A 18-pJ/Pulse OOK CMOS Transmitter for Multiband UWB Impulse Radio

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***Abstract*—This letter presents a new transmitter for multiband impulse radio ultra-wideband (IR-UWB) systems. The ultra low-power, low-complexity UWB transmitter operates over three 528-MHz subbands in 3–5 GHz band. It consists of an On-Off Keying (OOK) modulator and a pulse generator which is based on the ON/OFF switching operation of an LC oscillator. Measurements show a pulse duration of 3.5 ns and a spectrum that fully complies with the FCC spectral mask with more than 20 dB of sidelobe rejection. Implemented in 0.18-μm CMOS technology, the transmitter operates in burst mode and dissipates only 18 pJ of energy consumption per pulse. The transmitter is best suited for energy detection receivers.**

***Index Terms*—CMOS transmitter, impulse radio (IR), low-power transceiver, OOK, pulse generator, ultra-wideband (UWB).**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) impulse radio (IR) has been chosen as a candidate in the 802.15.4a low data rate wireless personal area network (W-PAN) standardization [1]. The purpose of this standard is to support high precision ranging combined with data transmission with low power consumption and cost. IR–UWB is also a promising technology for short-range, low data rate wireless RF tag, sensor networks [2], which provide location and tracking capabilities. In such networks, the main goal is to reduce power consumption and complexity for longer battery life and higher level of integration leading to low cost. Moreover, most of the information transmits from sensor nodes, which act as a transmitter, to the master device (a receiver). Therefore, it is essential to have an energy-efficient transmitter and shift the complexity to master device which has more relaxed power budget.

In the IR–UWB transmitter, a major challenge is to generate short pulses which can meet the spectral mask set by Federal Communication Commission (FCC) [3], with more than 20 dB of sidelobe suppression for outdoor. Furthermore, in multiband IR–UWB, where the UWB band is divided into several subbands for spectrum diversity and better co-existence with other systems, subband switching function is mandatory. In carrier-free UWB [4], this function can not be realized since the system operates in a single channel of UWB band. As for carrier-based UWB approach, which is flexible to define the pulse spectrum to accommodate multiple-access, the multicycle pulse is often generated by modulating the amplitude of a local oscillator (LO) with rectangular [5] or triangular signals [6]. Since the pulse envelope determines its spectral characteristics, the pulse reported in [5] has limited sidelobe rejection and requires extra filtering to meet FCC mask. Moreover, the aforementioned solutions are complex with a number of building blocks and consume high power since the LO operates at the center frequency pulse spectrum.

In this letter, a novel ultra low-power, low-complexity transmitter that generates OOK modulated pulses for multiband IR–UWB system is presented. The pulse generator block, which follows the approach in [7], is able to generate triangular-enveloped pulses over three 528-MHz subbands. Therefore, output pulse spectrum with more than 20 dB of sidelobe rejection is achieved and completely satisfies FCC spectral mask without additional filtering. The transmitter is designed to operate in burst mode to reduce the baseline power dissipation by removing the static current consumption. As a result, the lowest ever energy consumption per pulse of 18 pJ is obtained. Implemented in 0.18-μm CMOS process, the proposed transmitter is highly integrated and compact.

II. IR-UWB TRANSMITTER ARCHITECTURE

Fig. 1(a) presents the proposed transmitter with low complexity for multiband IR–UWB system operating in 3–5 GHz band. Considering the low data rate ($\sim$100 kbps) applications of IR–UWB system, OOK modulation is adopted for simplicity. In addition, there is no need for the drive amplifier since the regulated emission power is relatively low. Thus, the building blocks are a pulse generator, which is directly connected to the antenna, and an OOK modulator. In the oscillator based pulse generator, three subbands with 528-MHz bandwidth (BW) are generated and center frequencies are switched by the subband selection function. The modulator consists of NAND and inverter logic components. One input of NAND block is the baseband data while the other input is the square pulse clock. The clock is provided by the baseband processor with predetermined duration to control the output pulse width to ensure 528 MHz bandwidth for each subband. The input data and clock are combined and the resultant edge-combined square pulse signal drives the pulse generator. Thereby, the input baseband data is modulated into output UWB pulses. Furthermore, the proposed IR–UWB transmitter can operate in burst mode with low duty cycle, short-active and long-sleep period. The whole circuit is activated only during the pulse emission and then remains in the idle state without consuming dc current, leading to a substantial reduction of power dissipation.

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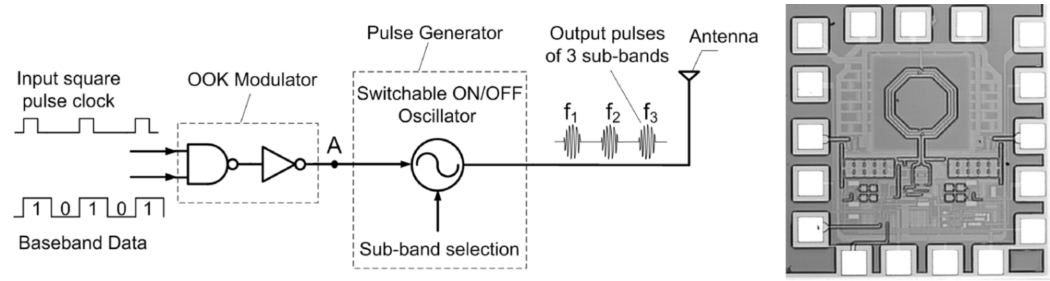

(a) (b)

Fig. 1. (a) Proposed OOK transmitter for multiband IR–UWB and (b) its die micrograph, 580 × 680 μm^2.

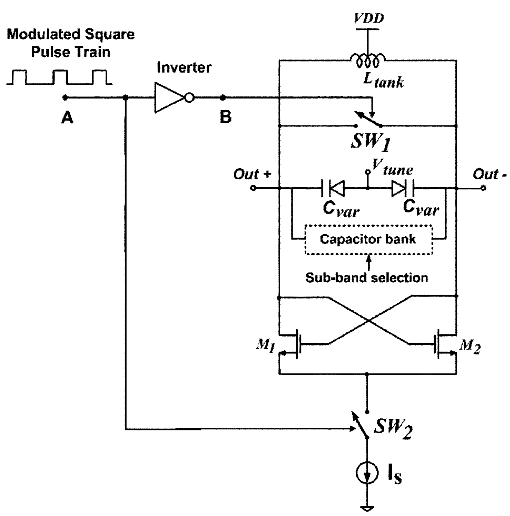

Fig. 2. Multiband IR–UWB pulse generator.

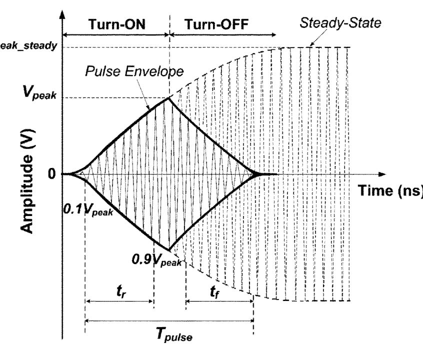

Fig. 3. Oscillator output waveform: (a) the steady-state (dashed part) and (b) the turn-ON/OFF transient (confined with solid line).

III. Pulse Generator Design

A pulse generation principle for IR–UWB, which is based on the ON/OFF switching operation of an oscillator, is introduced in [7]. In which, three approaches to generate pulses using switches (a switch across LC tank only, a switch at current source only, and combination of the two switches) in a LC voltage control oscillator (VCO) are discussed. The two-switch approach is the most advantageous among the three approaches in terms of power saving and spectral performances. This approach, however, is verified with only a single subband operation. In this work, a pulse generator is designed to operate over three subbands following the two-switch approach.

Fig. 2 shows the LC-VCO based pulse generator schematic. Switched capacitor bank is used for subband selection. Two switches, SW1 and SW2, control the LC tank and VCO current source (I_s), respectively. When SW2 is ON and SW1 is OFF, pulses are generated at the output. An inverter is used to make square pulse trains at node A and B with 180° of phase difference to drive SW2 and SW1, respectively. When one switch is ON, the other is OFF and vice versa.

The triangular-enveloped pulse is supposed to provide more than 20 dB of sidelobe rejection, which is important for adjacent channel interference suppression in multiband systems. The key idea to obtain the triangular-like pulse shape is to turn OFF the oscillation before its steady-state. Fig. 3 shows the output transient of an oscillator during the turn-ON/OFF (solid line) along with continuation to the steady-state (dashed line). The high performance pulse with maximum sidelobe rejection is achieved when rise time (t_r) is equal to fall time (t_f). Moreover, both t_r and t_f, which are supposed to be less than half of T_{pulse}, should be on the order of a nanosecond to ensure a minimum BW of 500 MHz for each subband. The output pulse envelope, which determines the pulse spectral characteristics, is characterized as follows:

$$t_r \approx 4.39\frac{Q}{(A_{OL}-1)\omega_0} = 4.39\frac{1}{(A_{OL}-1)} \times CR_T \quad (1)$$

$$t_f \approx 4.39 CR_D \quad (2)$$

where ω_0 is the resonant frequency, $A_{OL} = |g_m|R_T$ the open loop gain, g_m the negative tank transconductance, Q the quality factor, C capacitor taken into account parasitics, R_T tank loss resistance, and R_D the overall tank equivalent resistance during the turn-OFF period of the LC tank. From (1) and (2), the desired pulse envelope can be obtained by effectively selecting the right value I_s which determines A_{OL}, and the size of SW1 which determines R_D. Thus, SW1 provides a control over t_f by choosing its size for better pulse shape while SW2 makes the circuit operate without dissipating power during turn-OFF.

The proposed pulse generator dissipates dynamic current only during the pulse emission, for the remaining time of a period, no dc current is supplied since I_s is switched OFF by SW2.

The pulse spectrum center frequency, which is determined by the VCO oscillation frequency, can be shifted by varying the LC tank resonant frequency. Hence, subband switching capability is obtained by selecting switched capacitor bank values for different resonant frequencies, shown in Fig. 2.

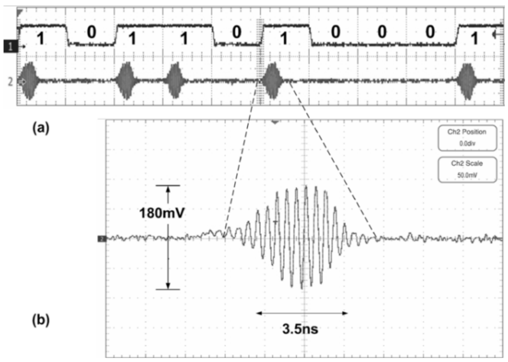

Fig. 4. (a) Measured timing diagram of OOK modulated UWB pulse train versus input data stream and (b) a single UWB pulse waveform.

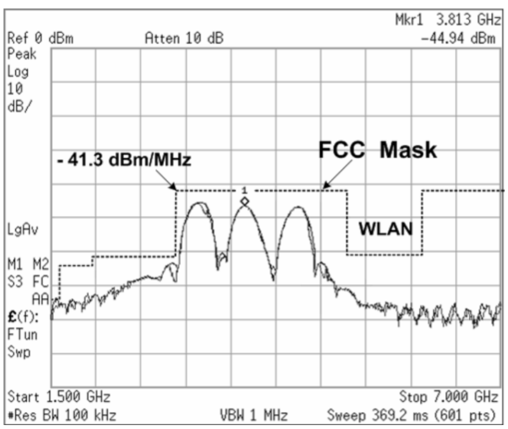

Fig. 5. PSD of three 528 MHz subbands in compliance with FCC mask.

Output pulse BW can be controlled since the pulse duration ($T_{\rm pulse}$ $\sim$1 BW) depends on that of input pulse clock. However, when input clock width varies, output pulse spectral power will be changed linearly.

IV. Experiment Results

The proposed transmitter shown in Fig. 1(a) is implemented in 0.18-μm CMOS process. The transmitter is compact and highly integrated. Its die micrograph is shown in Fig. 1(b) with the core size of 580×680 μm^2 excluding pads. At the input of the transmitter, baseband data with 100% duty cycle and clock with duration of 3.5 ns are applied at the same rate. The measured timing diagram of output pulse train versus the input data stream to demonstrate OOK modulation is shown in Fig. 4(a) at 100 MHz clock rate. Fig. 4(b) shows a single enlarged pulse with peak-to-peak amplitude of 180 mV. The rise and fall time of the output pulse envelope are relatively close which ensures a good spectral performance as predicted above with high amount of sidelobe suppression without any filtering. The pulse duration is 3.5 ns which corresponds to 528 MHz bandwidth at 10 dB from peak emission level.

Fig. 5 shows the measured power spectral density (PSD) of three subbands compliant with FCC mask in 3–5 GHz band. The amount of sidelobe rejection is more than 20 dB. By changing the capacitor bank values, the pulse center frequency is shifted. From Fig. 5, the three subbands with 528 MHz BW are centered at 3.2, 3.8, and 4.4 GHz, respectively. The center frequency may have drifted due to process variation. However, the frequency drift could be tolerable in UWB system since it is much smaller than a subband BW. Moreover, the proposed transmitter is designed for energy detection (noncoherent) receivers [8], where the amplitude information is more desired and the accuracy of pulse center frequency is less stringent. Hence, a phase locked loop, which is often used to stabilize the oscillation frequency in VCO design, is unwanted to maintain the simplicity and low power dissipation features of the transmitter.

The proposed transmitter operates from a 1.5-V supply and consumes only dynamic current, which linearly depends on the pulse repetition rate (PRR) of the pulse train. At PRR of 100 kHz, 40 MHz, and 100 MHz, the dynamic current is 1.2, 486, and 1215 μA, respectively. Leakage current during turn-OFF is negligible. The energy consumption per pulse emission is estimated as 18 pJ. To the best of authors' knowledge, this design achieves the lowest energy consumption per pulse.

V. Conclusion

A new multiband IR-UWB transmitter is proposed and implemented in 0.18-μm CMOS process, showing the potential realization of pulse-based UWB as a low-cost, low-power radio solution. The key building block, LC oscillator-based pulse generator can generate triangular-like pulses with high amount of sidelobe rejection without any filtering. OOK modulation and subband switching function are also demonstrated. Three 528 MHz subbands are achieved in 3–5 GHz band. Measured pulse PSD fully satisfies FCC mask with more than 20 dB of sidelobe suppression. The total transmitter dissipates only dynamic current in burst mode with 18 pJ of energy consumption per pulse. The proposed transmitter is not only power-efficient but also reduces power dissipation significantly and minimizes circuit complexity. It is well suited for noncoherent energy detection receivers.

References

[1] *Task Group 4a*, IEEE 802.15 [Online]. Available: http://www.ieee802.org/pub/15/TG4a.html

[2] I. Oppermann, L. Stoica, A. Rabachin, Z. Shelby, and J. Haapola, "UWB wireless sensor networks: UWEN – A practical example," *IEEE Commun. Mag.*, vol. 42, pp. S27–S32, Dec. 2004.

[3] "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems: First Report and Order," Federal Communications Commission, Washington, DC, ET-docket 98-153, FCC 02-48, 2002.

[4] R. J. Fontana, "Recent system applications of short-pulse ultra-wideband (UWB) technology," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 9, pp. 2087–2104, Sep. 2004.

[5] J. Zhao, C. Maxey, A. Narayanan, and S. Raman, "A SiGe BiCMOS ultra wide band RFIC transmitter design for wireless sensor networks," in *Proc. Rad. Wireless Conf.*, Sep. 2004, pp. 215–218.

[6] D. D. Wentzloff and A. P. Chandrakasan, "Gaussian pulse generators for subbanded ultra-wideband transmitters," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 4, pp. 1647–1655, Apr. 2006.

[7] T.-A. Phan, J. Lee, V. Krizhanovskii, L. Quan, S.-K. Han, and S.-G. Lee, "Energy-efficient low-complexity CMOS pulse generator for multiband UWB impulse radio," *IEEE Trans. Circuits Syst. I*, submitted for publication.

[8] S. Dubouloz, B. Denis, S. Rivaz, and L. Ouvry, "Performance analysis of LDR UWB non-coherent receivers in multipath environments," in *Proc. IEEE Int Conf. Ultra Wideband*, Sep. 2005, pp. 491–496.