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Design and Implementation of Low Power CMOS Super-Regenerative Receiver

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Abstract: *A low power and low-voltage super-regenerative receiver operating at 60 GHz and implemented in 180-nm CMOS technology is described. The receiver includes a low noise amplifier, a super-regenerative oscillator, an envelope detector. The receiver uses the simplicity and power efficiency architecture for short-range communication. The power consumption of super-regenerative receiver is 2.194-mW at supply voltage of 1 V.*

Keywords: *CMOS*, *Low noise amplifier, Super-regenerative Oscillator, Low power, ON-OFF keying modulation, CADENCE Virtuoso.*

1. INTRODUCTION

Super-regenerative receivers (SRR) have been used for many decades, after invented by Edwin Armstrong in 1922 [1].This type of receiver holds the edge in high gain, simplicity, low cost, low power consumption and small size area. Hence, the SRR architecture has more attractive to short-distance micro-power communications, comparing to classical solutions, such as the super-heterodyne, the low intermediate or direct conversion receivers.

The unlicensed 60 GHz millimeter-wave band has the potential for short-range applications such as the wireless data transfer between hard disks, storage devices, MP3 players and high definition video receivers. In this paper, we demonstrated a high data rate ON-OFF keying (OOK) modulation super-regenerative receiver at 60 GHz using the 180-nm CMOS technology. The 180-nm low power CMOS provides 1P9M process and exhibits a unit current gain frequency of (f_t) 150 GHz and a maximum oscillator frequency (f_{max}) of 150 GHz. The approach is based on the basic SRR configuration while using a half power reduction oscillator as the SRO [5]. This current-reuse LC-VCO was used to get low phase noise and low power consumption. The proposed receiver was a realistic configuration for short-distance communication applications.

Figure 1 depicts the typical block diagram of super-regenerative receiver including super-regenerative oscillator (SRO) and Low noise amplifier (LNA) [2]-[4]. The core of the diagram is the super-regenerative oscillator which is controlled by a low frequency quench oscillator. The quench oscillator is controlling the loop gain of the SRO and then making the closed-loop system alternatively stable and unstable. Therefore, the SRO periodically starts up and shuts off which is called "quenching". The primary function of LNA is reduced the RF leakage of the oscillation signal and provided an input matching network to the antenna. In normal operation, incoming RF signal is amplified by the LNA, and then directly injected onto the oscillatory nodes of the SRO. The presence of LNA can improve overall system performance in terms of noise.

2. BASIC THEORY OF SUPER-REGENERATION

Super-regeneration is best understood by studying the parallel resonant tank which forms the core of a resonant oscillator, as shown if Fig. 2. The resonant tank consist of an inductor *L*, a capacitor *C*, and a shunt conductance G_+ - G_-. Here G_+ represents the parasitic loss of the resonant circuit while -G_- represents the negative conductance provided by active devices. The active devices compensate for loss in the tank, and the overall conductance $G = G_+ - G_-$ can be either positive or negative depending on the energy supplied by the active devices. An injected input signal is modelled by a sinusoidal current source $A\sin(wt)$.

Summing the currents in Fig. 2, we have

$$C\frac{dv}{dt} + GV + \frac{1}{L}\int V\,dt = A\sin(wt)\,. \qquad (1)$$

Solving for *V*, the complete solution of the voltage across the tank can be written as

$$V = e^{-\propto t}\left(K_1 e^{jw_d t} + K_2 e^{-jw_d t}\right) + \frac{A\sin\,(wt + \emptyset)}{\sqrt{G^2 + (wC - 1/wL)^2}} \qquad (2)$$

Where the damping factor, $\propto = G/2C$, is directly proportional to the conductance *G* and the damping frequency,

$$w_d = \sqrt{\left(\frac{1}{LC}\right) - \left(\frac{G}{2C}\right)^2} = \sqrt{(w_0^2 - \propto^2}$$

The first term in (2) is a transient oscillation at frequency w_d with the damping factor $\propto$, representing the free response, and does not depend on the injected signal. If *G* is positive, the active device does not provide enough energy to compensate for all the loss in the tank so that the free oscillation dies out and only for second term, which represents the forced response to the injected signal, remains. On the other hand, if *G* is negative, the active device provides more energy than is dissipated in the resonant circuit, building up a free oscillation from an initial voltage. This special case is termed *super-regeneration*.

In order to detect the injected signal, we first make the conductance *G* positive, letting the free oscillation die out, and then change the conductance *G* from positive to negative. Thus, the initial voltage, at the moment that the total conductance turns negative, is solely determined by the forced response (i.e., the second term of (2)), which is proportional to the strength of the injected signal. Since the free oscillation begins from an initial voltage and its amplitude tends to grow towards infinity, this is a very effective way to achieve amplification. Once a free oscillation starts, the oscillation amplitude tends to grow regardless of the injected signal, and therefore to amplify and detect any subsequent input samples, it is necessary to reset any oscillation by periodically alternating the total conductance from negative to positive. Since an LC tank always has a certain positive conductance due to loss (i.e.,G_+), we only have to control the negative conductance $-G_-$ to vary the sign and value of the overall conductance. The value of the negative conductance is controlled by the quench signal. The rate at which we alternate the total conductance is called the *quench frequency.*

From the above discussion, we can draw the following conclusions.

1) Amplification is achieved through the reinforcement of the free oscillation and this growth in oscillation amplitude requires time to build up. In order to achieve a larger gain, (represented by $e^{-\propto t}$ in (2)), we either have to spend more time operating in super-regeneration or increase by increasing the absolute value of the negative conductance.
2) The initial voltage of the free oscillation is proportional to the strength of the injected signal. Thus, it is straightforward to use super-regeneration to detect amplitude modulated (AM) signals.
3) The system does not continuously respond to the injected signal; it only responds as the conductance turns negative. Therefore, a super-regenerative receiver is a sampling system that samples the incoming RF signal with a sampling frequency equal to the quench frequency.

One major limitation of the super-regenerative technique is poor frequency selectivity, since an injected signal at any frequency might cause a free oscillation. However, since the free oscillation in super-regeneration starts with an amplitude determined by the forced response, which has a band-pass characteristic (second term in (2)), the system can inherently provide a band-pass frequency response. Without active devices, the quality factor of the resonant tank is

$$Q = \frac{1}{G_+}\frac{1}{\sqrt{L/C}} \qquad (3)$$

An on-chip LC tank normally has a quality factor of 10 or less and, therefore, offers poor frequency selectivity. However, we can significantly improve frequency selectivity through *Q* -enhancement. As shown in Fig. 3, *Q* -enhancement is achieved by using the negative conductance G_- to cancel some of the positive conductance G_+ , while keeping the overall conductance *G* positive. The resulting enhanced *Q* can be expressed as [6]

$$Q_{en} = \frac{1}{G_+ - G_-}\frac{1}{\sqrt{L/C}} \qquad (4)$$

In summary, we first operate the circuit as a *Q*-enhanced band-pass filter to select the band of interest. Next, we increase the negative conductance to achieve super-regeneration and amplify the selected signal. The initial condition for super-regeneration is set at the moment when the overall conductance turns negative. Therefore, by periodically controlling the negative conductance, operating the circuit first in the *Q*-enhanced mode and then in the super-regenerative mode, we detect the signal sampled at the quench frequency.

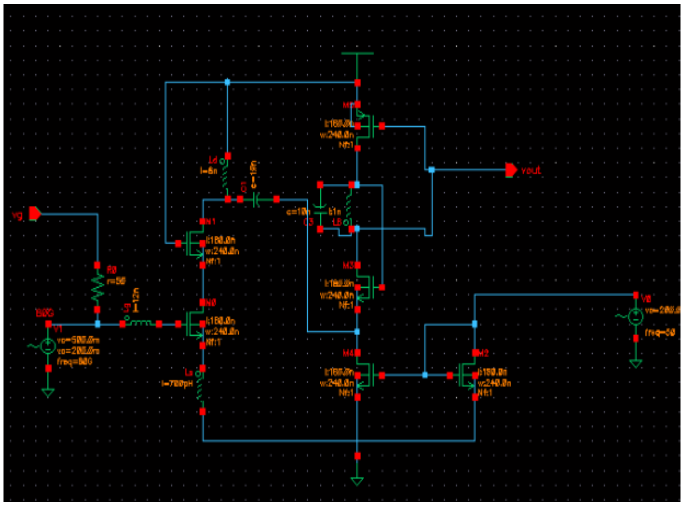


Fig. 1: Super-regenerative receiver block diagram and receiver circuit schematic [1].

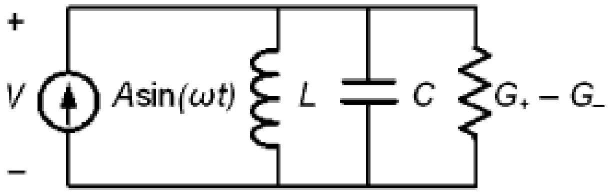


Fig. 2: Parallel resonant circuit representing an SRO [3]

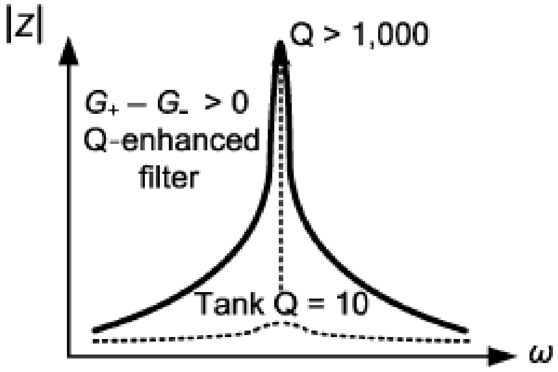


Fig. 3 Plot of impedance versus frequency with and without *Q*-enhancement [3].

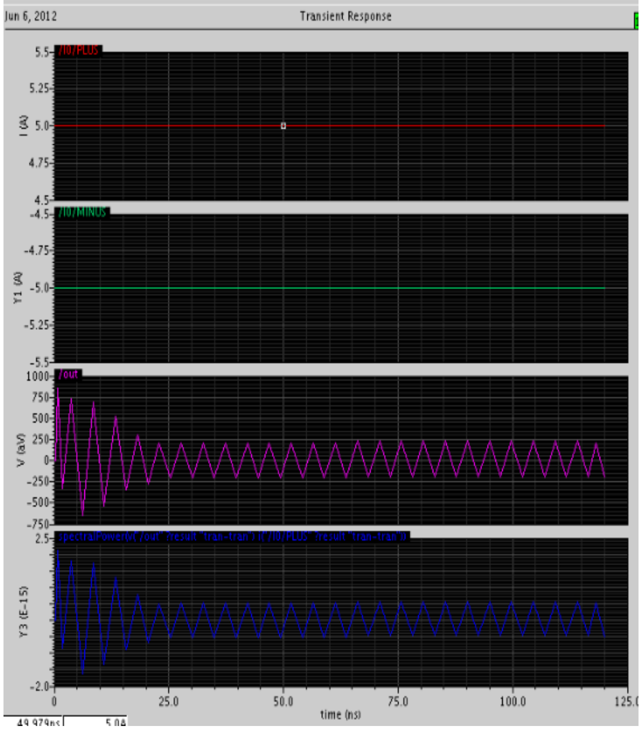


Fig. 4 Simulated Transient response and spectral power wave of SRO

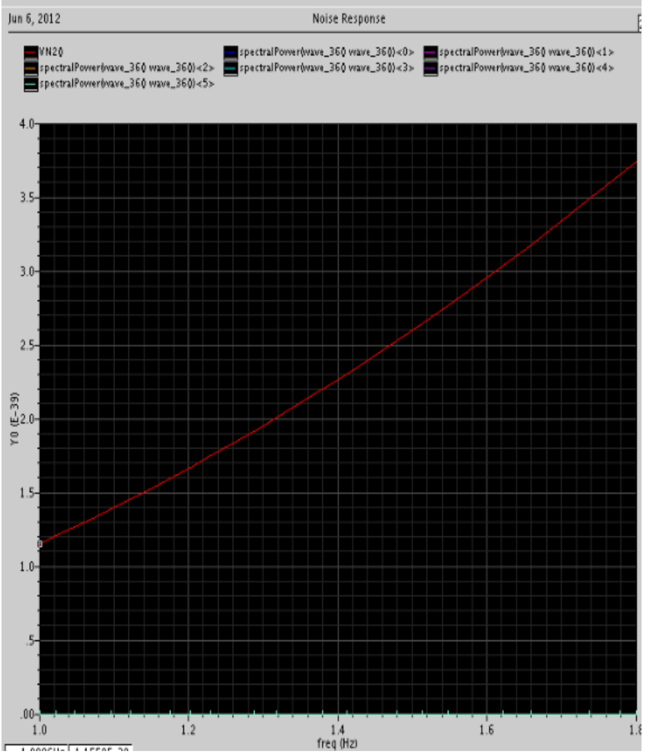


Fig. 5 Simulated Noise response of SRO

3. RECEIVER ARCHITECTURE

A. Super-regenerative Oscillator

The proposed SRO is based on the current-reuse differential LC oscillator which is first published in [5]. Figure 1 shows the circuit topology including an LC tank and two transistors M3 and M5. A 0.21 nH inductance and 9 fF capacitance are used in the tank and gate width of cross coupled pair are 180 µm and 240µm, respectively. Unlike the conventional VCO where the cross-coupled pairs switch alternatively, the transistors M3 and M5 switch on and off at the same time without common-source node. Therefore, this VCO is inherently immune to phase noise degradation causing by second harmonic terms. Moreover, the PMOS transistor M5 in the cross-connected pair helps to reduce the phase noise due to lower flicker noise and hot carrier effects [6]. Here, we used this topology and added a current source (consists of M4 an M2) which is modulated by the quench signal. The dc bias is 0.2 V while providing a 0.4 V peak-to-peak sinusoidal ac signal. Since threshold voltage of M2 is 405.5 mV, the tail current is directly modulated by the quench signals. The damping rate of the resonator is equal to the quench frequency. From the simulation results, the current source can be modulated up to 1 GHz. However, the describing 500 MHz data rate is a compromise between sensitivity and low current consumption.

B. Low Noise Amplifier

A cascode with source degenerated configuration is used in the LNA as shown in Figure 1. The LNA serves as a buffer between the antenna and oscillator. The input matching network is used to convert the impedance from antenna. In this case, we assumed a 50 ohms load at the input and the lumped elements L_G, L_S provide matching for optimum noise figure and impedance matching. Since the LNA is directly connected to oscillator, the output network (L_D and C_1) is a conjugate matching of the impedance looking into the oscillator. Moreover, the cascode configuration presents a high impedance to the oscillator preventing the load effect of the current source. Figure 6 shows the proposed test-bench of LNA,

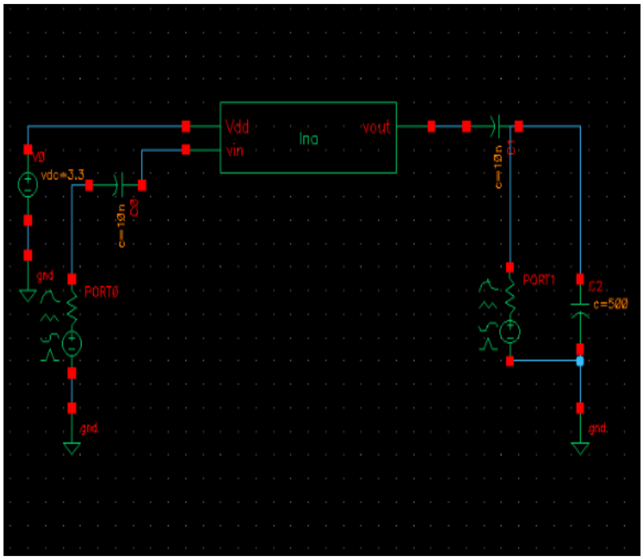


Fig. 6 Test-bench of LNA

It describe simulated parameter which are important in design and verification of LNA,s

Low-noise amplifier (LNA) is an electronic amplifier used to amplify possibly very weak signals (for example, captured by an antenna). It is usually located very close to the detection device to reduce losses in the feed-line. This active antenna arrangement is frequently used in microwave systems like GPS, because coaxial cable feed-line is very lossy at microwave frequencies, e.g. a loss of 10% coming from few meters of cable would cause a 10% degradation of the signal-to-noise ratio (SNR).

An LNA is a key component which is placed at the front-end of a radio receiver circuit. Per Friis' formula, the overall noise figure (NF) of the receiver's front-end is dominated by the first few stages (or even the first stage only). Using an LNA, the effect of noise from subsequent stages of the receive chain is reduced by the gain of the LNA, while the noise of the LNA itself is injected directly into the received signal. Thus, it is necessary for an LNA to boost the desired signal power while adding as little noise and distortion as possible, so that the retrieval of this signal is possible in the later stages in the system. A good LNA has a low NF (like 1dB), a large enough gain (like 20dB) and should have large enough inter-modulation and compression point (IP3 and P1dB). Further criteria are operating bandwidth, gain flatness, stability and input and output voltage standing wave ratio (VSWR).

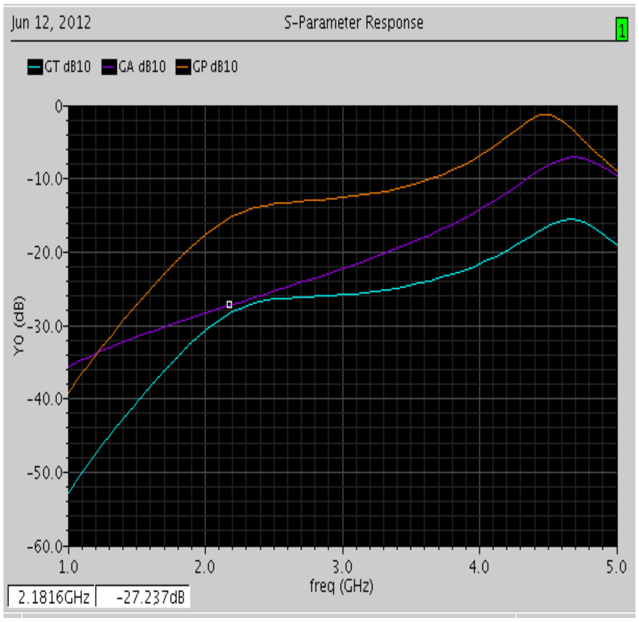


Fig. 7: Simulated LNA small-signal gain

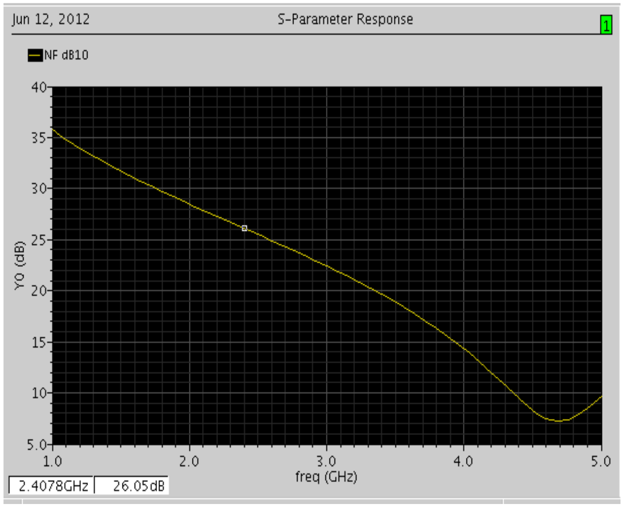


Fig. 8: LNA noise figure simulation result

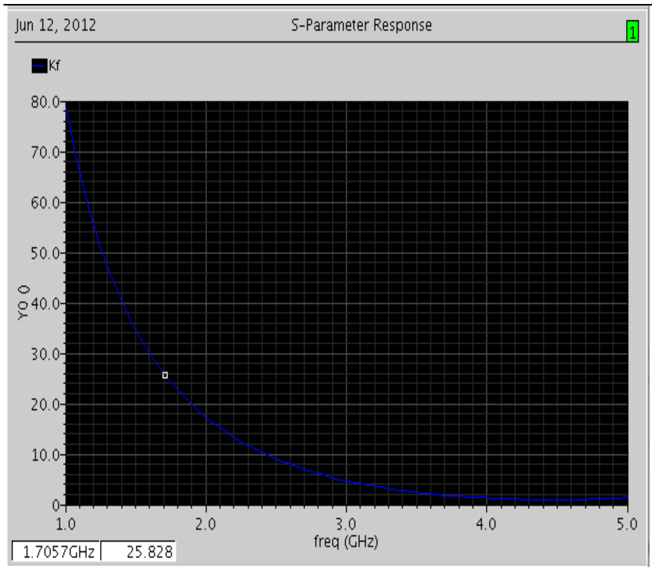


Fig. 9: LNA small signal stability simulation result.

Table I
Performance Comparison [1]

Reference	Technology (nm)	Frequency	DC Power (mW)
Tanomura [7]	CMOS 90	2.4 GHz	206
Sasaki [8]	CMOS 180	UBW	11
Zheng [9]	CMOS 180	UWB	137
Lee [10]	CMOS 90	UWB	35.8
This work	CMOS 180	60 GHz	2.194

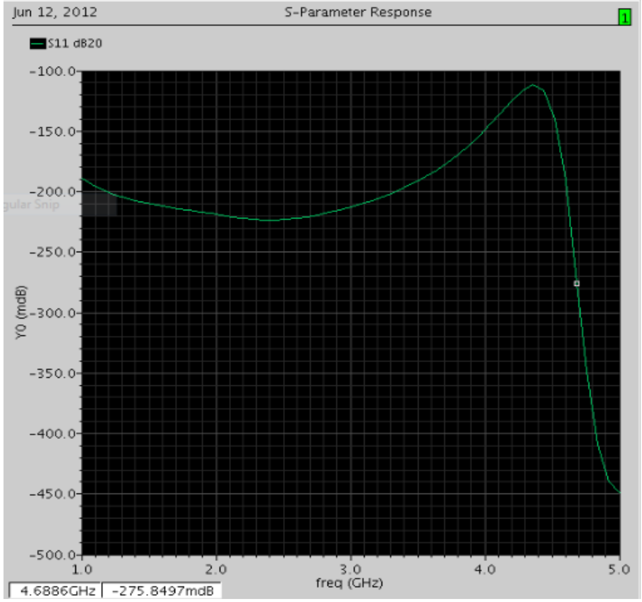


Fig. 10: LNA input port reflection coefficient simulation result.

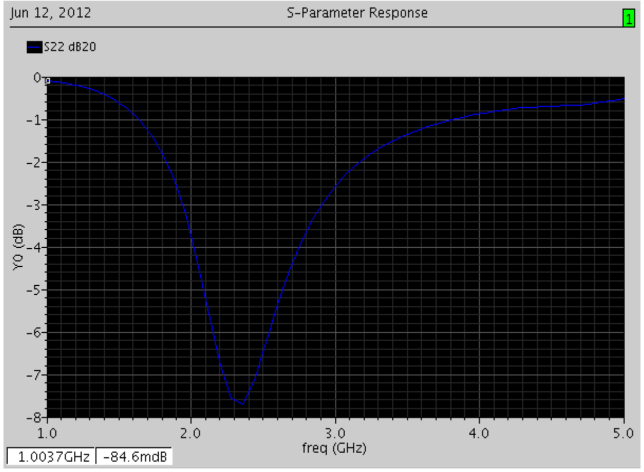


Fig. 11: LNA outport reflection coefficient simulation result

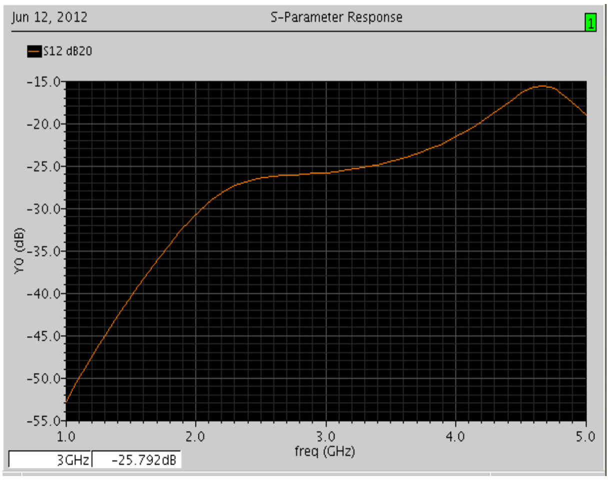


Fig. 12: LNA Reverse power gain simulation result

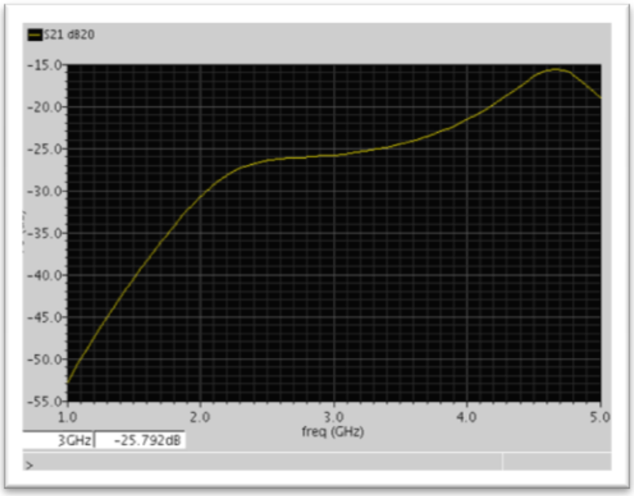


Fig. 13: LNA Forward power gain simulation result

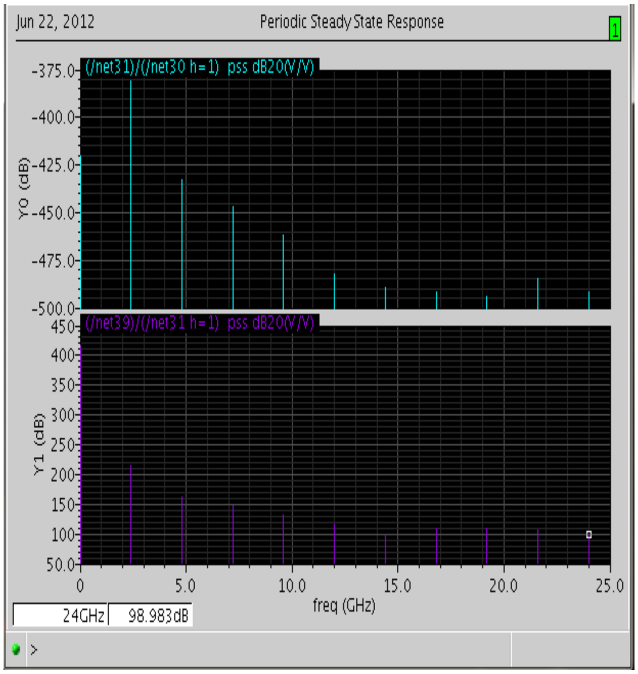


Fig. 14: LNA Voltage gain and Harmonic distortion simulation result

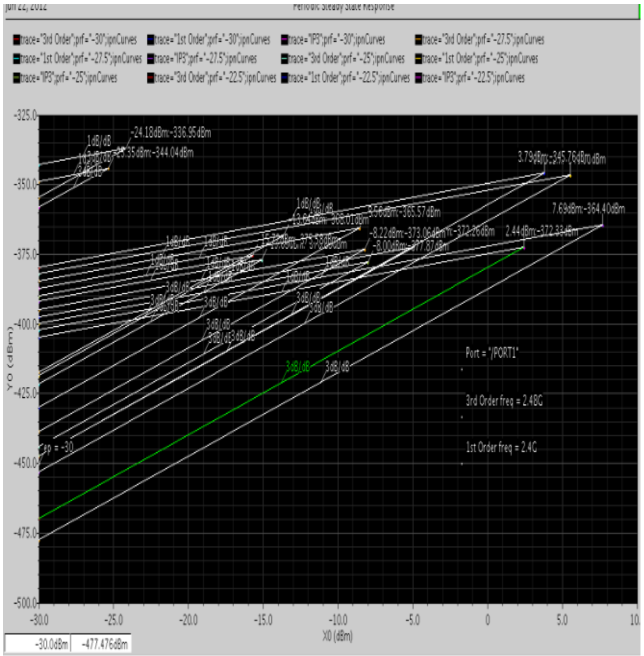


Fig. 15: LNA third-order intercept simulation result

Fig. 7 shows simulated LNA small-signal gain , there are three power gain are commonly used in LNA design. GT, Transducer power gain which is the ratio between the power delivered to the load and the power available from the source.

$$G_T = |S_{21}|^2 \qquad (5)$$

Second one is operating power gain, Gp is the ratio between the power delivered to the load and the power input to the network.

$$G_p = \frac{1}{1-|S_{11}|^2}|S_{21}|^2 \qquad (6)$$

And third one is available power gain, GA is the ratio between the power available from the network and the power from the source.

$$G_A = |S_{21}|^2 \frac{1}{1-|S_{22}|^2} \qquad (7)$$

Fig. 8 shows the LNA noise figure simulation result which is 7 dB at 4.7 GHz. Fig. 9 shows LNA small signal stability simulation result, Fig.10 and 11 shows LNA input and output port reflection coefficient simulation result respectively.

4. RECEIVER SIMULATION RESULTS

The simulated setup environment is according to the prototype receiver showing in Figure 1.

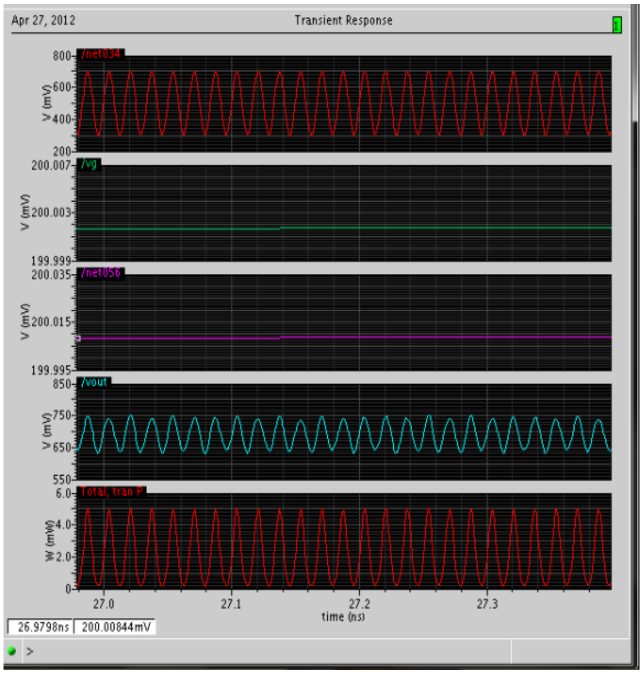
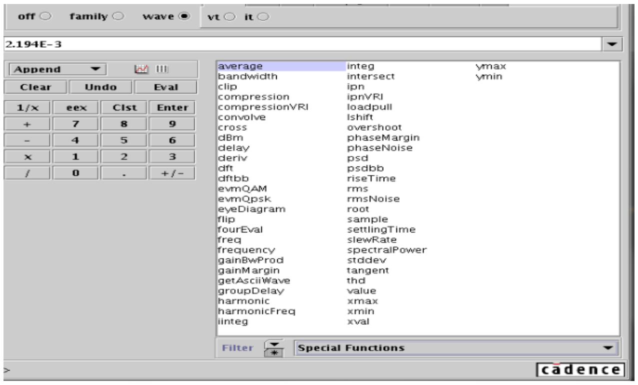


Fig. 16: Super-regenerative receiver output

Since the proposed receiver is an open loop architecture, the manual signal align is used for achieving higher data rate. Figure 15 illustrated the transient response of the super-regenerative receiver. The first waveform is a 12 MHz input signals with a 60 GHz carry frequency. The SOR was operated in a critical region as a detector. While SRO detects the sequent input signals then starts to damping. The second last is output waveform for baseband processor. After detecting from SRO, an ideal envelope detector is proposed to demodulate the data to the baseband.



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2.194E-3
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Fig. 17: Super-regenerative receiver DC Power simulation result

Figure 15 shows the DC Power of the super-regenerative receiver. Note that, in order to obtain a synchronous receiver providing the manual time delay (i.e 3.4 nano seconds) in simulation is need. However, the close loop receiver architecture is a general solution for achieving synchronous [3]- [4].The core of super-regenerative receiver is the SRO and SRO is a sensitive and a critical operation circuit. Therefore, the topology selection and operation knowledge of SRO are the key points in the super-regenerative receiver design. Table I summarizes the main features of the receiver [1].

5. CONCLSION

A high data rate low power CMOS super-regenerative receiver was proposed in this paper. The simple architecture was suitable for low-cost, low power and short-range wireless communication. In this work, we demonstrated a compatible low-power performance. The proposed receiver architecture can be operated at higher data rates in the simulation results. However, noise figure increases progressively 12 dBm due to the hangover limitations. The current design successfully simulated an unlicensed 60 GHz super-regenerative receiver with an excellent tradeoff between sensitivity, data rate and power consumption [1]. The receiver can be further realized in the future works.

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