A 3.54 nJ/bit-RX, 0.671 nJ/bit-TX burst mode super-regenerative UWB transceiver in 0.18- μ m CMOS

Zheng, Yuanjin; Zhu, Yao; Ang, Chyuen-Wei; Gao, Yuan; Heng, Chun-Huat

2014

Zheng, Y., Zhu, Y., Ang, C.-W., Gao, Y. & Heng, C.-H. (2014). A 3.54 nJ/bit-RX, 0.671 nJ/bit-TX burst mode super-regenerative UWB transceiver in 0.18- μ m CMOS. IEEE transactions on circuits and systems I : regular papers, 61(8), 2473-2481.

<https://hdl.handle.net/10356/103627>

<https://doi.org/10.1109/TCSI.2014.2332244>

© 2014 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at: [<http://dx.doi.org/10.1109/TCSI.2014.2332244>].

Downloaded on 26 Apr 2023 22:45:51 SGT

A 3.54nJ/bit-RX, 0.671nJ/bit-TX Burst Mode Super-Regenerative UWB Transceiver in 0.18- μ m CMOS

Yuanjin Zheng, *Member, IEEE*, Yao Zhu, *Student Member, IEEE*, Chyuen-Wei Ang, Yuan Gao, *Member, IEEE* and Chun-Huat Heng, *Senior Member, IEEE*

Abstract—Non-coherent ultra-wideband (UWB) transceiver employing energy detector suffers from degradation in output SNR due to the squarer. A burst mode super-regenerative UWB transceiver which can recover the received signal to rail-to-rail with relatively fewer post-amplification stages is proposed. Unlike other super-regenerative receiver architectures that use oscillator, the proposed architecture employs a positive feedback loop to achieve the super-regeneration of received signal and thus eliminates the need for external resonator or quench signal. The transceiver is suitable for low data rate sensor networks application covering spectrum of 3-5 GHz. Manufactured in CMOS 0.18- μ m technology, the transceiver occupies an area of 2.2mm $\times$ 2mm. By exploiting the duty cycle and the transceiver on-time through the burst mode operation for a given data rate of 1Mbps, it can achieve transmitter energy efficiency of 0.671 nJ/bit and receiver energy efficiency of 3.54 nJ/bit.

Index Terms— super-regenerative, ultra-wideband, transceiver, burst mode.

I. INTRODUCTION

LOW rate Wireless Personal Area Network (LR-WPAN) has seen tremendous growth in recent years due to the need for simple, low cost and low power devices in wireless sensor networks based on the IEEE 802.15.4a standard [1]. Some targeted applications include search and rescue missions, health and environmental monitoring, wildlife observation, logistics tracking and military surveillance [2]. Since these networks can consist of up to hundreds or thousands of sensor nodes deployed over a large and possibly remote area, energy and cost efficient sensor nodes are a must as it is impractical to replace

the sensor node batteries frequently [3]. Ultra-Wideband (UWB) impulse radio (IR), having been identified as one of the key technologies for IEEE 802.15.4a compliant devices, is the ideal candidate technology for efficient power management, location and ranging capability in sensor networks due to its sub-nanoseconds pulse transmission and potential of achieving ultra low average power at low data rates [4], [5]. However, conventional simple non-coherent UWB IR transceiver [6]–[8] suffers from severe signal loss due to the squarer, and usually requires extensive subsequent post-amplification stages and integrator that cost both area and power.

Super-regeneration has been successfully employed in RF front-end for narrowband system. Its main attraction lies in its ability of achieving extremely high gain using relatively few stages and thus resulting in very low power consumption [9][10]. However, to date, most super-regenerative amplifiers are based on oscillator-type circuit which depends on additional quench signal to toggle the circuit function between bandpass filter and high gain amplifier. High-Q resonator is also required to improve the signal selectivity which mandates either external high-Q passive components [14], [29] or additional tuning circuitry for high-Q bandpass filtering [13]. Recently, oscillator-type based super-regenerative receiver has also been successfully demonstrated for UWB technology [4], [11], [12]. Unlike the narrowband system where the signal selectivity is important, the UWB super-regenerative receiver relies on the incoming UWB signal to determine the start-up envelope of the oscillator and thus achieve signal detection and amplification. A quench signal is still required for the proper operation of the receiver and its waveform will affect the actual performance of the receiver [4], [13], [14], [15]. Techniques to generate the quench signal internally within the receiver have been proposed in [13], [16], [17] and [10]. However, such techniques usually present a tradeoff between receiver performance and system complexity. Recursive receiver has been proposed in [18] which is similar to the function of super-regeneration without the need for quench signal. However, in this case, it can only be applied to narrowband signals.

In this work, we steer away from the oscillator-type based super-regenerative receiver at the RF front-end ([therefore regenerating gain at RF](#)) and explore the feasibility of [applying the super-regeneration concept to generate substantial conversion gain \(from RF to baseband\) for the energy detection](#)

Y. Zheng is with the School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore 639798 (e-mail: yjzheng@ntu.edu.sg).

Y. Zhu is with School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore 639798 and the Institute of Microelectronics, Singapore Science Park II, Singapore 117685 (e-mail: zhuy0015@ntu.edu.sg).

C.-W. Ang was with the Institute of Microelectronics, Singapore Science Park II, Singapore 117685 and the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576. He is now with Micron Technology, Inc., Singapore 339942.

Y. Gao is with the Institute of Microelectronics, Singapore Science Park II, Singapore 117685.

C.-H. Heng is with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576.

and the post amplification stages through positive feedback to overcome the significant signal loss incurred by the squaring action. We exploit the feature of positive feedback to achieve a novel super-regenerative burst mode non-coherent UWB transceiver that can achieve steady low energy/bit across few orders of data rates. Without require additional high-Q resonator or quench signal to start or decay the oscillation, a fully integrated system in small silicon area with reduced circuit complexity is realized. The paper is organized as follows. Section II introduces the proposed super-regenerative UWB transceiver architecture. The circuit implementations of the transmitter and receiver are discussed in Section III and Section IV respectively. Section V presents the measurement results which are followed by the conclusion in Section VI.

II. SYSTEM ARCHITECTURE

A. Conventional Super-Regenerative Architecture

Conventional oscillator-type based super-regenerative architecture can be modeled as shown in Fig. 1. The current source and LC network represent the input RF signal and the resonator respectively. The tank loss can be modeled by a positive passive conductance, G_p . Additional negative conductance (G_n) is introduced through an active element to cancel the tank loss, and the effective conductance ($G = G_p + G_n$) can be varied by the quench signal. When the tank loss is not fully cancelled ($G > 0$), the resonant network behaves like a lossy filter network and the oscillation cannot be sustained. When G becomes negative, the resonator oscillates and the output can be represented by the following equation [13]:

$$(k \quad) \quad \frac{n(\omega t \quad \varphi)}{\sqrt{\quad \quad \quad}}, \quad (1)$$

where $\quad \quad \quad$ is the damping factor and $\sqrt{\quad \quad \quad}$ is the damping frequency.

For narrowband super-regenerative amplifier, signal selectivity is very important so that only desired signal gets amplified, and thus external high-Q element or additional tuning circuitry for biasing the circuit in regenerative mode for high selectivity bandpass filtering is usually required [13], [14] and [29]. At the onset of incoming signal, quench signal is varied so that the amplifier is set to the oscillation mode. The presence of an incoming signal acts as an additional excitation and speed up the oscillation start-up to produce a larger envelope. This results in the super-regenerative amplification of the incoming signal. In the absence of the incoming signal, only thermal noise will cause the oscillation start-up and thus generate a smaller envelope. Quench signal has to be used to alternate the receiver between the two different operating modes for proper operation. It has been observed that different types of quench waveforms such as sawtooth, triangular, etc. will impact the sensitivity and selectivity performances of the receiver [19]. In addition, the generation of this quench signal is also non-trivial [13]. In UWB super-regeneration receiver [4], the amplifier is initially reset to lossy filter tank using the

Fig. 1. Simplified equivalent model of super-regenerative architecture.

Fig. 2. Conceptual view of the super-regenerative UWB detector.

Fig. 3. Transfer characteristic of the super-regenerative UWB detector.

quench signal.

B. Power Management

The “effectiveness” of a UWB IR transceiver in sensor networks is commonly judged by a figure of merit, known as the energy efficiency per bit [5], [13]. Since power is an important consideration in sensor nodes, energy efficiency per bit provides an indication of how much power is required to transmit/receive a single bit. The energy efficiency of a transceiver that operates under “always-on” scenario is very inefficient in terms of energy usage for low data rate sensor networks. For better efficiency, burst mode operation can be incorporated which only turns on the transceiver momentarily for a short duration during both transmitting and receiving [5]. The traditional compromise between data rate and energy efficiency can thus be eliminated. The method is most effective when it is incorporated into the power hungry blocks, such as the LC oscillator, LNA and super-regenerative UWB detector, which accounts for up to 95% of the total power consumption. In addition, the nanoseconds' pulses of a typical UWB transceiver, which are much shorter than the data period, will result in very low duty cycle especially for low data rates. Greater power saving can therefore be achieved by exploiting the burst mode operation and the low duty cycle feature. The energy efficiency can be represented as follows:

$$\left[\quad \right] \quad \frac{ON[s]}{e[s]} \quad \frac{r[W]}{e[-]} \quad [s] \quad er[W] \quad (2)$$

Fig. 4. Plot of the regeneration time, t_r as a function of input SNR for different $(A_{CL})'$.

Fig. 5. Plot of the detector output as a function of regeneration time, t_r .

Fig. 6. Plot of the regeneration time gap, t_g as a function of input SNR for different $(A_{CL})'$.

It should be pointed out that the “ON” period (T_{ON}) should include the turn-on settling time, the signal processing time and the turn-off settling time of various transceiver blocks, which would add up to be much larger than the UWB pulse width. Therefore, higher energy efficiency can be attained by minimizing the average power consumption as well as the turn-on and turn-off transient time of various transceiver blocks.

C. The Principle of the Proposed UWB Super-Regenerative Detector

The conceptual view of a new super-regenerative detector which is able to produce high gain after energy detection is illustrated in Fig. 2. It eliminates the need of quench signal and does not require an external resonator. The positive feedback concept is utilized here to achieve the super-regenerative

amplification. An energy detector (dual input squarer represented by SQ_1 and SQ_2), amplifier and integrator are connected in positive feedback configuration as shown. Based on the conceptual view, the loop gain, A_{CL} and its derivative, $(A_{CL})'$ can be derived as follows:

$$kx, (A) \quad (3)$$

where x is the input to the squarer SQ_2 . A_{CL} represents the signal-dependent loop gain and $(A_{CL})'$ represents the signal-independent loop gain.

As the squarer gain is signal dependent, rail-to-rail amplification is only achieved for A_{CL} larger than unity. Using this unique characteristic of signal dependent loop gain, the detector is designed such that the input noise will experience loop gain less than unity and die down, whereas the desired signal will produce loop gain larger than unity and achieve rail-to-rail amplification. After signal detection, the detector output will be automatically reset by a RC discharging network. An intuitive understanding of the proposed super-regeneration principle is shown in Fig. 3. The two curves represent the transfer characteristics of the loop output ($y=kx^2 \times A \times B=ABkx \times x$) and the unity gain ($y=x$), where x is the input to the squarer SQ_2 . The unity gain line represents the feedback action where the output becomes the input. According to Fig. 3, an input threshold (x_0) can be determined when A_{CL} is equal to unity and this value can be set according to the squarer and amplifier gain. Below this input threshold, the input signal will experience attenuation. This attenuated signal, after feedback, would be reduced further, and finally dies down to zero. This is indicated by the route $x_1-y_1-x_2$ in Fig. 3. On the other hand, above this threshold, the input signal will be amplified. This amplification would be reinforced by the feedback path and eventually result in super-regenerative amplification, as illustrated by the route $x_3-y_2-x_4$.

A more rigorous formulation of the closed loop operation which will help defining the specifications of the circuitry is discussed here. Based on Fig. 2, the output of the detector V_{OUT} is derived to be

$$V_{OUT}(t) = AB \int_0^t [GV_{IN}^2(\tau) + kV_{OUT}^2(\tau)] d\tau \quad (4)$$

$$V_{OUT}'(t) = ABGV_{IN}^2(t) + ABkV_{OUT}^2(t) \quad (5)$$

The complete analytical solution for the differential equation is not practical as the system is nonlinear and time-variant. The intuitive analytical derivation is performed to provide more insight into the system operation.

Assume that the input V_{IN} to the detector is noise only with the RMS value of V_N and initially the output of the detector V_{OUT} is zero. At the first time instance t_0 , $V_{OUT}(t_0) = ABGV_N^2$.

At time t_1 and t_n ,

$$V_{OUT}(t_1) = ABkV_{OUT}(t_0)^2 + ABGV_N^2 \quad (6)$$

$$V_{OUT}(t_n) = ABkV_{OUT}(t_n)^2 + ABGV_N^2 \quad (7)$$

It can be seen from (7) that the speed of the amplification is determined by the feedback loop gain and the input signal level sets the initial condition of the loop. If input power is very small, which is a valid assumption for noise, the incremental due to the term $ABkV_{OUT}(t_n)^2$ will be close to linear at a very small slope for a long time.

The moment when a short UWB pulse comes in, the term $ABGV_N^2$ in (7) will need to be modified to be $ABGV_N^2 + ABGV_{SIG}^2$, where V_{SIG} is the UWB pulse RMS voltage at LNA output. When this signal goes into feedback loop, the amplification will speed up by the ratio of $(ABkV_{SIG}/V_N)^{2N}$ for N rounds of feedback iterations (assuming $k=G$), comparing to the condition when only noise V_N is present. Therefore, large regenerative time gap (illustrated in Fig. 6) can be achieved by choosing large A , B , G , and k value. However, since this receiver aims for low power consumption, the gain and power consumption trade-off has to be considered.

The contour plots of the energy detector performance for different values of signal-independent loop gain $(A_{CL})'$ is shown in Fig. 4. Fig. 4 is plotted under the condition whereby detector input power is varying with a fixed noise power. The regenerative behavior can be split into 2 regions, namely the signal regeneration and the noise regeneration regions. The line separating the 2 regions is used to determine the minimum required detector input SNR (threshold level) for different $(A_{CL})'$. At very low input SNR, regeneration of input and circuit noise power dominates and the regeneration time, t_r (time taken for the output to reach rail-to-rail level) is relatively long but constant. The detector is designed such that this noise regeneration is longer than the time period imposed by the minimum data rate so that noise does not trigger a signal at the output. As detector input SNR increases beyond the threshold level, the regeneration time t_r reduces exponentially. The choice of loop gain $(A_{CL})'$ imposes an upper limit on the regeneration time, which will impact the power-on duration and thus energy efficiency of the receiver. Fig. 5 shows the detector output as a function of regeneration time t_r for a given SNR. As presented, the regeneration time gap, t_g is defined as the time difference between the regeneration of signal as compared to regeneration of noise. Fig. 6 shows the regeneration time gap, t_g as a function of detector input SNR. It can be observed that for smaller values of $(A_{CL})'$, the time gap increases primarily due to the smaller regenerative gain experienced by noise.

An example is illustrated for the derivation of the loop gain parameter. Based on sensitivity of -80 dBm for bit error rate (BER) of 10^{-3} and noise power of -81 dBm (for 3-5 GHz UWB spectrum) at the input of the LNA, the input SNR to the LNA is calculated to be 1 dB. Assuming 5 dB NF and 40 dB voltage gain for the LNA, the SNR at the detector input is calculated to be -4 dB. Based on the peak power consumption and the desired energy efficiency, the "ON" period T_{ON} can be calculated using (2). Since T_{ON} includes both the regeneration time t_r and settling time of the system during power-on, t_r can thus be chosen given

Fig. 7. Plot of regeneration time in different noise environment (input power unchanged).

Fig. 8. Super-regenerative UWB transceiver.

Fig. 9. The transmitter circuit.

a sufficient margin for system settling time. For example, to achieve an efficiency of 3.5 nJ/bit for peak power consumption of 35 mW, T_{ON} is calculated to be 100 ns. Assuming a worst-case settling time of 60 ns during the closed loop, thus t_r should be designed to be within 30 ns at the desired sensitivity. As shown in Fig. 4, the loop gain is chosen to be 20k with t_r of 25.9 ns at -80 dBm sensitivity. Also, in the absence of signal, the regeneration time t_r should be more than 40 ns after the detector settling time (60 ns) to avoid a false data. From Fig. 4 and Fig. 6, at a loop gain of 20k, the regeneration time t_r in the presence of noise only is around 67 ns.

This concept can be applied to this system in a noisier environment or other systems with different noise powers/receiver bandwidths at the detector input. Fig. 7 shows the same plot as Fig. 4 but with fixed input power (-80 dBm) and varying noise powers. The regeneration time t_r and the

Fig. 10. Current reuse LNA with single-ended-to-differential conversion, with power up/down switch (EN) implemented in current mirror.

Fig. 11. Measured LNA S21, S11 and noise figure.

necessary loop gain can then be determined using the approach described in the previous paragraph. In Fig. 7, regeneration time increases with input SNR for very low levels of SNR. When SNR increases until it is sufficiently large (decreasing noise powers), the regeneration time becomes relatively constant as now signal regeneration dominates. Thus, with a known input noise profile (power and bandwidth), the system can be designed to meet the minimum SNR at the energy detector input.

D. Proposed Super-Regenerative Transceiver Architecture

Fig. 8 shows the proposed 3-5 GHz super-regenerative UWB

transceiver architecture. Non-coherent on-off keying (OOK) signaling scheme is chosen due to its simplicity and low power consumption compared to the coherent approach, which requires additional timing synchronization circuitry.

The transmitter consists of a pulse generator using time gated LC voltage controlled oscillator (VCO). It is capable of achieving high output swing of 2 V suitable for long range communication with low power consumption. The balun and buffer convert the differential input signal into the single-ended output and provide the desired 50 Ω output impedance matching to the antenna.

For the receiver, incoming signal received by the antenna is firstly amplified by the high gain low noise amplifier (LNA). High gain is necessary for the LNA to compensate for the significant signal loss for small signals due to the squarer ($y=kx^2$, where y and x are the output and input of the squarer SQ_2 in Fig. 2) and thus improve the overall sensitivity. It should be pointed out that the post super-regenerative amplification would not be achieved for input signal less than the desired input threshold, x_0 . Therefore, sufficient LNA gain is required to ensure that the criterion is being met. The signal is then processed by the super-regenerative UWB detector discussed in the earlier section. Due to the rail-to-rail amplification, a simple differential-to-single-ended amplifier can be used as a slicer to recover the digital data. A gating circuitry utilizes this final output to synchronize the power up/down control signal (assuming data rate is known) with the incoming signals so as to turn on the receiver only for a short period at the correct instant. The settling times of the various circuit blocks will be taken into consideration in generating the control signal.

III. CMOS IMPLEMENTATION OF TRANSMITTER

Fig. 9 illustrates the transmitter circuit which consists of a gated differential LC VCO, two shunt-peaked amplifiers and a LC balun. The VCO core, consisting of the complementary NMOS/PMOS cross-coupled pairs (M_3 - M_6) and the LC tank

Fig. 12. Proposed UWB energy detector and discharging network.

(L_1 and C_1) [20], is chosen so that smaller inductance is required compared to NMOS- or PMOS-only cross-coupled oscillators [21]. In addition, the symmetry introduced also results in lower flicker noise up-conversion. Accumulation-MOS varactor C_1 is used to achieve 800 MHz tuning range for fine tuning the center frequency of the output spectrum. This will allow us to compensate for process variations or inaccurate component model and centre the output spectrum to around 4.0~4.1GHz. A low data rate gated pulse controls the tail current transistors M_1 - M_2 to turn on/off the circuit depending on the transmitted data. Their size (W/L) is chosen to be large to reduce voltage headroom and speed up the oscillator start-up transient so that nanoseconds UWB pulse can be generated. The bandwidth enhanced shunt-peaked amplifier (M_7 - M_8 and L_2 - L_3) buffer and simple passive LC lattice-network balun (C_4 - C_5 and L_4 - L_5) are employed to drive the antenna.

IV. CMOS IMPLEMENTATION OF RECEIVER

A. LNA

To improve the sensitivity due to the inherent loss of the squarer, LNA with voltage gain higher than 35 dB is desirable. Current reuse concept is adopted in this design to achieve the desired gain with relatively small power consumption [22], [23]. Two current-reuse LNAs with 4 gain stages are cascaded with a single-ended-to-differential amplifier as shown in Fig. 10. An external balun is not directly employed at the input for cost and power considerations. With external balun, a fully differential LNA will be needed, leading to an increase in the overall current consumption for the same gain. Thus, a single-ended LNA structure is adopted to save the current consumption and minimize the noise figure. However, this is done at the expense of a poorer common-mode rejection ratio (CMRR) and higher sensitivity to substrate noise, which can be mitigated with careful layout as well as separate power and ground pads for the LNA. The single-ended-to-differential conversion is only employed after LNA to reject common mode noise for subsequent analog processing blocks. Common-gate (CG) amplifier with wideband input matching is used as the first input stage. The signal is then AC coupled to the second stage common-source (CS) amplifier, which shares the same current as the initial CG amplifier. The third and fourth gain stages employ similar current-reuse and signal coupling topology. The LC tank for each gain stage is chosen to give a band-pass characteristic within 3-5 GHz. Switching between high gain and low gain mode can be achieved by switching V_{FB} between 1.8 V and 0 V to vary the triode resistance M_{FB} and thus the equivalent feedback resistance. For the single-ended-to-differential stage, the inductor L_5 and the parasitic capacitances at the source terminal of the differential pair form a high impedance path at 3-5 GHz to prevent signal leakage through the tail current and provide more effective conversion. Consuming 10.2 mA (including biasing currents), the designed LNA can achieve a high and low power gain of 31 dB/21 dB with a noise figure of 4.8 dB/6.2 dB respectively covering a bandwidth of 3-5 GHz as measured on-wafer using

Fig. 13. (a) Amplifier and (b) offset cancellation circuit.

Fig. 14. Gating circuitry flowchart.

RF probes (Fig. 11). Neglecting the loss of the LNA output buffers (-8.4 dB) by simulation, the LNA can achieve voltage gains of 39.4 dB/29.4 dB within 3-5 GHz.

The LNA can be switched on/off by simply switching on/off the current mirror biasing network as illustrated in Fig. 10. By turning on M_{11} and turning off M_{10} simultaneously, R_2 , M_8 and M_{12} together form a basic current mirror configuration which produces the desired biasing current (I_1 , I_2 , I_3) to the LNA. On the other hand, by turning off M_{11} and turning on M_{10} , transistor M_{12} is open circuited and no current can flow through the resistor R_2 . In addition, the resulting zero gate bias will switch off the biasing current to the LNA. To speed up the turn-on transient, additional pre-charging/discharging network (M_{13} - M_{15}) is incorporated. When the LNA is turned off, the MOS capacitor M_{14} will be pre-charged to V_{DD} through M_{15} . When the LNA is turned on, the charge stored in the MOS capacitor M_{14} will be transferred to the gate capacitance of M_8 and M_{12} to speed up the settling time. With this technique, the time needed to fully power-up the LNA can be reduced to less than 22 ns. The control signals EN and ENB will be generated

by the gating circuitry.

B. Super-Regenerative UWB Detector

The energy detector with discharging network employed in the proposed super-regenerative UWB detector is illustrated in Fig. 12. The energy detector is formed using two identical differential squarer circuits (M_1 - M_4 and M_5 - M_8) [24] sharing a common active load with common mode feedback. For each differential squarer, the left transistor pair M_1 - M_2 (or M_5 - M_6) will generate both a squared term and a DC term while the right transistor pair M_3 - M_4 (or M_7 - M_8) will produce an identical DC term. Using the ideal square-law characteristic equation of MOS transistor in the saturation region ($V_{GS} \geq V_{th}$), the following equation can be derived:

$$I_1 + I_2 = \beta_A \left(2V_{B1}^2 + \frac{1}{2}v_x^2 \right), \quad I_3 + I_4 = 2\beta_A V_{B1}^2, \quad (8)$$

where I_n represents the current flowing through transistor M_n ,

– $\left(- \right)$ is the transistor device parameter,

V is the gate-to-source overdrive and v_x is the differential input signal to the squarer. Similar result can be obtained for the other squarer with differential input signal v_y .

The first squarer (M_1 - M_4) would process the output from the LNA (v_x), whereas the second squarer (M_5 - M_8) would take the amplifier output (v_y) and form a positive feedback loop. Taking the differential output will eliminate the DC term for both squarers and result in the desired squared terms of the input v_x and the feedback signal v_y as shown:

$$V_{out} = V_{out+} - V_{out-} = Z_L \left(\frac{1}{2} \beta_A v_x^2 + \frac{1}{2} \beta_B v_y^2 \right), \quad (9)$$

where Z_L is the output load impedance.

It should be noted that unlike the first squarer, the DC bias for the second squarer is extracted from the detector output through a simple RC filter (R_3 - R_6 and C_3 - C_6). This will provide the necessary decay after the signal detection. The cut-off frequency of this RC filter not only determines the decay rate but also the stability of the proposed positive feedback loop. A larger cut-off frequency generates smaller amount of positive feedback, which results in faster decay rate and a more stable system with reduced overall detector gain. The limit of the cut-off frequency is determined from Fig. 4 based on the upper limit of regeneration time, t_r , under the chosen loop gain value. To further speed up the decay of rail-to-rail output, a discharging network shown in Fig. 12 is used. It consists of two high output impedance current source and sink with limited voltage operating range. V_{B2} and V_{B3} bias the gates of the current source M_{17} and sink M_{18} , respectively, to ensure that when $V_{discharge}$ is around half V_{dd} (small signal swing). Both M_{17} and M_{18} work at saturation region and their drain currents are the same. When the $V_{discharge}$ change is small and does not pull either one of M_{17} and M_{18} out of saturation region, the drain currents does not change much. For close to rail-to-rail $V_{discharge}$,

Fig. 15. Simulated gating circuitry performance at data rate of 5Mbps.

Fig. 16. Die Photograph of the test structure.

either the current source or sink will remain functional, thus causing the capacitor C_5 and C_6 to quickly charge or discharge back to its initial state.

Simple differential amplifier employing active load and offset cancellation is used as the amplifier in the super-regenerative detector as shown in Fig. 13. Its input is DC coupled from the output of the energy detector to maximize the regenerative gain of the detector and avoid long settling time during switching. To avoid output voltage saturation due to offset, a DC offset cancellation circuit employing Nauta's transconductor [25] is used. Together with the energy detector, the resulting super-regenerative UWB detector is able to achieve rail-to-rail amplification with input signal as small as 26mV. Similar switching technique used in the LNA is also applied here to enable the burst mode operation.

Due to the high super-regenerative gain, the switching glitches resulting from the burst mode operation can be easily

get amplified and saturate the output. Therefore, two pairs of reset switches (M_{15} , M_{16} for the energy detector and M_7 , M_8 for the amplifier) are used to reset the output to zero during the power up of the various transceiver blocks. The detailed operation will be further explained in next section.

C. Gating Circuitry

A gating circuitry with the flow chart shown in Fig. 14 has been implemented through digital synthesis to generate the desired control signals (EN and V_{ctrl}) for powering up/down the various blocks and thus reducing the average power consumption of the receiver. It is assumed that the data rate is known beforehand, and the gating circuitry operating cycle can be made programmable through a programmable counter based on the given data rate. Initially, the whole transceiver is powered up and searching for the incoming signal with the counter free running. Once the incoming signal is detected, the counter would be reset to mark the beginning of the data cycle. The desired control signals, EN and V_{ctrl} , would then be generated according to the counter value. The corresponding timing diagram is shown in Fig. 15. As illustrated, the onset of incoming data successfully resets the counter and a periodic EN and V_{ctrl} are generated thereafter. The main objective of the V_{ctrl} is to avoid false detection of the data caused by the switching glitches resulting from the powering up of the various transceiver blocks. Once all the blocks are successfully powered up, the V_{ctrl} would go low to enable the normal operation of the super-regenerative UWB detector. In the simulation, EN signal of pulse width of 160 ns and V_{ctrl} of 90 ns are used for a given data rate of 5 Mbps.

V. MEASURED RESULTS

The transceiver chip is packaged and mounted onto a Rogers Printed Circuit Board (PCB) for measurements. The die, implemented in 0.18- μm GF CMOS technology and occupying 2.2 mm $\times$ 2 mm (excluding pads), is shown in Fig. 16.

Fig. 17 shows the measured transmitter performance. The peak power of the transmitter is 129 mW with a 3.3 V supply. The transmitter is able to achieve an output pulse width of a few nanoseconds. With a 20 Mbps baseband input signal, the output pulse has a width of 5.2 ns. The transmitter output spectrum, with a -10 dB signal bandwidth of 1.36 GHz, satisfies the UWB spectrum mask and consumes an average power of 13.4 mW at 20 Mbps, which translates to an energy efficiency of 0.671 nJ/bit. The frequency spectrum in Fig. 17 shows spurious source that violates the frequency mask at lower frequencies (below 1.2 GHz). The spurious source can be attenuated through the use of an actual 3-5 GHz UWB antenna. In the current test setup, the transmitter is directly connected to a spectrum analyzer with 50 Ω input impedance within the entire measured spectrum. The performance of the transmitter is compared with recent published UWB transmitter in Table I.

The recovered data for different transmitted pulse widths at 100 kbps, 1 Mbps and 5 Mbps measured in laboratory is shown in Fig. 18. The peak power consumption for the receiver is 34.4 mW, with almost 95% of it belonging to the LNA and super-regenerative UWB detector. Using the gating circuitry

Fig. 17. Measured transmitter performance (time domain and frequency spectrum).

Fig. 18. Measured receiver performance for different transmitter pulse widths at 100kbps, 1Mbps and 5Mbps.

TABLE I
TRANSMITTER PERFORMANCE COMPARISON WITH RECENT WORKS

References	Vp-p (V)	Vdd (V)	BW (-10dB)	Width (ns)	CMOS (μm)	Power Cons.	Ep (/pulse)	η (pJ/p/V)	Band (GHz)	Modulation
[26]	1.42	1.2	6.8GHz	1.75	0.13	3.48mW@100MHz	9pJ	6.4	3.1-10.6	OOK
[27]	0.025	1.8	1.3GHz	1	0.18	11.8mW@120MHz	98.3pJ	3932	6-10	OOK
[28]	0.16	1.5	0.52GHz	3.5	0.18	-	16.8pJ ⁺	105	3.1-10.6	OOK
This work	2	3.3	1.36GHz	5.2	0.18	129mW@20Mbps	671pJ	335.5	3-5	OOK

TABLE II
TRANSCIEVER PERFORMANCE COMPARISON WITH RECENT WORKS

References	[11]	[4]	[9]	[10]	[13]	This Work
Technology	0.18- μm CMOS	0.13- μm CMOS	90-nm CMOS	90-nm CMOS	0.13- μm CMOS	0.18- μm CMOS
Frequency [GHz]	3.244-3.744	3 – 4	2.4	0.42-0.45	2.4	3 – 5
Approach	UWB Super-Regen	UWB Super-Regen	Super-Regen	Super-Regen	Super-Regen	UWB Super-Regen with time gating
Modulation	OOK	PPM	OOK	OOK(RX) FSK/MSK(TX)	OOK	OOK
Power Consumption [mW]	10.8 @ 1.5V (RX)	11.2 @ 1.2V (RX)	0.534(RX) 2.53(TX) @1V	0.4 (RX) 0.35 (TX)	2.8 @ 1.2V	34.4 (RX) @ 1.8V 129 (TX) @ 3.3V
Energy Efficiency [nJ/bit]	0.24(RX) @10Mbps	1.12	0.11(RX) @5Mbps	10 (RX) 2.9 (TX) @ 120kbps	5.6 @ 500kbps	3.54 (RX) 0.671 (TX) @ 1Mbps
Sensitivity [dBm]	-66	-99	-75	-93	-90	-81
Quench Signal	External	External	Internal	Internal	Internal digital	Not required

for burst mode operation at data rate of 1 Mbps with a power on duration of 100ns, the average power consumption is 3.54 mW (with static power consumption of 195 μW), corresponding to an energy efficiency of 3.54 nJ/bit. By exploiting the duty cycle in burst mode operation, the gating circuitry helps to achieve larger power saving at low data rate compared to the conventional transceivers with continuous operation, and is suitable for wireless sensor networks application.

Table II shows the performance comparison with state of the art receivers/transceivers. [4], [11] and our proposed transceiver are suitable for implementation in UWB systems. The operating frequency of this receiver is the widest compared to all recent super-regenerative works, covering the lower band (3-5 GHz) of the UWB spectrum. Its performance in terms of frequency, energy efficiency and sensitivity is comparable to the super-regenerative receiver in [4] and [11] when normalized to the same data rate, whereas the proposed architecture is simplest as both [4] and [11] require a quench signal since the super-regeneration is based on conventional oscillator technique. Furthermore, the circuit can be optimized more thoroughly to achieve even better energy efficiency for ultra-low power short-range sensor network application.

VI. CONCLUSIONS

A burst mode super-regenerative transceiver for the low power short range wireless applications such as wireless body area networking (WBAN) or wireless sensor networking (WSN) has been designed and successfully implemented using CMOS 0.18- μm technology. A fast switching and symmetric transmitter has been designed with an energy efficiency of 0.671 nJ/bit. A new type of super-regenerative UWB detector with huge post amplification gain after energy detection has

been demonstrated. Based on the positive feedback concept, the proposed detector eliminates the need for external high-Q resonator and quench signal commonly found in conventional oscillator-type based super-regenerative transceivers employed in RF front-end. Current reuse LNA, super-regenerative UWB detector and burst mode operation with gating circuitry together enable the receiver to achieve energy efficiency of 3.54 nJ/bit, which is suitable for low data rate sensor networks applications.

REFERENCES

- [1] IEEE 802.15.4a Task Group Website, <http://www.ieee802.org/15/pub/TG4a.html>.
- [2] K. Römer and F. Mattern, "The Design Space of Wireless Sensor Networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 54-61, Dec. 2004.
- [3] M. A. M. Vieira, C. N. Coelho, Jr., D. C. da Silva Junior, and J. M. da Mata, "Survey on Wireless Sensor Network Devices," in *Proc. 10th IEEE Int. Conf. Emerging Technol. Factory Autom.*, Sep. 2003, pp. 537-544.
- [4] M. Pelissier, D. Morche and P. Vincent, "Super-Regenerative Architecture for UWB Pulse Detection: From Theory to RF Front-End Design," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 56, no. 7, pp. 1500-1512, Jul. 2009.
- [5] F. S. Lee and A. P. Chandrakasan, "A 2.5 nJ/bit 0.65 V Pulsed UWB Receiver in 90 nm CMOS," *IEEE J. Solid-State Circuits*, vol. 42, no. 12, pp. 2851-2859, Dec. 2007.
- [6] M. Mroue and S. Haese, "An Analog CMOS Pulse Energy Detector for IR-UWB Non-Coherent HDR Receiver," in *IEEE ICUBW Dig. Tech. Papers*, Sep. 2006, pp. 557-562.
- [7] S. R. Dueñas, X. Duo, S. Yamac, M. Ismail and L. R. Zheng, "CMOS UWB IR Non-Coherent Receiver for RF-ID Applications," in *Proc. IEEE Northeast Workshop Circuits Syst.*, Jun. 2006, pp. 213-216.
- [8] S. Tiuraniemi, L. Stoica, A. Rabbachin and I. Oppermann, "Front-End Receiver for Low Power, Low Complexity Non-Coherent UWB Communications System," in *IEEE ICUBW Dig. Tech. Papers*, 2005, pp. 339-343.
- [9] M. Vidojkovic, X. Huang, P. Harpe, Simonetta Rampu, C. Zhou, L. Huang, K. Imamura, B. Busze, F. Bouwens, M. Konijnenburg, J. Santana, A. Breeschoten, J. Huisken, G. Dolmans and H. Groot, "A 2.4GHz ULP

- OOK Single-Chip Transceiver for Healthcare Applications,” in *IEEE ISSCC Dig. Tech. Papers*, Feb. 2011, pp. 458-460.
- [10] J. L. Bohorquez, A. P. Chandrakasan and J. L. Dawson, “A 350 μ W CMOS MSK Transmitter and 400 μ W OOK Super-Regenerative Receiver for Medical Implant Communications,” *IEEE J. Solid-State Circuits*, vol. 44, no. 4, pp. 1248-1259, Apr. 2009.
- [11] P. E. Thoppay, C. Dehollain, M. M. Green and M. J. Declercq, “A 0.24-nJ/bit Super-Regenerative Pulsed UWB Receiver in 0.18- μ m CMOS,” *IEEE J. Solid-State Circuits*, vol. 46, no. 11, pp. 2623-2634, Nov. 2011.
- [12] M. Anis, M. Ortmanns and N. Wehn, “A 2.5mW 2Mb/s Fully Integrated Impulse-FM-UWB Transceiver in 0.18 μ m CMOS,” in *IEEE MTT-S Dig.*, Jun. 2011, pp. 1.
- [13] J.-Y. Chen, M. P. Flynn and J. P. Hayes, “A Fully Integrated Auto-Calibrated Super-Regenerative Receiver in 0.13- μ m CMOS,” *IEEE J. Solid-State Circuits*, vol. 42, no. 9, pp. 1976-1985, September 2007.
- [14] B. Otis, Y. H. Chee and J. Rabaey, “A 400 μ W-RX, 1.6mW-TX Super-Regenerative Transceiver for Wireless Sensor Networks,” in *IEEE ISSCC Dig. Tech. Papers*, Feb. 2005, pp. 396-397.
- [15] F. O. Fernández-Rodríguez and E. Sánchez-Sinencio, “Advanced Quenching Techniques for Super-Regenerative Radio Receivers,” *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 59, no. 7, pp. 1533-1545, Jul. 2012.
- [16] K. Kim, S. Yun, S. Lee and S. Nam, “Low-Power CMOS Super-Regenerative Receiver With a Digitally Self-Quenching Loop,” *IEEE Microw. Wireless Compon. Lett.*, vol. 22, no. 9, pp. 486-488, Sep. 2012.
- [17] F. X. Moncunill-Geniz, P. Palà-Schönwälder, C. Dehollain, N. Joehl and M. Declercq, “An 11-Mb/s 2.1-mW Synchronous Superregenerative Receiver at 2.4 GHz,” *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 6, pp. 1355-1362, Jun. 2007.
- [18] J. Han and R. Gharpurey, “Recursive Receiver Down-Converters With Multiband Feedback and Gain-Reuse,” *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1119-1131, May 2008.
- [19] P. Favre, N. Joehl, A. Vouilloz, P. Deval, C. Dehollain and M. J. Declercq, “A 2-V 600- μ A 1-GHz BiCMOS Super-Regenerative Receiver for ISM Applications,” *IEEE J. Solid-State Circuits*, vol. 33, no. 12, pp. 2186-2196, Dec. 1998.
- [20] L. Jia, J.-G. Ma, K. S. Yeo and M. A. Do, “9.3-10.4-GHz-band cross-coupled complementary oscillator with low phase-noise performance,” *IEEE Trans. Microw. Theory Tech.*, vol. 52, pp. 1273-1278, no. 4, Apr. 2004.
- [21] A. Hajimiri and T. H. Lee, “Design issues in CMOS differential LC oscillators,” *IEEE J. Solid-State Circuits*, vol. 34, no. 5, pp. 717-724, May 1999.
- [22] Y. Gao, Y. Zheng and C. H. Heng, “Low-Power CMOS RF Front-end for Non-Coherent IR-UWB Receiver,” in *Proc. Eur. Solid-State Circuits Conf. (ESSCIRC)*, Sep. 2008, pp. 386-389.
- [23] S. R. Karri, M. A. Arasu, K. W. Wong, Y. Zheng and F. Lin, “Low-Power UWB LNA and Mixer using 0.18- μ m CMOS Technology,” in *Proc. Eur. Solid-State Circuits Conf. (ESSCIRC)*, Sep. 2006, pp. 259-262.
- [24] K. Kimura, “Some Circuit Design Techniques for Low-Voltage Analog Functional Elements Using Squaring Circuits,” *IEEE Trans. Circuits Syst. I*, vol. 43, no. 7, pp. 559-576, Jul. 1996.
- [25] P. Andreani and S. Mattisson, “On the Use of Nauta’s Transconductor in Low-Frequency CMOS gm-C Bandpass Filters,” *IEEE J. Solid-State Circuits*, vol. 37, no. 2, pp. 114-124, Feb. 2002.
- [26] S. Bourdel, Y. Bachelet, J. Gaubert, R. Vauché, O. Fourquin, N. Dehaese, and H. Barthélemy, “A 9-pJ/Pulse 1.42-V_{pp} OOK CMOS UWB pulse generator for the 3.1–10.6-GHz FCC band,” *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 1, pp. 65–73, Jan. 2010.
- [27] Y. T. Lo, C.-C. Yui, and J.-F. Kiang, “OOK/BPSK-Modulated Impulse Transmitters Integrated With Leakage-Cancelling Circuit,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 1, pp. 218–224, Jan. 2013.
- [28] A. T. Phan, J. Lee, V. Krizhanovskii, Q. Le, S.-K. Han, and S.-G. Lee, “Energy-efficient low-complexity CMOS pulse generator for multiband UWB impulse radio,” *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 55, no. 11, pp. 3552–3563, Dec. 2008.
- [29] P. Favre et al., “A 2-V 600- μ A 1-GHz BiCMOS super-regenerative receiver for ISM applications,” *IEEE J. Solid-State Circuits*, vol. 33, no. 12, pp. 2186–2196, Dec. 1998.

Yuanjin Zheng (M’02) received the B.Eng. and M.Eng. degrees from Xi’an Jiaotong University, Xi’an, China, in 1993 and 1996, respectively, and the Ph.D. degree from the Nanyang Technological University, Singapore, in 2001. From July 1996 to April 1998, he was with the National Key Laboratory of Optical Communication Technology, University of Electronic Science and Technology of China. In 2001, he joined the Institute of Microelectronics (IME), Agency for Science, Technology and Research (A*STAR), and had been a principle Investigator and group leader. With the IME, he has led and developed various projects like CMOS RF transceivers, baseband system-on-a-chip (SoC) for wireless systems, ultra-wideband (UWB), and low-power biomedical ICs etc. In July 2009, he joined the Nanyang Technological University, as an assistant professor and program directors. His research interests are gigahertz RFIC and SoC design, bio-sensors and imaging, and SAW/BAW/MEMS sensors. He has authored or coauthored over 100 international journal and conference papers, 16 patents filed, and several book chapters.

Yao Zhu (S’12) received the B.Eng. (First-Class Honors) in electrical and electronic engineering from Nanyang Technological University (NTU), Singapore in 2009. She is currently a Ph.D. candidate in Nanyang Technological University (NTU), Singapore. Her research interests include acoustic micro-resonator and filter design, as well as Wireless Transceiver and Sensor Circuits and Systems.

Chyuen Wei Ang received the B.Eng. (First Class Honors) and M.Eng. degrees in electrical engineering from the National University of Singapore, in 2005 and 2010, respectively.

He was a Research Engineer with the Institute of Microelectronics, Singapore, where he worked on the design of RF receiver front end and analog circuit blocks. His research interests include CMOS RF and analog low-power integrated circuits.

Yuan Gao (S’04-M’08) received the B.Eng. and M.Eng. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China in 2000, 2003, respectively, and the Ph.D. degree in electrical engineering from the National University of Singapore, Singapore, in 2008.

Since 2007, he has been with Institute of Microelectronics (IME), Agency for Science, Technology and Research (A*STAR), Singapore, where he is currently a research scientist and the principal investigator of Biomedical IC group in Integrated Circuits and Systems Laboratory. His current research interests include low-power low-voltage circuit

technologies for wireless and biomedical applications, energy harvesting and biosensor interface circuits design. He has authored or coauthored more than 40 peer-reviewed international journal and conference papers and has 7 patents granted or filed.

Chun-Huat Heng (S'96–M'04–SM'13) received the B. Eng. and M. Eng. degrees from the National University of Singapore (NUS), Singapore, and the Ph.D. degree from the University of Illinois at Urbana-Champaign, Urbana and Champaign, IL, USA, in 1996, 1999, and 2003, respectively. From 2001 to 2004, he was with Wireless Interface Technologies,

which was later acquired by Chrontel. Since 2004, he has been with NUS, where he is currently Area Director of Integrated Circuits and Embedded Systems. He has been working on CMOS integrated circuits involving synthesizer, delay-locked loop, and transceiver circuits. Dr. Heng received the NUS Annual Teaching Excellence Award in 2008 and 2011. He also won the Faculty Innovative Teaching Award in 2009. He has served as an Associate Editor for IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS II: EXPRESS BRIEFS, and is a Technical Program Committee member for Asian Solid-State Circuits Conference.

The authors would like to express their appreciation to the reviews for the constructive suggestions which make the paper more concrete and concise.

Review Number 1.

Does the revision adequately address the concerns expressed in the original review?

Partially.

Comments to the Author

My main concern: (quoted from my first review) Concept incorrectly denoted as "super-regenerative detector.

The name "super-regenerative detector" is used for something that is completely different. The authors only present a trigger circuit with non-linear positive feedback, coming *after* their RF detector. The usual meaning of "super-regenerative detector" involves super-regenerative gain for RF frequencies.

Reply:

We agree the conventional super-regenerative detector generates super-regenerative gain for RF frequencies. The proposed super-regenerative detector is with different architecture, which basically regenerates the *conversion gain* (from RF to baseband) for the receiver through the overall positive feedback. Hence, in terms of gain regeneration, they have some similarity, both through positive feedback. We understand it is better to differentiate this structure than conventional ones, and maybe it is better to name it as a 'quasi super-regenerative' architecture. However, we believe the proposed architecture belongs to the general category of super-regenerative approach. In order to explain it in the same framework of 'super-regenerative' (which emphasized the gain regeneration through positive feedback), we feel it is good to keep the name of 'sup-regenerative UWB receiver' but did specify the difference of it than the conventional ones in the revised context.

Amendments have been made in manuscript page 1, right column, last paragraph.

Review Number 2.

Does the revision adequately address the concerns expressed in the original review?

Yes.

Comments to the Author

Relative to Figure 18 please specify the environment (lab, outdoor...) where the measurements were performed.

Are measurements in other environments planned?

Please also specify the immediate next target application of the transceiver.

Reply:

The data in Figure 18 was measured in lab. Furthermore measurements in the environment such as outdoor, multipath intensive, or with interference etc. will be conducted. Resultantly, the further improvements on the transceiver design may be done and the corresponding results will be reported elsewhere.

Our immediate next targeted application is to use it for the low power short range wireless applications such as wireless body area networking (WBAN) or wireless sensor networking (WSN). An example of using it in WBAN is to connect those implanted neural recording sensors to external base-stations; or in a WSN, it can be used to connect medical devices such as ECG/EEG sensors to the central control units.

Amendments have been made in manuscript page 8, left column, last paragraph, and page 9, left column, last paragraph.