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A Synchronous Super-Regenerative Receiver for UWB Pulse Detection

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Abstract: Super-regenerative receivers have been dedicated for impulse based Ultra Wide Band (UWB) receivers for their simplicity and low power consumption. Our proposed research studies the behavior of super-regenerative receivers at 4.8 GHz and how parameter optimization is carried out to tailor them for UWB signaling. Synchronization issue is handled and system architecture is proposed to fix this issue.

Key words: Super-regeneration receiver; time synchronous circuit; ultra-wideband, bandwidth optimization, quench frequency, sensitivity curve

INTRODUCTION

The demand for low power consumption receiver is one of the important properties for short range wireless communications. This due to the dramatic improvement in many applications such as remote sensing, short distance telemetry and wireless sensor networks (Moncunill-Geniz *et al*., 2007). In such receivers, communication is generally done by an impulse based UWB signal across a short range of coverage area that doesn't exceed 10 m. Super-regenerative receivers that depends on energy detection seems a promising candidate to receive and detect this type of impulse based signal for its simplicity in design, low cost, low power consumption and high RF gain (Vouilloz *et al*., 2001). On the other hand, correlator based receiver (Lee and Chandrakasan, 2006, 2007) suffers from complexity in design, low RF gain and high power consumption particularly when using active mixers.

Zahabi *et al*. (2012) present a 2.4 GHz super-regeneration amplifier with capacitive-loaded integrated transmission line for a short range RF-pulse width transceiver. The degenerative quenching technique is employed in the super-regenerative amplifier to improve the linearity and reduces the sensitivity of negative transconductance (GM) to the bias current.

Fernandez-Rodriguez and Sanchez-Sinencio (2012) propose an optimal super-regenerative-receiver quench signal that achieves 48% narrower 3 dB bandwidth than state of the art and in addition allows independent selection of receiver gain, 3 dB bandwidth and maximum quench frequency, facilitating design.

Bohorquez *et al*. (2009) present a frequency-domain model for analyzing super regenerative receivers and use this models to predict the response of super regenerative receivers to arbitrary deterministic and stochastic signals including sinusoids, pulsed-sinusoids and additive white Gaussian noise.

Yoon *et al*. (2011) proposed a frequency tunable Super-Regenerative Oscillator (SRO) for channel selective receivers in short-range sensor networks. The SRO is designed with the Voltage-Controlled Injection Locked Oscillator (VC-ILO) and an external quenching signal. A varactor diode is mounted on the resonator in order to achieve frequency tunability. From the experimental results, the proposed SRO has regenerated the output signal with excellent frequency selectivity from 2.41-2.50 GHz at tuning voltage of 0 V-5 V. For injected On-Off Keying (OOK) modulated signal with a data rate of 50 kbps and sinusoidal quenching signal 200 kHz, the SRO has presented 10-MHz channel selectivity for ISM band of 2.41-2.50 GHz.

One of the drawbacks in super-regenerative receiver that it is sensitive for a short duration in time, this drawback make this kind of receivers more tailored for UWB signal in which the signal energy is concentrated in a short time duration (Kalyanasundaram *et al*., 2012).

Thus, the objective of this research is to introduce the concept of super-regenerative receiver in UWB systems and to overcome the problem of synchronization issue. This motivation is presented in our proposed system model of the super-regenerative oscillator SRO which is the core of the super-regenerative receivers. We will develop the procedure to evaluate the characteristic parameters of super-regenerative oscillator and how they can be tailored and optimized for UWB signal. We will also handle two important defects which are hangover phenomena and synchronization.

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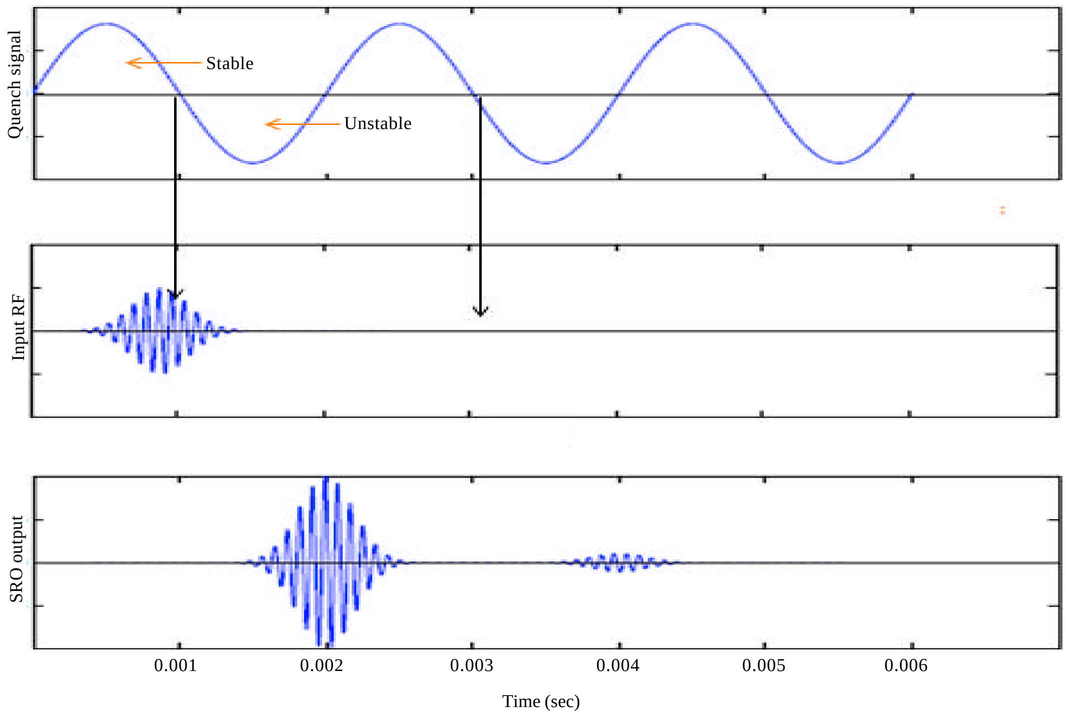

Fig. 1: Quench signal, RF input and SRO output

System modeling: Super Regenerative Oscillator (SRO) is a normal oscillator that can be switched on and off periodically through a control signal named the quench signal. During the on state (unstable state) the oscillator builds up their oscillation from noise producing an output oscillation voltage with certain envelop. If an RF signal is injected to the oscillator during the on state it turns out that the envelop of oscillation is larger than that produced due to noise only as shown in Fig. 1. Hence, the more energy or power of input RF signal the faster growth of the oscillation voltage yielding a larger envelops. Thus super-regenerative receivers is much favorable for ASK modulation schemes but due to technology scaling and supply voltage shrinkage as well leaving no room for swing, super-regenerative receivers is limited to on/off keying modulation scheme.

The SRO can be modeled in Fig. 2 using a feedback system formed by a band pass selective network (resonant tank circuit) of a transfer function H(s) defined in Eq. 1 which represents the open loop gain or the feed forward while the feedback network represented by an amplifier with variable gain $K_a(t)$ in which the gain is controlled and varied by the quench signal:

$$H(s) = \frac{v_o(s)}{v_{in}(s)} = \frac{2k_o \zeta_o \omega_o s}{s^2 + \zeta_o \omega_o s + \omega_o^2} \quad (1)$$

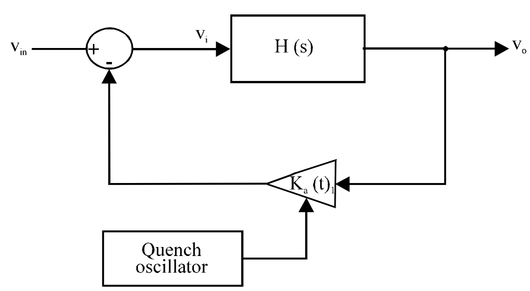

Fig. 2: Block diagram of SRO

Table 1: System and circuit level representation of the SRO

Parameter	System level	Circuit representation
v_O	Output of the SRO	Voltage
v_i	Input of the SRO	Current
K_O	Open loop gain of the feed forward selective network	$1/G_O$ where, G_O is the tank parasitic conductance
ω_O	Selective network central frequency	Tank Resonance frequency $1/\sqrt{lc}$
ζ_O	Selective network damping ratio	$1/2Q_O$ where, Q_O is the unloaded tank quality factor
$K_O(t)$	Feedback factor	$G_a(t)$ periodic negative conductance

The parameters of the selective network H(s) and the feedback network are defined in Table 1 and its equivalent representation in the circuit level considering a parallel resonant tank circuit (selective network) (Moncunill-Geniz *et al*., 2005a).

Including the feedback factor $K_a(t)$ and after solving the differential equation by Moncunill-Geniz *et al.* (2005a), a periodic damping factor is obtained (quench signal) as in Eq. 2:

$$\zeta(t) = \zeta_O(1\text{-}K_O K_a(t)) \quad (2)$$

Equation 2 reveals that as $K_a(t)$ increases the damping factor decreases driving the feedback system to the unstable state (which represents the SRO in the ON state) and the system starts to oscillate when the damping factor becomes negative. Decreasing $K_a(t)$ eventually will change the state of the system to be stable and the oscillation is shutdown since the damping factor becomes positive. In this work the analysis is done using a sinusoidal quench signal creating a sinusoidal damping factor of amplitude ζ_{ac} and quench frequency f_q formulated in Eq. 3:

$$\zeta(t) = \zeta_{ac} \sin(2\pi f_q t) \quad (3)$$

The impulse-based UWB signal, injected to the system and represented in Eq. 4, can be modeled by a sinusoidal signal filtered by a Gaussian window p(t) (Pelissier *et al.*, 2006):

$$\begin{aligned} V_{in}(t) &= Vp(t)\cos(2\pi f_c t) \\ p(t) &= e^{[-(t/\tau)]^2} \end{aligned} \quad (4)$$

where, V is the amplitude of the RF signal, f_c is the impulse central frequency and should be of the same resonance frequency of the SRO and τ is the spreading factor of the Gaussian window which controls the -10 dB bandwidth. Figure 3 shows different spreading factor for different signal bandwidth.

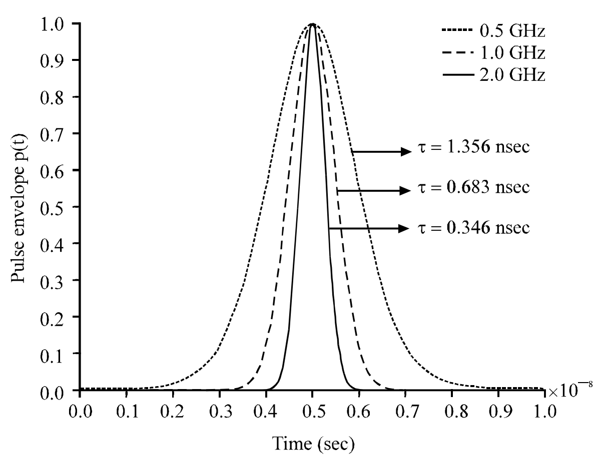

Fig. 3: Signal envelops of different BW

Optimizing SRO parameters for UWB signal: In coherent detection (Lee and Chandrakasan, 2007; Lee and Chandrakasan, 2006) where signal is recovered and detected by correlating the input pulsed signal with internally generated template suffers from lack in RF gain and more power consumption for high gain LNA and template generator (Pelissier *et al.*, 2009). In SRO the multiplier and the template generator are replaced by the sensitivity curve or sensitivity function which is a normalized function.

Bandwidth optimization: SRO is sensitive to the input RF signal for a short interval of time reaching its maximum sensitivity at the zero crossing of the sinusoidal damping factor $\zeta(t)$ and starts to decrease outside the zero crossing as shown in Fig. 4. Since, UWB signal has all its energy concentrated in a short time duration; then if the intervals-of the sensitivity function and RF pulse envelop-are matched this will lead to optimum sensitivity and detection.

The sensitivity function is strongly dependent on the instantaneous slope of the quench signal at zero crossing, hence the fast transition leads to a narrower sensitivity curve as in Eq. 5:

$$s(t) = e^{\omega_o \int_{t_{oo}}^{t} \zeta(\lambda) d\lambda} \quad (5)$$

The envelop of the sensitivity function is a normalized Gaussian like the input RF pulse and defined in Eq. 6:

$$s(t) = e^{[(t - t_{oo}/\tau_s)]^2} \quad (6)$$

where, V is the sensitivity period or the spreading factor of the sensitivity function, the influence of the input

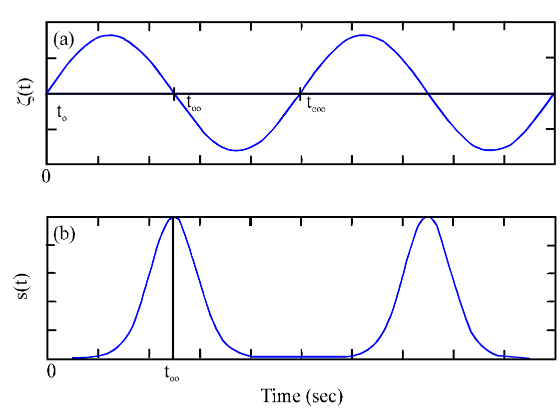

Fig. 4(a-b): (a) Quench signal and (b) Sensitivity function signal is very small or negligible outside this spreading factor. From (Pelissier *et al*., 2009), τ can be defined in Eq. 7 that's showing the dependence on the zero crossing of the quench signal:

$$\tau_s = \sqrt{\frac{2}{|\zeta'(t_{oo})|\omega_o}} \tag{7}$$

For optimum sensitivity both the spreading factor of the pulse envelop and the sensitivity function should be the same, thus the frequency response of the SRO should match the bandwidth of the input RF pulse. The frequency response of the SRO is given by:

$$H(\omega) = \frac{\omega\psi(\omega-\omega_o)}{\omega_o\psi(0)} \text{ where, } \psi = TF^*\langle s\rangle \tag{8}$$

Since, the analysis is carried out on sinusoidal quench signal, then increasing the amplitude of the sinusoidal damping factor ζ_{ac} as well as the quench frequency f_q will increase the zero crossing slope of the quench signal creating a narrow sensitivity function or in other words a small spreading factor τ_s achieving a wider bandwidth to match different bandwidth of UWB signal. Figure 5 shows the dependence of the frequency response or the SRO bandwidth on ζ_{ac} for different f_q:

Gain optimization: Since, UWB signal level is very low in the order of hundreds of micro volts making the detection not easy and needs lots of gain at the receiver to recover and detect the received signal. Fortunately the SRO offers a very high RF gain with low power consumption relaxing the requirements of the base band amplifier that follows the SRO. The SRO gain consists of three parts intrinsic gain K_O regenerative gain K_r and super-regenerative gain K_S.

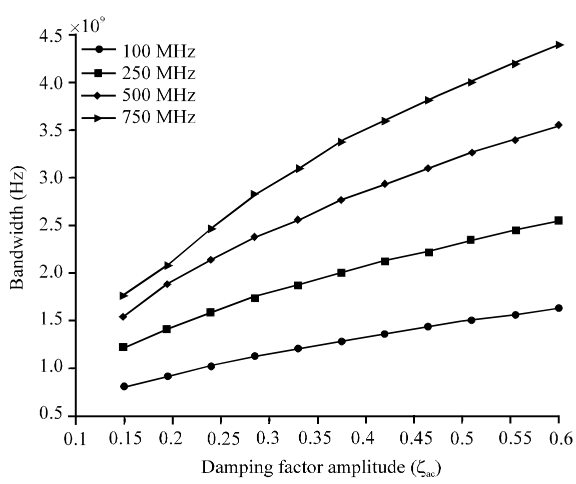

Fig. 5: Dependence of the BW on ζ_{ac} for different f_q

The intrinsic gain K_O is the gain of the feed forward selective network and its value depends on the parasitic conductance of the selective network as shown in.

On the other the side regenerative Gain K_r gain depends on the overlapped area between the envelop of the sensitivity function and the input RF envelop as shown in Eq. 9. The larger the area the higher the regenerative gain. Any miss-synchronization leads to degradation in the receiver gain. This synchronization issue will be discussed later in this study:

$$K_r = \zeta_o\omega_o \int_{t_{ooo}}^{t_b} p_i(\lambda)\, s(\lambda)\, d\lambda \tag{9}$$

Assuming perfect synchronization, achieving a high regenerative gain needs a wider sensitivity function and of course wider pulse envelop, making the regenerative gain in UWB context very low. Using Eq. 3, 6 and 9, we analytically illustrate the effect of the quench frequency and the damping factor amplitude on the regenerative gain as shown in Fig. 6. Figure 6 shows the degradation of the regenerative gain on increasing the quench frequency f_q ($\zeta_{ac} = 0.15$ and $\zeta_{dc} = 0.025$) and the amplitude ζ_{ac} as well as achieving a narrow sensitivity function.

The Super-regenerative gain K_S is the main gain of the SRO and depends on the area of the negative portion of the sinusoidal damping factor as defined in Eq. 10:

$$K_s = e^{-\omega_o \int_0^{t_{ooo}} \zeta(\lambda)d\lambda} \tag{10}$$

Fortunately, increasing ζ_{ac} to achieve a narrow sensitivity curve will increase the super-regenerative gain while increasing f_q leads to degradation in the super-regenerative gain as shown in Fig. 7.

The output waveform is a sinusoidal signal under a normalized Gaussian envelop given in the following equation:

$$\begin{aligned} v_o(t) &= V_i K_r K_s K_o P(t)\cos(\omega_o t + \phi) \\ P(t) &= e^{-\omega_o \int_{t_{ooo}}^{t} \zeta(\lambda)d\lambda} \end{aligned} \tag{11}$$

Equation 11 reveals the linear relation between the output and input envelop with an amplification factor of K_r K_s K_O. Stated Moncunill-Geniz *et al.* (2007) and Pelissier *et al.* (2007) another mode of operation which is Logarithmic mode. Logarithmic mode operation

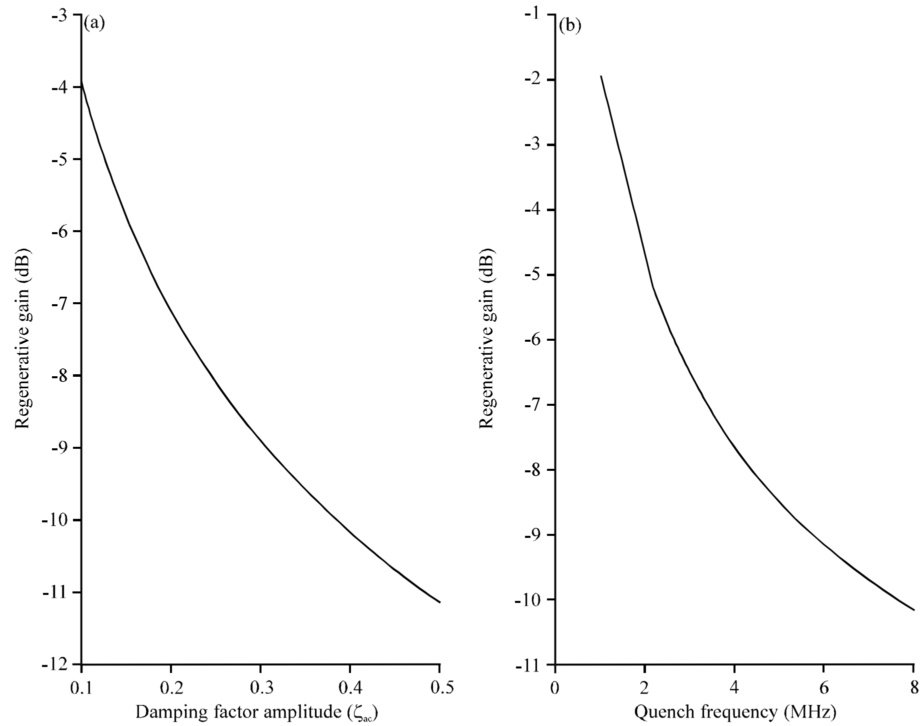

Fig. 6(a-b): Effect of (a) ζ_{ac} (f_q = 250 MHz ζ_O = 0.025) and (b) f_q (ζ_{ac} = 0.15 ζ_O = 0.025) on the regenerative gain

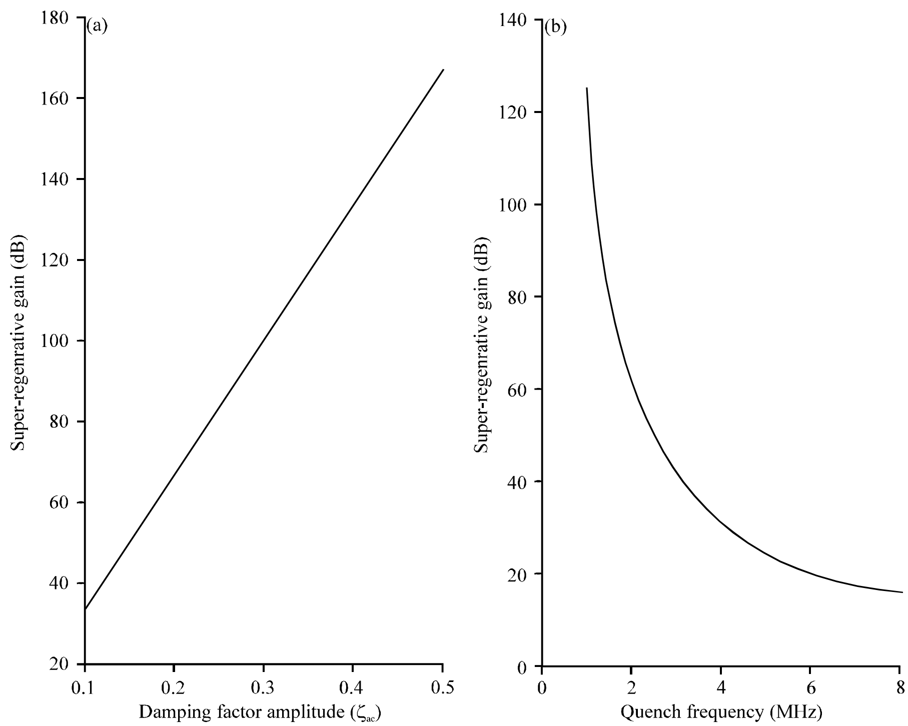

Fig. 7(a-b): Effect of (a) ζ_{ac} (f_q = 250 MHz ζ_O = 0.025) and (b) f_q (ζ_{ac} = 0.15 ζ_O = 0.025) on the super-regenerative gain.

is a serious problem due to technology scaling but it is beyond the scope of this study.

The previous analysis reveals that the quench signal in general and the sinusoidal damping factor in particular

(ζ_{ac} and f_q dominates the BW as well as the gain of the super-regenerative oscillator. In order to tailor the SRO for UWB signal, a high gain is needed to amplify the low level input signal besides a large BW (over 0.5 GHz). Figure 8 shows a low quench frequency f_q will achieve a high gain (K_rK_S) but this won't fulfill a large BW. Since, the super-regenerative gain is the main gain so increasing ζ_{ac} is the way to achieve both a high gain and large bandwidth.

Issues in super-regenerative oscillator: One of the most important issues in SRO is the operation in the logarithmic mode. This issue is due to the nonlinearity of the transistors which limits the build-up of the oscillation and modifies the behavior of the SRO where the relation between the input and the output pulse is no longer linear. Another circuit issue is the deviation from central frequency. This issue is due to the mismatch in the passive elements of the resonant circuit (selective network). Any deviation in the resonance frequency of the SRO and the central frequency of the incoming input pulse leads to degradation in the SNR and more BER. We handle the issues related to the system level. This can be shown in the hangover phenomena and synchronization between input impulse and sensitivity function.

Hangover phenomena: It is very important to kill the oscillation before the arrival of the next RF pulse to make the output oscillation in the next quench period built from only the injected RF pulse energy and not from the remnant of the previous one (Lee and Chandrakasan, 2007), otherwise this will increase the probability of error in detection. This issue can be fixed by shifting the sinusoidal damping factor by a positive DC value ζ_{dc} that increases the positive portion of the quench signal giving enough time and enough damping ratio to kill the oscillation. From (Lee and Chandrakasan, 2006) the DC shift can be calculated from the following relation:

$$\zeta_{dc} \geq \frac{f_q}{\omega_o} \ln \frac{1}{h} \tag{12}$$

Equation 12 introduced a new parameter which is the hangover coefficient h and this value should be less than 1% to guarantee a complete elimination of oscillation.

Adding the DC component to the quench signal causes a change to the instantaneous zero crossing slope of the quench signal which leads to a change in the bandwidth of the SRO as shown in Fig. 9. This change can be negligible for a large value of ζ_{ac} while keeping the hangover coefficient h small. This is because ζ_{dc} will be small and negligible compared to ζ_{ac}. Avoiding a large value of h is something essential as it must be guaranteed that ζ_{ac} is greater than ζ_{dc} otherwise damping factor will be always a positive value keeping the SRO always in the stable state.

From stand point of gain, adding ζ_{dc} causes degradation in the super-regenerative gain since the negative half cycle of the damping factor which represents the unstable state will decrease. Figure 10 show the dependence of the SRO gain (K_r K_s K_O) on the hangover coefficient h.

Synchronization issue and proposed architecture: Recall from section I, the influence of the input signal is very small outside the sensitivity function. This is due to the regenerative gain that indicates how much both the input

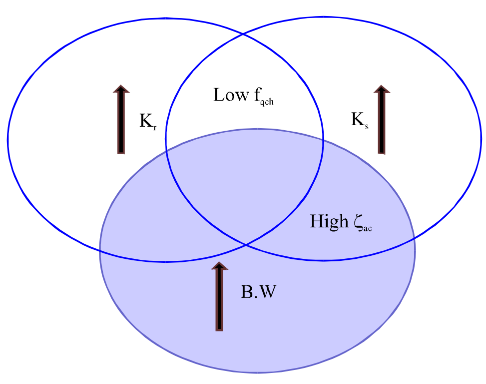

Fig. 8: Tradeoff between gain and BW

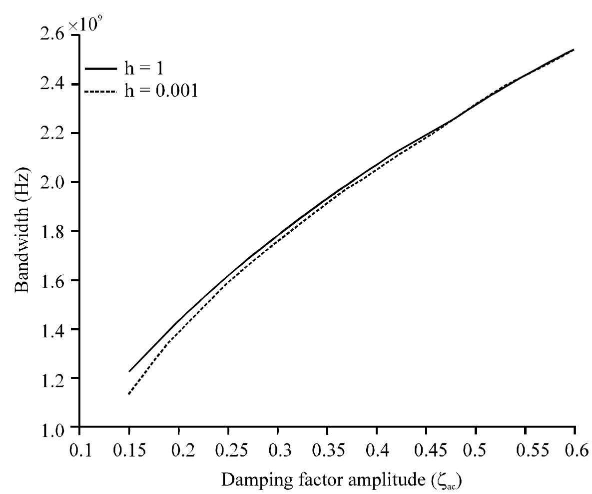

Fig. 9: Effect of adding ζ_{dc} on the BW (f_q = 250 MHz)

RF pulse envelop and the sensitivity function envelop are overlapped. The larger the overlapping the higher the regenerative gain in particular and the higher the overall gain in general since the gain is $K_r\, K_s\, K_O$.

Figure 11 shows the gain degradation with respect to the percentage of deviation from the peak of sensitivity curve envelop which is the zero crossing of the quench signal.

Much architectures have been implemented with the aid of Phase-Locked Loop (PLL) to adjust synchronization (Moncunill-Geniz *et al*., 2005b, c). This work proposed a novel architecture with the aid of digital circuits which is presented in Fig. 12. The idea is based on choosing a certain threshold of the gain to be dropped and finding the corresponding deviation time shift **δ**. In this design a -1 dB gain degradation was chosen. Synchronization is achieved by delaying the quench signal in each cycle by **δ**, as long as the output envelop is less than a reference value V_{ref} which corresponds to the intended amplified version of the input signal with a gain greater than the threshold value, a counter is incremented to add more delta steps to the quench signal. This process continues till both envelops reach the locked condition which doesn't mean a perfect synchronization but at least the phase shift between both envelops is constant during all quench cycles within the accepted gain error. Once the locked condition is achieved the feedback loop is disengaged and the receiver starts to detect the data. This suggested architecture requires sending a training sequence of impulses before the data to be processed, in order to fulfill the locked condition.

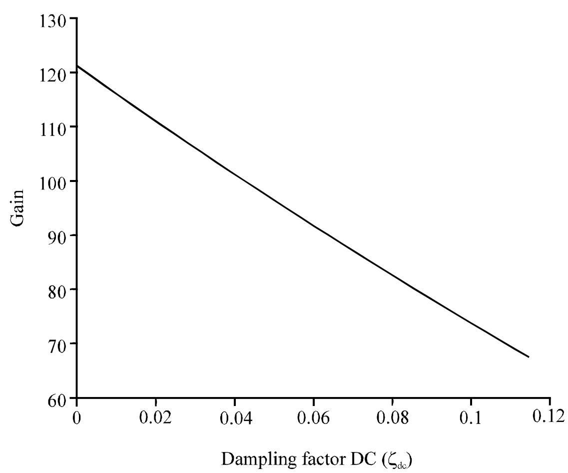

Fig. 10: Gain degradation due to ζ_{dc} (ζ_{ac} = 0.375 ζ_O = 0.0025 f_q = 250 MHz)

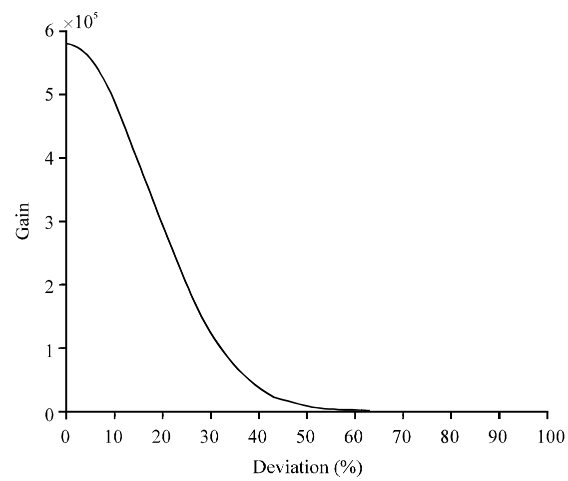

Fig. 11: Gain degradation with respect to the deviation of sensitivity curve from the peak of pulse envelop (ζ_{ac} = 0.375 ζ_O = 0.0025 f_q = 250 MHz ζ_{dc} = 0)

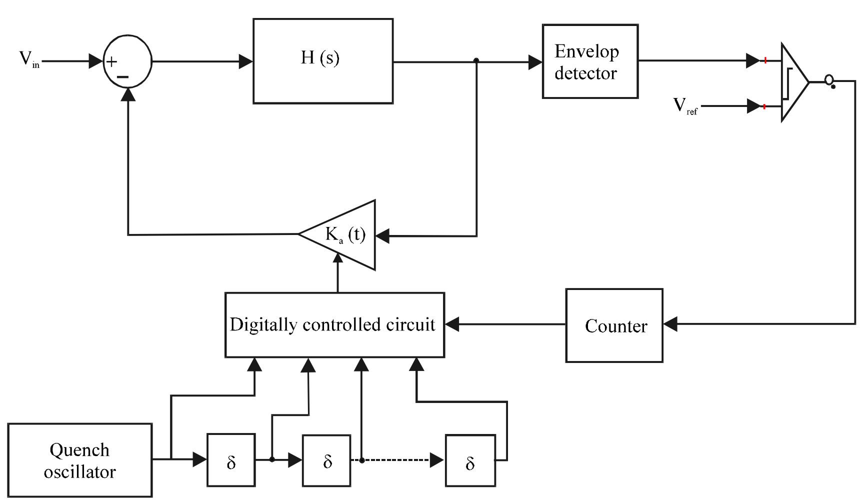

Fig. 12: Proposed system architecture

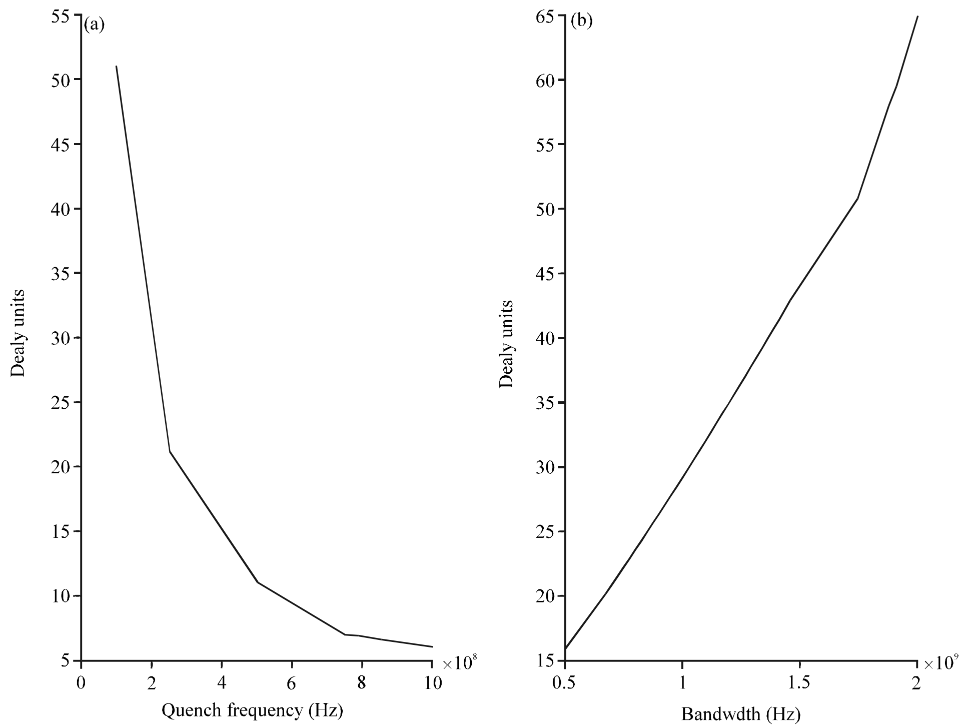

Fig. 13(a-b): Dependence of the number of delay units on (a) f_q and (b) BW

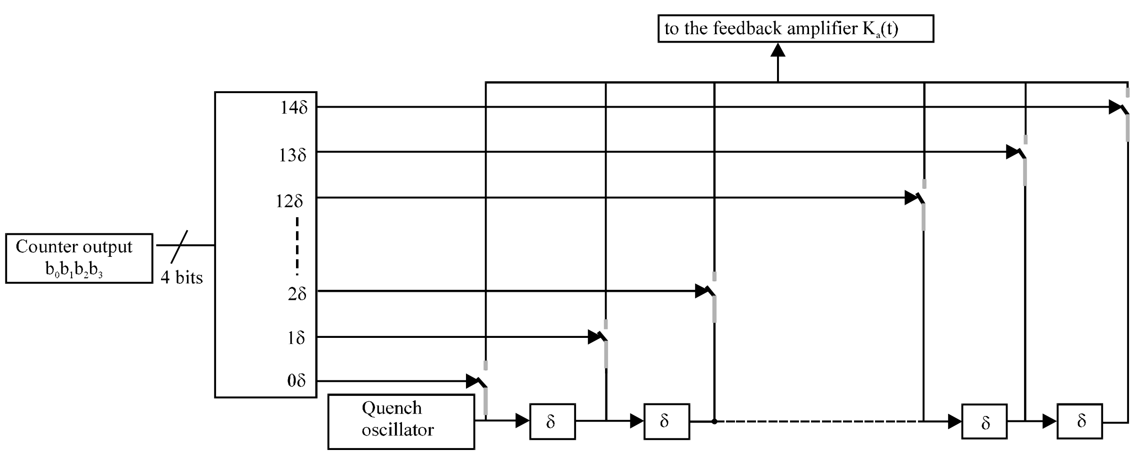

Fig. 14: Block diagram that illustrates the switching mechanism between different versions of quench signal

A new issue arises here concerning the number of delay units N_d used in the architecture. Since, the summation of all deltas δ must cover the entire quench, this leads to a dependence of the delay units N_d on the bandwidth and the quench frequency where:

$$N_d \propto \frac{BW}{f_q} \tag{13}$$

Equation 13 shows that in order to increase the BW for a fixed quench frequency f_q, a large number of delay units N_d is required. This is due to the shrinkage of the sensitivity curve. Also for a fixed BW, low f_q value requires increasing the delay units, since the quench period is increased. The dependence of N_d on the bandwidth and f_q can be shown in Fig. 13.

Switching between different versions of quench signal is achieved through digitally controlled switches. Figure 14 shows the proposed architecture of 14 delay units that perform this task in this design. A bank of AND gates as shown in Fig. 14. Figure 15 is designed in such a way to connect the intended version of the quench signal

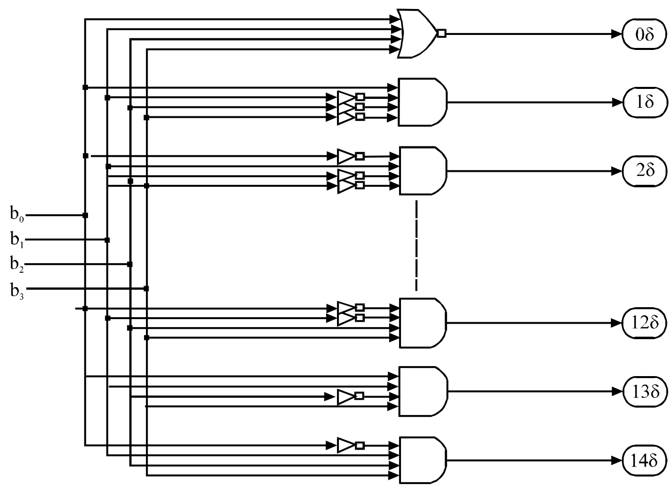

Fig. 15: Block diagram of the digital gates that control the switches

Table 2: Parameters of the SRO in the application example

Parameter	Numerical value
Peak damping value (ζ_{ac})	0.1500
Hangover coefficient (h)	0.0010
DC damping factor (ζ_{dc})	0.0573
Selective network damping factor (ζ_O)	0.0250
Selective network gain (K_O)	1.0000
Peak gain for perfect synchronization ($K = K_r, K_S, K_O$)	8.3800
-10 dB bandwidth (GHz)	1.1300
-1 dB gain degradation	7.5700

according to the counter output where 0000 corresponds to a zero phase shift (or zero delta is added) while 0110 corresponds to 6×δ of time shift addition the quench signal.

Example on super-regenerative oscillator at 4.8 GHz and quench frequency of 250 MHz: A model has been built to verify the dynamic behavior of the proposed architecture. At -1 dB gain degradation, a delta δ of 0.278 ns is calculated and the number of delay units N_d required is 14,388. It is better to round up the number to be 15 delay units to fulfill lower gain degradation and the new delta will be 0.266 ns. The input RF signal is a sinusoidal signal filtered by a Gaussian window of a spreading factor τ equals to 0.58 nsec which corresponds to -10 dB bandwidth of 1.13 GHz and the amplitude of the input signal is 1 V peak. The parameters of the super-regenerative oscillator are summarized in Table 2.

Considering perfect synchronization and to achieve the peak gain of 8.38 a time shift of 5.6×δ is required which is inapplicable as an output of the counter. According to this analysis, count number 5 and 6 are expected to fall within the allowable gain degradation which is greater than 7.5 at the locked condition. Figure 16 shows the dynamic behavior of the proposed architecture. In each quench period the quench signal is delayed a delta causing a change in the output envelop reaching its maximum at counts 5 and 6 which achieve the locked condition. At this point, the feedback loop should be disconnected but that was not the case in this example since the analysis is carried out to observe the degradation of the output envelop across all versions of quench signal.

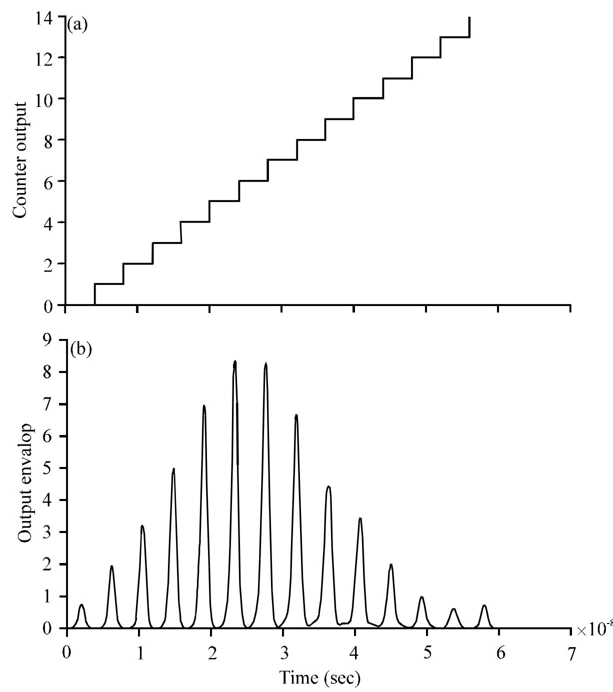

Fig. 16(a-b): (a) Counter output and (b) The output envelops for different delayed version of quench signal

CONCLUSION

This study presented a behavioral modeling on super-regenerative oscillator and introduced the parameters that affect the gain and BW of the super-regenerative oscillator. Parameter optimization is carried to suit the SRO for UWB signal; reaching a conclusion that to achieve that (high gain and large BW) the amplitude of the sinusoidal damping factor ζ_{ac} should be increased. A trade-off between the gain as well as the BW and DC damping factor ζ_{dc} has been described, where a certain value of ζ_{dc} is required for negligible hangover. Finally synchronization between the input pulse and sensitivity function envelops is handled and the analysis showed that any miss synchronization leads to a dramatic gain degradation. Absolute synchronization couldn't be achieved in our proposed architecture, however, the time shift between the input pulse and sensitivity function envelops is fixed across all cycles achieving the locked condition.

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