The Design of an Energy-Efficient IR-UWB Transmitter With Wide-Output Swing and Sub-Microwatt Leakage Current

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Abstract—In this brief, we present an impulse-radio ultrawideband (IR-UWB) transmitter for low-power communication and radar sensing applications. To improve the leakage power for the IR-UWB transmitter, we have adopted transistor stacking technique in the design of our digitally controlled oscillator (DCO) and mask generator. The DCO and mask generator circuit generate the UWB carrier frequency and pulse mask signals, respectively. These signals are combined through a cascode output driver stage with an on-chip inductor load. The cascode structure significantly reduces the leakage power. The on-chip inductor load improves the transmitted pulse amplitude. As a result, our proposed transmitter has significantly reduced the leakage power to sub-micro watt and achieved a maximum amplitude of 0.94 V. Therefore, we are able to achieve a maximum efficiency of 8.6% and the transmitted energy per pulse is 3.6-pJ.

Index Terms—Impulse-radio ultra-wideband (IR-UWB), all-digital IR-UWB transmitter, digitally-controlled oscillator (DCO).

I. INTRODUCTION

IMPULSE-RADIO ultra-wideband (IR-UWB) technology has been widely studied for low power biomedical wireless applications [1]. It can be used in short-range wireless data communication systems in the wireless body area network (WBAN), or in radar sensors which remotely detect vital signs such as heartbeat and respiration. An IR-UWB transmitter-receiver was proposed in our previous work to reconfigure the same IR-UWB front-end for both communication and radar modes [2]. IR-UWB transceivers show its unique advantage in integrating with the emerging asynchronous analog sensing platform [3], [4]. In this brief, we proposed an energy efficient IR-UWB transmitter with low leakage current and high transmission efficiency.

In an IR-UWB transmitter, IR-UWB pulses can be generated in the same way as in narrow-band transmitter by multiplying the baseband signal with a Local Oscillator (LO) signal [5]. This circuit implementation is not suitable for low-power biomedical application. Alternatively, pulsed oscillator method was proposed where the IR-UWB pulse is generated when the oscillator is started and stopped by the baseband pulse [6]–[8]. However, the response time of the oscillator limits the transmitter output bandwidth. In this brief, we proposed a new IR-UWB transmitter to overcome the existing limitations while achieving state-of-the-art performance.

In the design of an IR-UWB transmitter for biomedical applications, it is important to achieve low leakage power and high transmission energy efficiency simultaneously. The leakage power must be minimized to prolong the lifespan of the portable sensor. In our previous work, we have demonstrated that the use of asynchronous sensing with an IR-UWB transmitter can reduce the data rate of digitalized ECG signals to 2 kbps [3]. Under this low data rate, the dynamic power of the IR-UWB transmitter is comparable with the leakage power. To improve the transmission energy efficiency and distance, the transmitted pulse energy and output voltage amplitude should be large. This requires large transmitter output driver transistors in which the leakage power becomes significant. Therefore, it is challenging to achieve high transmission energy efficiency and low leakage power for IR-UWB transmitter at the same time.

In this design, we have reduced the leakage power of our IR-UWB transmitter by adopting transistor stacking technique in the design of the digitally-controlled oscillator (DCO) and mask generator. The DCO and mask generator circuits generate the UWB carrier frequency and pulse mask signals, respectively. The combination of the UWB carrier frequency and pulse mask signals produce an IR-UWB pulse, which is achieved through the use of a cascode output driver stage with an on-chip inductor load. Since the transistor sizes of the output driver are big to drive the antenna impedance, cascode output driver structure significantly reduces the leakage power. The on-chip inductor load improves the transmitted pulse amplitude. Therefore, we are able to achieve sub-microwatt leakage power and increase transmitted pulse amplitude.

This brief is organized as follows. Section II introduces the transmitter architecture and circuitry. Section III presents the measurement results and comparison with other works. Conclusion is given in Section IV.

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II. TRANSMITTER ARCHITECTURE AND CIRCUIT DESIGN

A. Transmitter Architecture

The system architecture of the transmitter is presented in Fig. 1. First, the rising edge of the incoming data is used to generate a narrow pulse by the one-shot circuit (Fig. 2). This narrow pulse is used to turn on and off the DCO and mask generator. Thus, this method helps to reduce the leakage current when no data is transmitted. A twelve-bit coarse-fine frequency tuning is implemented in the DCO to control the center frequency of the UWB pulse. An eight-bit mask generator circuit is implemented to control the shape of the IR-UWB pulse. Both the frequency signal and the pulse shaping signal are used to drive the cascode amplifier with an inductive load. The on-chip inductor resonates with the output capacitance and increases the output voltage swing.

B. One-Shot Circuit

As shown in Fig. 2, the schematic of our one-shot circuit consists of a NAND gate and an inverter. In this brief, we have designed our IR-UWB signal maximum bandwidth to be 400-MHz, which corresponds to a pulse width of 2.5-ns. Therefore, the delay of the pulse should be larger than 3-ns.

C. Digital-Controlled Oscillator

The DCO uses a fast start-up, duty-cycled and current-starved ring-oscillator topology. To achieve a low power consumption in the transmitter, the startup time of the DCO must be within a few ns in order to benefit from the duty-cycled operation. This can be achieved by presetting the DCO nodes to a predefined state using switches and the fast startup is obtained by releasing the switches simultaneously at the input signal’s rising edge. As shown in Fig. 3, the DCO consists of a single-ended three stage ring oscillator with the first two stages consisting of an inverter gate while the third stage is built of a NAND gate. Transistors M1 and M2 are the switches which predefine all the nodes in the DCO. The enable signal (EN) is controlled by the output of the one-shot circuit and triggers the oscillation. The center frequency of a DCO is highly dependent on the process variation, layout mismatch, voltage and temperature variations. A coarse-range tuning is obtained by a programmable capacitor array with a 4-bit thermometer-coded code \( C_{1:4} \) to achieve an immediate frequency change, which provides a fast compensation. A fine-range tuning is obtained by a programmable current source with an 8-bit binary-coded code \( F_{1:8} \) to obtain small frequency steps, which compensates for any voltage and process variation over time.

We perform a foreground calibration based on the frequency spectrum of output signal. The tuning methodology to control the UWB frequency spectrum is described as follow: 1) Preset the 8-bit binary code \( F_{1:8} \) as “10000000”. 2) Sweep the coarse code to adjust the peak of the frequency spectrum to be within the desired frequency range. 3) Perform binary search using the 8-bit binary code \( F_{1:8} \) to tune the peak of the frequency spectrum to be the desired frequency. There is a sufficient overlap between the frequency range to overcome gaps created by process variation.

D. Mask Generator

The circuit of the mask generator is shown in Fig. 4. The timing diagram of the mask generator is shown in Fig. 5. The EN signal is the output of the one-shot circuit. When the EN changes from low to high, the transition edge will propagate through the stages. \( A_{<1>}, A_{<3>}, A_{<5>}, A_{<7>}, A_{<13>}, A_{<15>}, A_{<17>} \) and \( A_{<19>} \) are then synthesized by digital gates to generate the mask. The four masks, \( M_{1:4} \), could be chosen from the multiplexer by \( M_{<1:4>} \) to generate different mask combinations. By dynamically adjusting the number of enabled cascode output stages for sub-pulses, pulse shaping is realized. The output of the mask generator drives the output driver stage.

E. Output Driver Stage

In order to drive the nominal 50-\( \Omega \) antenna impedance, the transistors in the transmitter output driver stage are big. The
leakage power of the output stage is dominant in the whole transmitter. Simple inverter can be used as the driver stage of the IR-UWB transmitter. However, the leakage power of the simple inverter increases significantly as the sizes the transistors get larger. In this design, the output driver is composed of parallel digital cascode stages which also combine the DCO output with the mask signal. When no pulse is transmitted, both the gates of the cascode NMOS transistors are connected to ground and the leakage current is significantly lower than a single-transistor stage. The parasitic capacitors of the parallel output driver stages limit the output bandwidth, and an on-chip inductor is used to extend the bandwidth. The maximum simulated output capacitance is 0.5-pF. A 2.5-nH on-chip inductor is chosen to resonate with the output capacitance at 4-GHz.

III. MEASUREMENT RESULTS AND COMPARISON

The transmitter was fabricated using the 130-nm CMOS process and was directly wire-bonded to a FR4 PCB to minimize parasitic and reduce packaging cost. The die micrograph is shown in Fig. 7 and the core occupies an active area of 470-μm × 310-μm with a total area is 0.146-mm². The measurements were taken with the Tektronix DPO71254 Digital Oscilloscope and the Rohde Schwarz ZVL13 Vector Network Analyzer.

A. IR-UWB Pulse Measurement

The measurement of the transmitter reveals that it is capable of generating pulses up to a pulse repetition frequency (PRF) of 140-Mpulses/s. The turn-on time is 2-ns due to the propagation delay from the I/O pad driver and the level shifter.

Fig. 8 shows a time-domain view of the IR-UWB pulse using rectangular and Gaussian masks and the nominal measured pulse width is approximately 2.5-ns. The maximum
Fig. 9. Transmitter output in the frequency domain and its compliance with the FCC mask.

Fig. 10. Transmitter output in the frequency domain for various supply voltages.

output voltage swing is 940-mV, as shown in Fig. 8. With a PRF of 10-Mpulses/s, the resulting spectrum of the output pulse achieves both indoor and outdoor FCC compliance with more than 24 dB of sidelobe suppression without requiring the use of an off-chip filter, as shown in Fig. 9. The power spectrum density (PSD) $-10 \text{ dB bandwidth}$ is about 480-MHz and the PSD is below $-42.15 \text{ dBm/MHz}$. The measured spectrum also achieves FCC compliance within the supply voltage range from 1.1 to 1.3-V, as shown in Fig. 10.

B. Power Measurement

The power consumption of the transmitter was analyzed for various PRFs from 100-pulse/s to 140-Mpulses/s, as shown in Fig. 11 (a). The average leakage power, $P_L = 725.9 \text{ nW}$. The PRF dependent part is $36.9 \pm 4.4 \mu \text{W/PRF(Mpulse/s)}$. As can be seen in Fig. 11 (b), the overall energy (active and leakage) per pulse, $E_{dTX}$ ranges from 7.6-nJ/pulse at a PRF of 100-pulse/s to $37.9 \pm 4 \text{ pJ/pulse}$ with PRF beyond 200-kpulse/s. The average deviation of $\pm 4 \text{ pJ/pulse}$ arises from different masking modes. The transmitted pulse energy is $E_{pTX} = 3.6 \text{ pJ/pulse}$, based on calculation from the time-domain output waveform. Thus, the transmitter achieves a maximum efficiency $\eta = 8.6\%$.

Fig. 11. (a) Power consumption of the transmitter versus the PRF, (b) Energy per pulse of the transmitter versus the PRF.

C. Frequency Tuning Measurement

The measured center frequencies of the transmitter output versus different coarse and fine tuning codes are shown in Fig. 12. The coarse tuning codes of $C_{<1:4>} = “0000”$ meet the UWB frequency spectrum requirement. One of the measurement observations is that the fine tuning is nonlinear and only a few MSBs of $F_{<1:8>}$ are effective. In UWB applications there is no requirement for linear fine tuning of the center frequency.

Fig. 12. Center frequency of the transmitter output versus different tuning codes.
TABLE I
TRANSMITTER PERFORMANCE COMPARISON

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</thead>
<tbody>
<tr>
<td>Technology (nm)</td>
<td>90</td>
<td>130</td>
<td>130</td>
<td>90</td>
<td>130</td>
<td>130</td>
<td>130</td>
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<tr>
<td>Frequency Band (GHz)</td>
<td>3.1 - 5</td>
<td>3.1 - 10.6</td>
<td>7.25 - 8.5</td>
<td>2.9 - 3.8</td>
<td>3.1 - 5</td>
<td>3.1 - 4</td>
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<tr>
<td>Output Amplitude $V_{pp}$ (V)</td>
<td>0.65</td>
<td>1.42</td>
<td>2.2</td>
<td>0.61</td>
<td>0.6</td>
<td>0.53</td>
<td>0.94</td>
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<td>Pulse Rate (Mpulse/s)</td>
<td>10</td>
<td>100</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Energy per pulse $E_{TX}$ (pJ)</td>
<td>47</td>
<td>38.4</td>
<td>186.3</td>
<td>83</td>
<td>20</td>
<td>26.5</td>
<td>37.9</td>
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<tr>
<td>Transmitted Pulse Energy $E_p$ (pJ)</td>
<td>1.4</td>
<td>1.9</td>
<td>13.2</td>
<td>1.9</td>
<td>1.5</td>
<td>1.27</td>
<td>3.6</td>
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<td>Efficiency $E_p/E_{TX}$ (%)</td>
<td>3</td>
<td>4.9</td>
<td>7</td>
<td>2.4</td>
<td>7.5</td>
<td>4.8</td>
<td>8.6</td>
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<td>Die Area (mm²)</td>
<td>0.08</td>
<td>0.54</td>
<td>-</td>
<td>0.6</td>
<td>0.13</td>
<td>0.1</td>
<td>0.146</td>
</tr>
<tr>
<td>Leakage Power (μW)</td>
<td>96</td>
<td>3200</td>
<td>-</td>
<td>164</td>
<td>7.2</td>
<td>1.7</td>
<td>0.73</td>
</tr>
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</table>

D. Measurement Result Comparison

The reference works which are chosen to be compared with this brief are those with leakage power reported. The summary of the transmitter performance is shown in Table II and comparison results with other references are shown in Table I. The FOM of energy per pulse of this brief is larger than those from [12] and [13], but the output swing of this brief is also larger than theirs. Due to the large output voltage swing, which indicates large transmitted energy per pulse, the transmitted efficiency of this brief is the highest among all the works in the table. The most significant contribution of this brief is the reduction of the leakage power. The leakage power of 0.73-nW is the lowest. It should be noted that not all the designs referred in the comparison table had the goals of minimizing the leakage power. Many of them are focused on the system level, in which the transmitter is not optimized specifically.

IV. CONCLUSION

An all-digital low-leakage IR-UWB transmitter operating in 3.1-5 GHz for communication and radar is presented. A simple and all-digital design is adopted to reduce both the active and leakage power. A digitally-controlled oscillator generates the carrier frequency and a TSPC mask generator generates the pulse mask. The IR-UWB transmitter consumes 37.9 pJ/pulse for a PRF of 10 MHz and only consumes 730 nW leakage power when the transmitter is in idle.

REFERENCES


