at 100 Mbps with -0.75 dBm average output power.

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II. A DC Current-Reused and RF Current-Combining Structure PA for Low-Power Applications

Generally, the optimum load impedance of a PA for maximum power and efficiency should be transformed into the antenna's input-impedance. When the ratio of the two impedance values decreases, the matching-circuit loss is reduced and the bandwidth becomes wider due to the relationship between the transformation ratio and the Quality factor [7].

Fig. 1 shows the block diagram of OOK transmitter including the proposed power amplifier. $\mathrm{R_{opt}}$, $\mathrm{I_{opt}}$, $\mathrm{V_{opt}}$ are optimum impedance, current, and voltage of a conventional PA with a supply voltage (VDD), respectively. $\mathrm{R_{ANT}}$ is an antenna's input impedance.

Since the powers of the current-reuse N-power amplifiers are combined in parallel at the output node, the output voltage is lowered to one Nth of the conventional amplifier's and the amplitude of the output current is N times that of the conventional

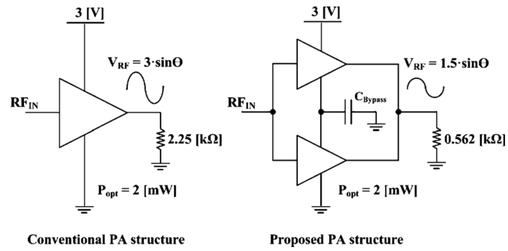

Fig. 2. Example for comparing conventional PA with proposed PA.

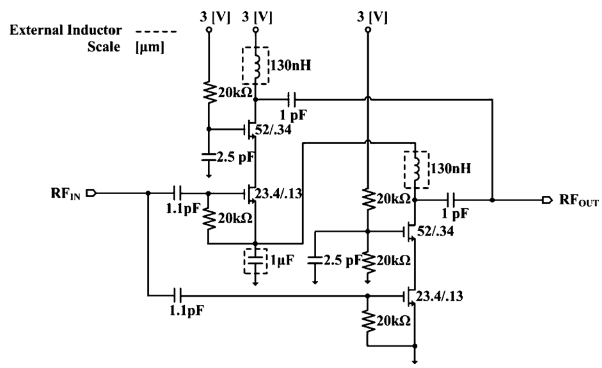

Fig. 3. Schematics of proposed PA comprised of two amplifier units.

amplifier's. Therefore, the optimum impedance value of the proposed PA structure becomes $1/\mathrm{N}^2$ times of that of a conventional type of PA structure.

The quantitative example is shown in Fig. 2. The optimum impedance of a conventional PA for 2 mW of output power with 3 V supply voltage is 2.25 kΩ without considering the knee voltage. The optimum impedance of the proposed PA, whose N equals two, is about 0.562 kΩ under the same conditions. Thus, the output matching circuit of the proposed PA has to transform 0.562 kΩ into the antenna's impedance. The example suggests that the proposed PA has an inherently lower matching loss and wider bandwidth than a conventional PA.

III. Circuit Design

Fig. 3 shows the schematic of the PA, which consists of two-amplifier units employing a current-combining and current-reused structure. The two-stack is chosen for minimizing the number of external components and a knee voltage effect at 3 V supply voltage. A knee voltage limits the voltage swing of PA [8]. The proposed PA is biased Class C, which has a high efficiency due to its low conduction angle and zero idle current without using a gate bias switch. The external inductor of 130 nH (LQW18ANR13G00) and output capacitor of 1 pF (GRM1555C1H1R0CZ01) transform the optimum load impedance (1.125 kΩ) into twice that of the antenna's input impedance (0.4 kΩ) in a single amplifier. These passive components are a choke inductor and a dc block capacitor, respectively, in the ideal case shown in Fig. 2.

A ring-type oscillator is adopted for this work, since a ring oscillator has faster start-up time than an LC oscillator [9], making it suitable for a high-speed OOK modulator. Moreover, the frequency stability exhibited by ring oscillator will suffice in the human body, maintaining a constant temperature. Fig. 4 shows the schematic of ring oscillator including buffers to deliver an RF signal to the PA input. The size of buffers is carefully chosen for driving a signal to PA. The NAND gate switch is adopted for

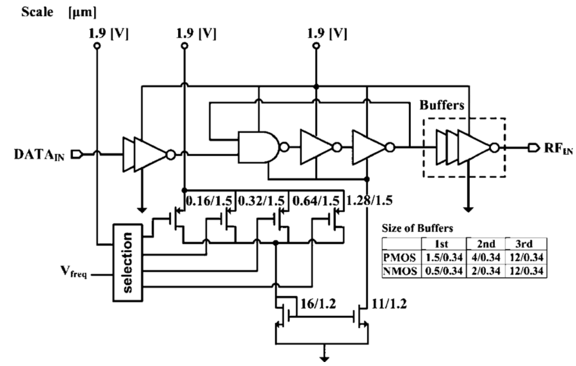

Fig. 4. Schematics of ring oscillator.

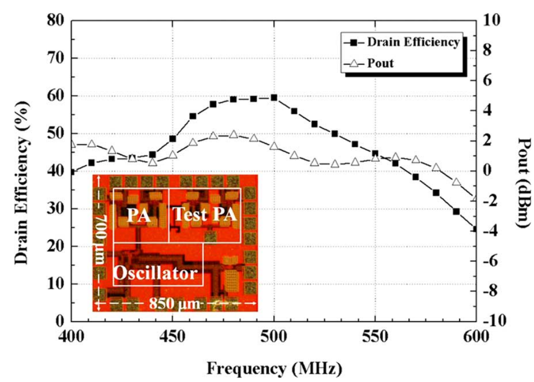

Fig. 5. Measured drain efficiency and output power of proposed power amplifier. A chip photo of the designed transmitter is also shown.

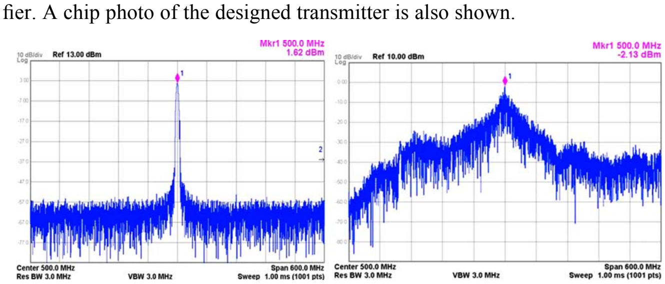

Fig. 6. Measured output spectrum of PA under the continuous power state (a) and modulated power state (b) with 100 Mbps data-rate of PRBS pattern.

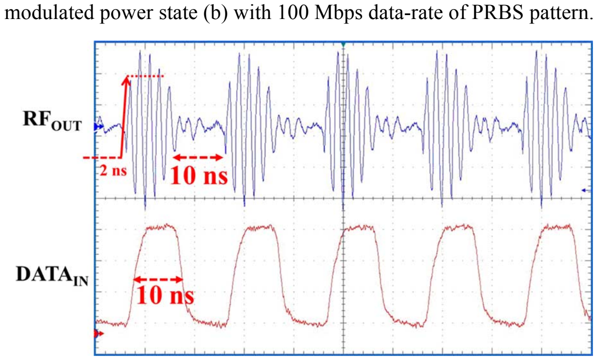

Fig. 7. Measured time-domain output signal of transmitter with '1010' data at 100 Mbps.

OOK modulation and its oscillation frequency is tuned by V_{freq} bias with transistor size selection. The supply voltage of 1.9 V is used to limit the input voltage swing of the PA stage and its time period from startup to steady state is 1.5 ns in simulation.

IV. Experimental Results

A prototype was fabricated using a 0.13 μm CMOS process in the block diagram shown in Fig. 1. The chip size is about

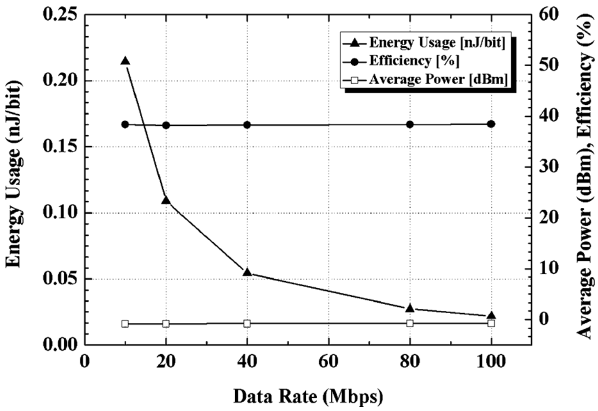

Fig. 8. Measured efficiency and average output power, energy usage of transmitter at each data rates with PRBS pattern.

TABLE I
COMPARISON WITH OOK TRANSMITTERS

Parameter	[1]	[2]	[3]	[4]	[5]	This work
Tech (nm)	130	130	180	90	40	130
Method	Class-B & Bias Switch	FBAR VCO	[1]CR VCO	Pulse Shape	[2]C-VCO	[3]CRCC PA
Freq. (GHz)	0.5	1.9	0.44	2.4	2.4	0.5
VDD (V)	3.1	0.65	3	1	1.5	[4]3, 1.9
Data Rate (Mbps)	20	0.33	40	10	136	100
DC Power (mW)	2.53	1.35	2.58	2.3	3	2.19
Modulated Output Power (mW)	0.7	1.2	[5]0.48	1	0.04	0.84
Efficiency (%)	27.7	46	18.6	26	1.3	38.4
Energy Usage (pJ/bit)	126.5	409	64.5	23	22	22
[6]FOM (pJ/bit/mW)	180.7	341	134	230	550	26

[1]Current Reused Voltage Controlled Oscillator (VCO), [2]Complementry-VCO.
[3]Current Reused and Current Combining PA.
[4]VDD of PA: 3 V, VDD of ring oscillator: 1.9 V.
[5]Assuemd Modulated Output Power = On-time Output Power [3] /2.
[6]FOM = Energy Usage / Output Power [4].

0.6 mm^2 including the pads. For the test, an additional matching circuit between the spectrum analyzer and transmitter was used to transform 50 Ω into 200 Ω, because the PA was designed for the antenna's input impedance of 200 Ω.

To verify the proposed PA performance, the PA stage was tested in a frequency domain using an Agilent N9020A spectrum analyzer. The output power and its drain efficiency were measured without an input-matching circuit, because a ring oscillator practically delivers the voltage signal to the PA. When the continuous RF signal with 3 dBm was injected into the PA, the measurement results are shown in Fig. 5. The variation of the output power is less than 3 dB and the efficiency exceeds 40% in the 450–550 MHz range. The maximum efficiency was 59.5% at 500 MHz with 1.62 dBm output power.

The transmitter including a ring oscillator was measured to verify the overall performance of the designed OOK transmitter. The total efficiency of the transmitter at 500 MHz was 44.9% with 1.62 dBm output power during the On-state. Fig. 6 shows the measured frequency domain output spectrum during the On-state (a) and the modulated power stated (b) with 100 Mbps data rate. The time-domain OOK signal with "1010" data at 100 Mbps rate is shown in Fig. 7, which shows the falling and rising time of around 2 ns. And, the transmitter's frequency error caused by the frequency drift is 0.058%.

When the transmitter is in the On-Off state, the modulation makes the power spread within a certain frequency range. Therefore, the average power was measured with the channel bandwidth of each data rate. Fig. 8 shows the results of the measured average power and efficiency, and energy usage at each data rate of Pseudo Random Binary Sequence (PRBS). The maximum efficiency is 38.4% and the minimum energy usage is 22 pJ/bit at 100 Mbps data-rate with -0.75 dBm output power. The self-biasing effect of an OOK modulated pulse input to the gate of PA causes the more output power than that expected, -3 dB.

Table I shows a comparison of the designed transmitter and the OOK transmitters described in publications [1]–[5]. The results show the low-power/high-data-rate characteristics of the designed transmitter.

V. CONCLUSION

In this letter, we propose an OOK transmitter with a high efficiency wideband PA that employs a current-reused and RF current-combining structure for low-power/high-data rate applications. The designed transmitter exhibits good efficiency (38.4%) and, low energy usage (22 pJ/bit) at 100 Mbps. The experimental results show that the designed transmitter is suitable for low-power medical implant applications or capsule endoscopy applications, which require high speed and efficiency.

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