Super-regenerative Receiver

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1 Introduction

The super-regenerative receiver operates on the direct conversion principle where an oscillator can perform RF detection. This resulted in a low component-count receiver. In comparison, the more commonly used super-heterodyne receiver operates by mixing the RF signal down to IF for demodulation. The performance is hence better but the tradeoff is a more complex receiver.

In 1922, Armstrong invented super-regenerative receiver architecture. However, super-regenerative receiver architecture was progressively abandoned followed his later invention of super-heterodyne receiver architecture, which give better selectivity and sensitivity performance.

Currently, super-regenerative receives implemented using discrete components are still being used in low cost application where performance is not critical. The advantages are: low power consumption, simple architecture, small silicon size and lower cost as external IF filter are not required. The disadvantages are: low data rate, only work on on-off keying, poor sensitivity and poor selectivity. Hence, it can only serve in niche application where performance is not critical.

Companies such as Telecontrolli and Mipot have products that using super-regenerative principle.

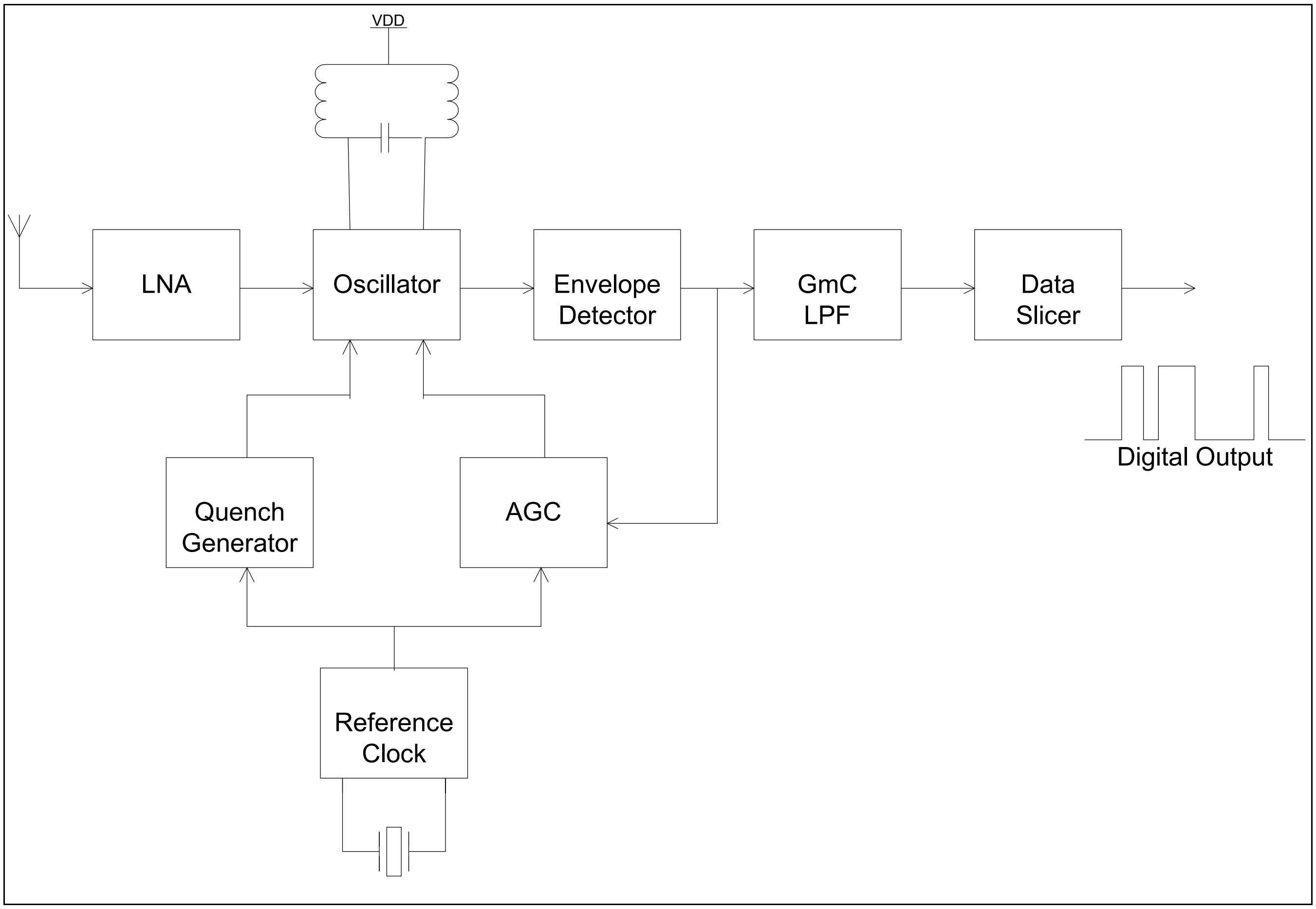
Literatures and papers on principle of super-regenerative receiver are rare. A search through IEEE explorer for the relevant papers resulted in less than 10 hits. The more relevant are: [1], [2] and [3]. There is only one book that devoured entirely to the principle of super-regenerative receiver [4].

The papers are very difficult to understand as lots of mathematical derivations and circuit details are hidden.

The principle of operation will not be explained in this report as this will require substantial amount of effort to re-produce lots of material into the report.

The purpose of the report is to understand the quench waveform on the performance of super-regenerative receiver. In the process, two analytical equations for linear mode of operation [4] will be compared to the result of circuit simulation.

2 Overview Of Super-regenerative Receiver



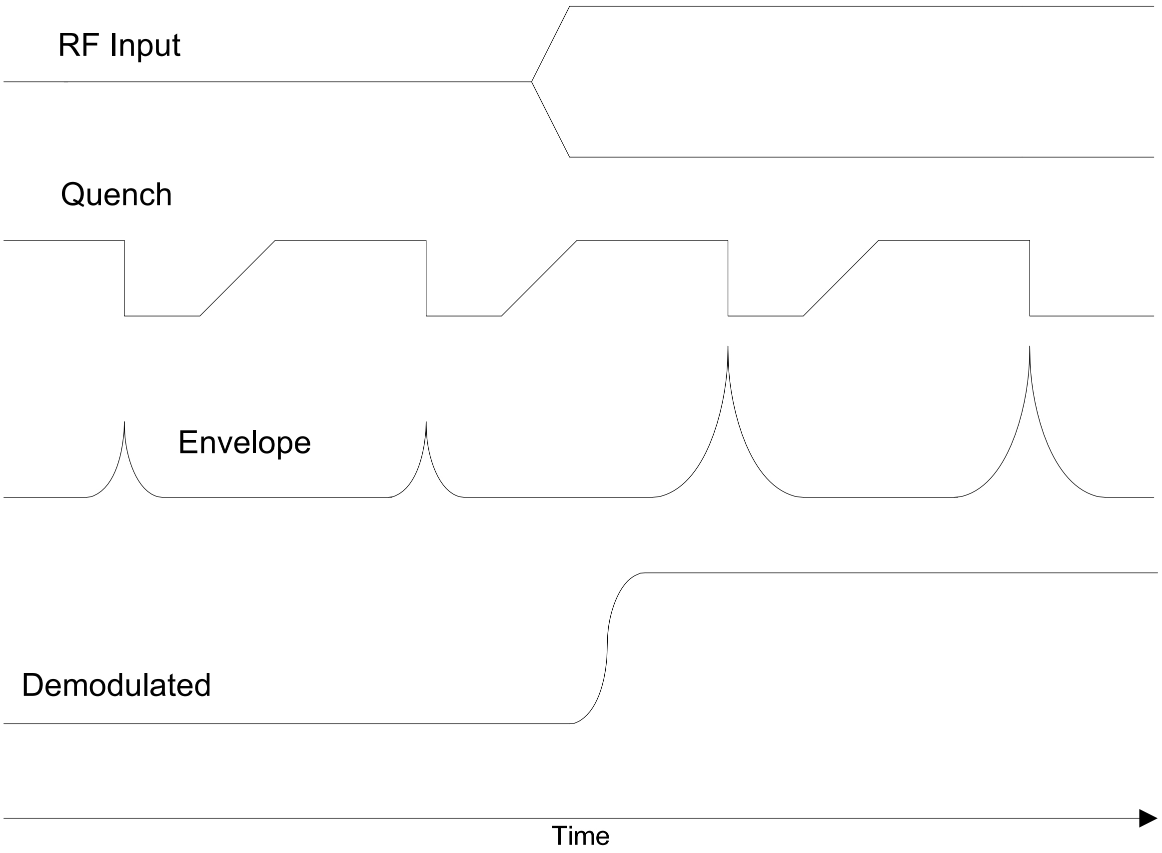
The LNA provides matching and gain for RF signal. It also provides reverse isolation to prevent the oscillation signal of oscillator from re-radiate to the air. Envelope detector extracts the envelope of the oscillation signal. After low pass filtering, data slicer produces the digital waveform.

The quench generator supplies the quench signal for the oscillator. Due to variation of temperature, supply voltage and processes, it is necessary to have an AGC to maintained the desired operating region of the receiver.

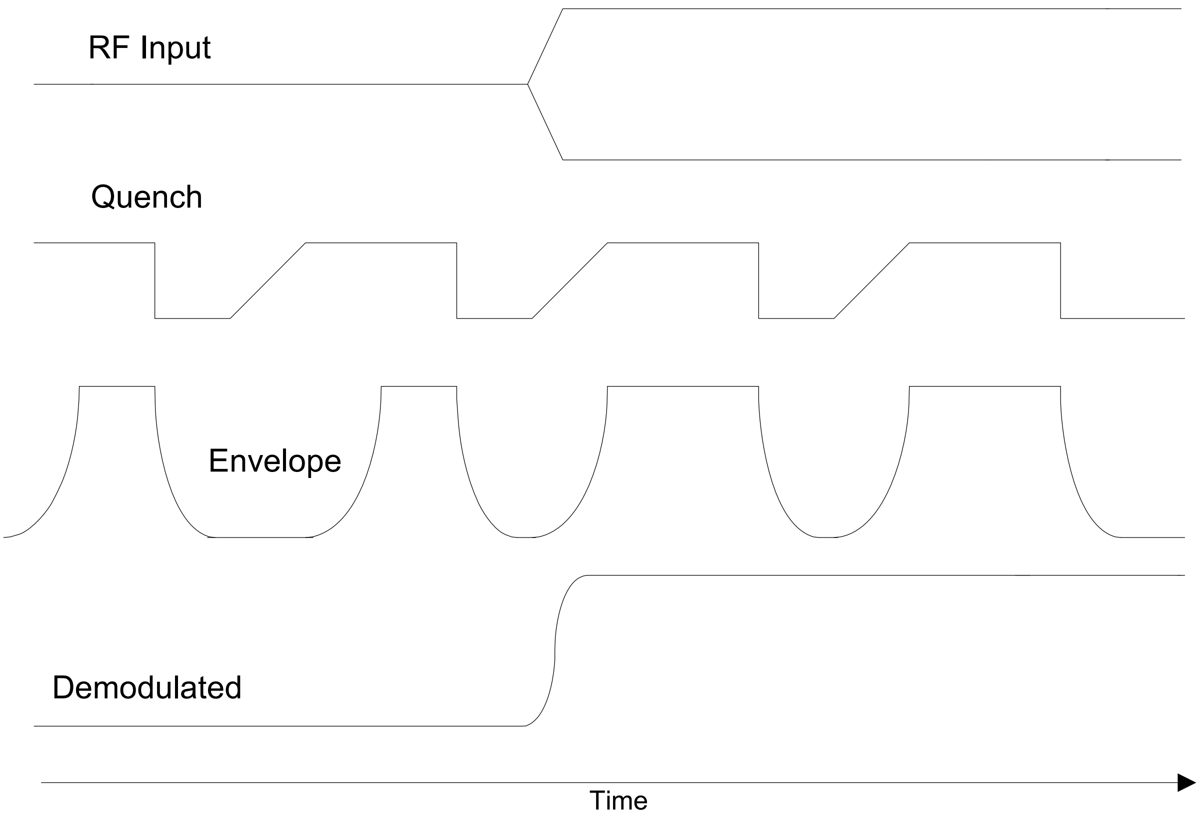
3 Mode Of Operation

Super-regenerative receiver has two modes of operation: linear and logarithmic.

The figure below shows the linear mode of operation. RF input is a 100% on-off keying signal. The quench signal showed is trapezoidal-shaped. Different quench waveform will give different performance tradeoff. Waveform such as rectangular, sine, saw-tooth are possible, though the resulting receiver performances have their own strengths and weaknesses.



Linear mode is characterized by linear relation between the amplitude of the RF input signal and the amplitude of the envelope. In this mode, the oscillator does not reach its steady-state during the quench period.

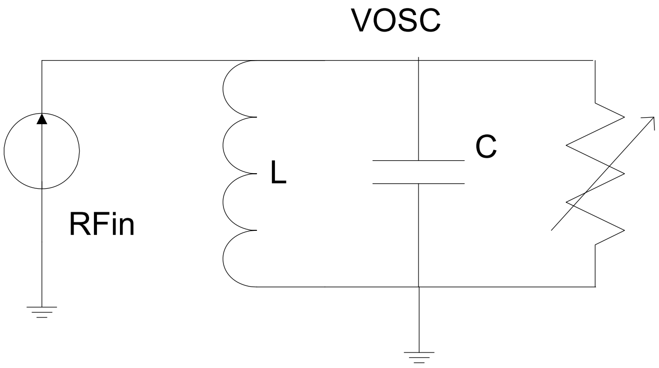


The figure above shows the logarithmic mode. The logarithmic mode is characterized by a logarithmic relation between the amplitude of the RF input signal and the amplitude of the demodulated output. In this mode, the oscillator reaches its steady-state amplitude at each quench cycle.

4 Quenching Signal

In [4], analytical equations are derived for two quenching signals: sine and square waveform. Note that these equations are meant for linear-mode only. Sine wave has a sloped zero-crossing whereas square wave has a step zero-crossing.

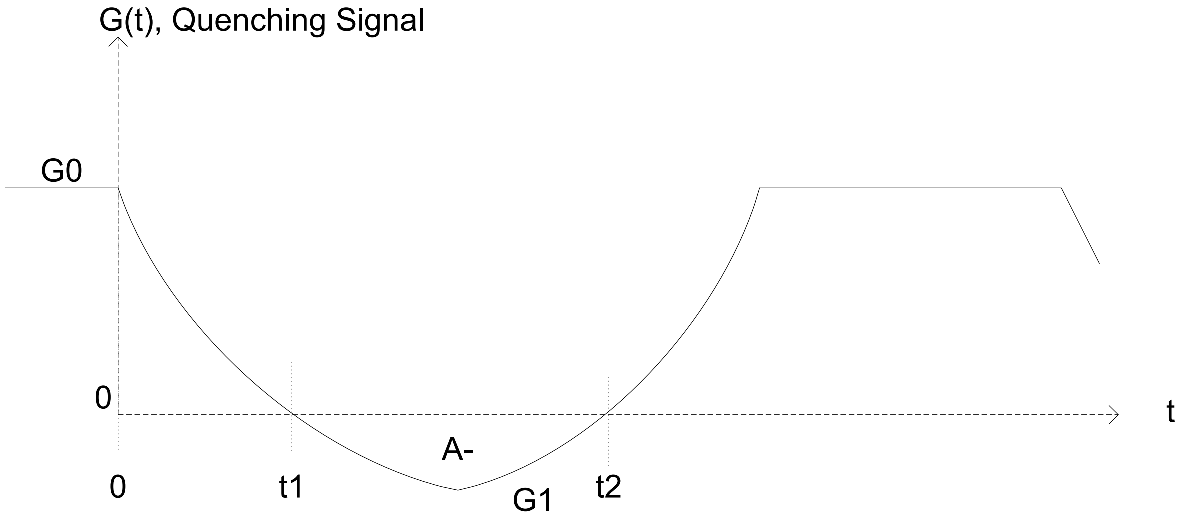
The core of the super-regenerative receiver is the oscillator, which can be represented as parallel combination of R, L and C in its simplest form. L and C act as the resonator or tank of the oscillator. G(t) represents the loss of the tank circuit and the negative conductance provided by active element. RFin is the RF signal represented as a current source.



When G(t) is positive, oscillation is not possible. When G(t) is negative, oscillation occurs.

The two equations are extracted and simplified for discussion.

When G(t) is a sine waveform, the equation is:

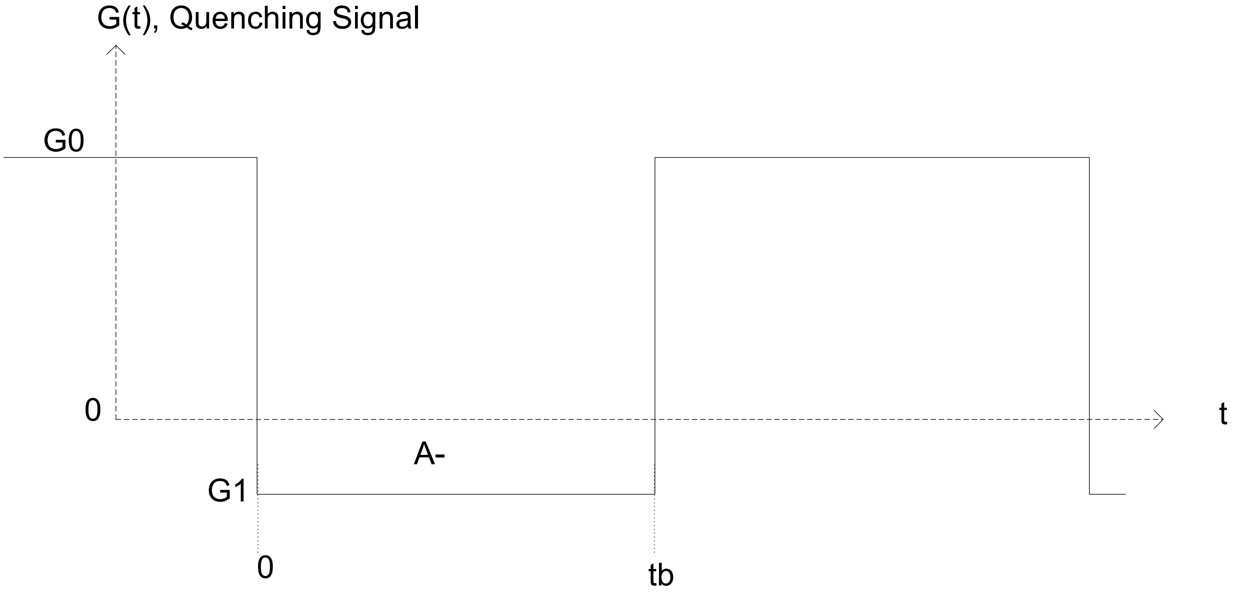


$$Vosc = Vrf * \mu o * \mu t * S * \sin[Wo * t + (W\text{-}Wo)t1]$$

Where:

Voltage Amplitude of RF input	Vrf = A/G0	A G0	Current Amplitude of RF input Conductance of Tank
Slope Gain	$\mu o = G0\sqrt{\frac{\pi}{C\lvert G'(t1)\rvert}}$	G'(t1)	Rate of Zero Cross of G(t) at t=t1
Super-regenerative Gain	$\mu t = e^{\frac{A-}{2C}}$	C A-	Capacitance of Tank Area of G(t) < 0
Total Gain	G = μo * μt		
Selectivity	$S = \frac{f}{fo} e^{\frac{-4\pi^2 C(f-fo)^2}{\lvert G'(t1)\rvert}}$	f fo	Input Frequency Tank Resonant Frequency

When G(t) is a square waveform, the equation is:



$$Vosc = Vrf * \mu o * \mu t * S * \sin[Wo * t]$$

Where:

Voltage Amplitude of RF input	Vrf = A/G0	A G0	Current Amplitude of RF input Conductance of Tank
Step Gain	$\mu o = \frac{G0 + \lvert G1 \rvert}{\lvert G1 \rvert}$	G1	Peak Negative Conductance
Super-regenerative Gain	$\mu t = e^{\frac{A-}{2C}}$	C A-	Capacitance of Tank Area of G(t) < 0
Total Gain	G = μo * μt		
Selectivity	S = $\frac{G0G1 / 4C^2}{\sqrt{(W - Wo)^2 + \left(\frac{G0}{2C}\right)^2}\sqrt{(W - Wo)^2 + \left(\frac{G1}{2C}\right)^2}}$	W Wo	=2πf =2πfo

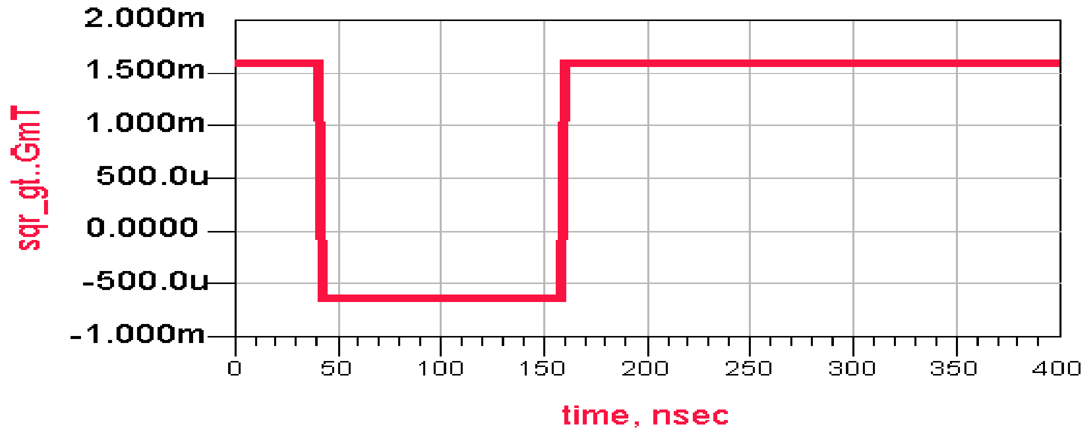
5 Comparison

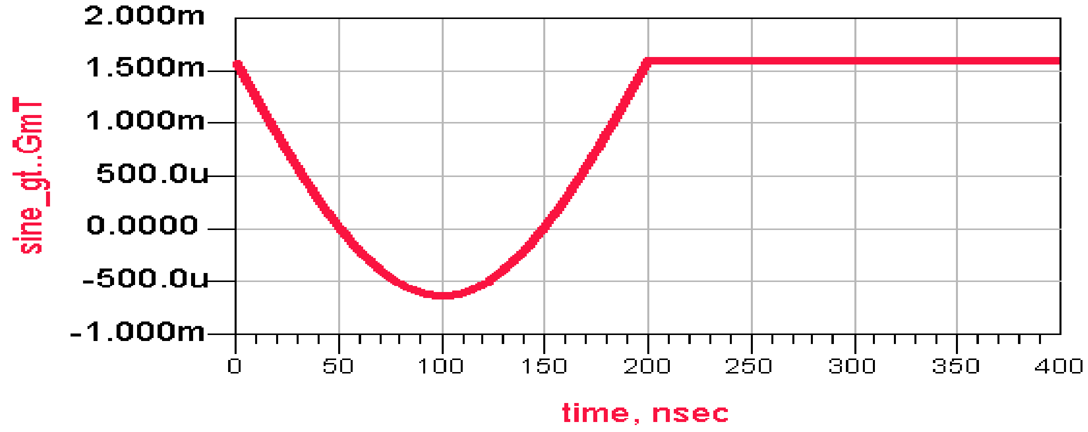
To compare performance of super-regenerative receiver in the linear mode, two quenching signals are generated for comparison.

The common circuit parameters are:

Parameter	Value	Remark
L	5nH	Inductor value
QL	20	Q factor of Inductor
Fo	1GHz	Tank resonation frequency
Fq	2.5MHz	Quenching frequency
A	1uA	Current amplitude of RF input

The two quenching signals are generated for comparison.





The parameters for sine quenching signal are:

Parameter	**Value**	**Remark**
G0	1.592m	Tank conductance
G'(t1)	-30	Zero-crossing rate of G(t) at t1
t1	44	Time of zero-crossing (positive-to-negative transition of G(t)).
t2	156	Time of zero-crossing (negative-to-positive transition of G(t)).
Aminu	67p	Area of G(t) <0

The parameters for square quenching signal are:

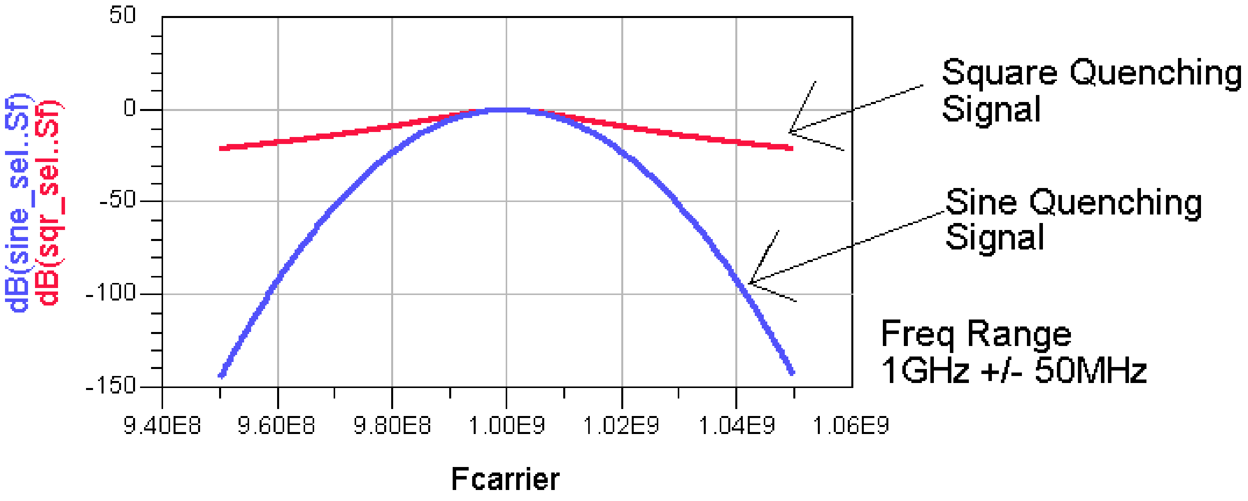
Parameter	**Value**	**Remark**
G0	1.592m	Tank conductance
G1	-638u	Peak negative conductance
Tb	114ns	Build up period
Aminu	75.34p	Area of G(t) <0

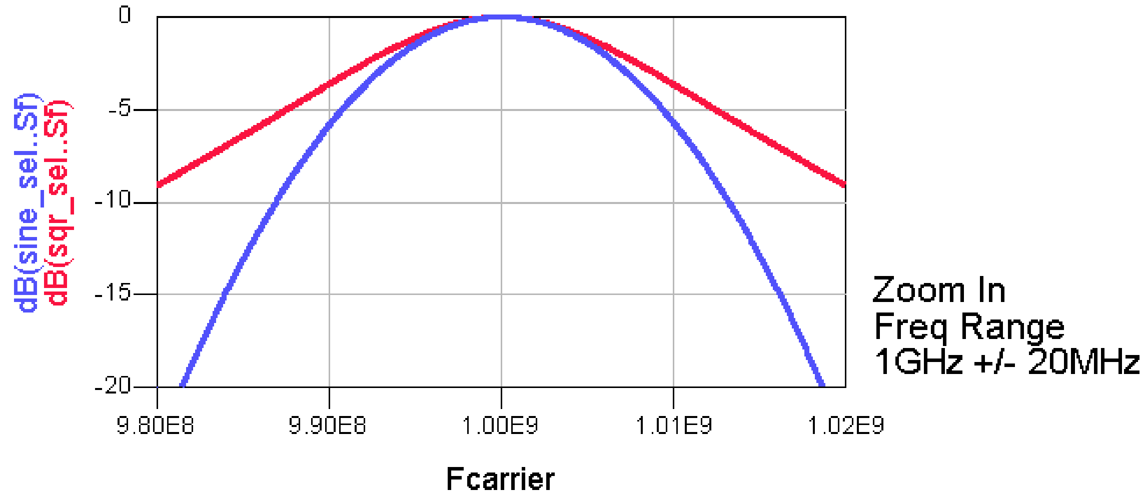
The respectively total gain (calculated using equations) of super-regenerative receiver using the two quenching signals is:

	Sine	Square
Total Gain	74.63dB	75.45dB

Note that the total gains are adjusted to almost equal for comparison.

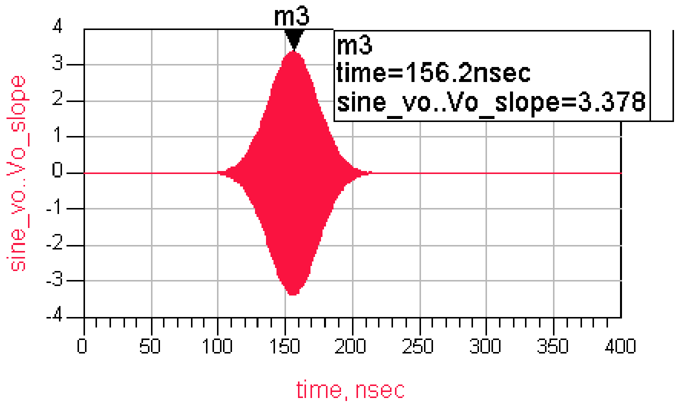
The selectivity are:

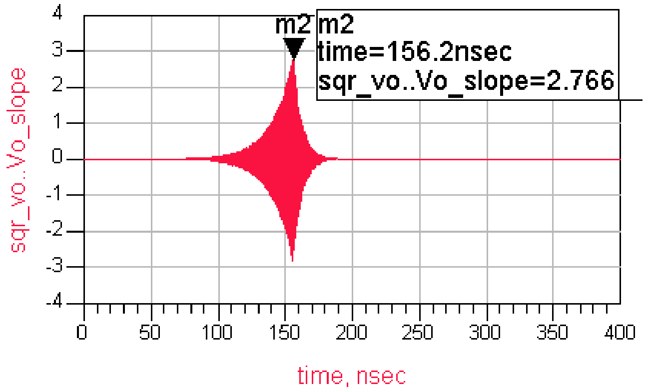


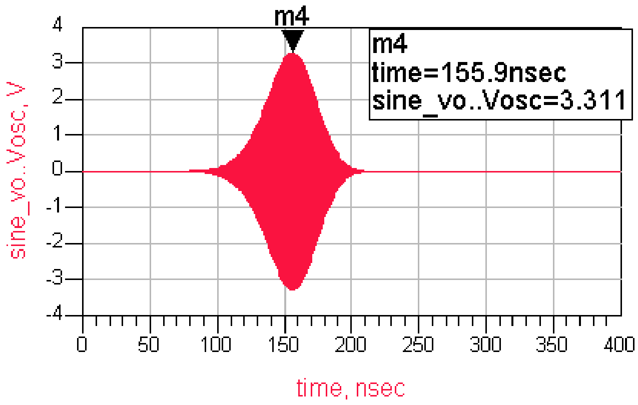


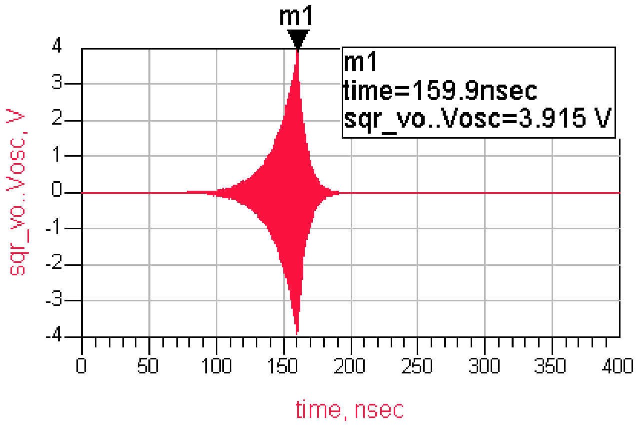
The result shows that sine quenching signal will have better selectivity. Hence to have good selectivity, the zero-crossing of G(t) must be sloped.

Next, the result of using equation and circuit simulation (time domain) are compared.









The Top-left plot is sine quenching signal using equation and Bottom-left plot is sine quenching signal using circuit simulation. The results are very closed with only 0.2dB of error.

The Top-right plot is square quenching signal using equation and Bottom-right plot is square quenching signal using circuit simulation. The results are reasonably closed with 3dB of error.

This confirms that the two equations are very accurate and circuit simulations are correctly done.

6 Conclusion

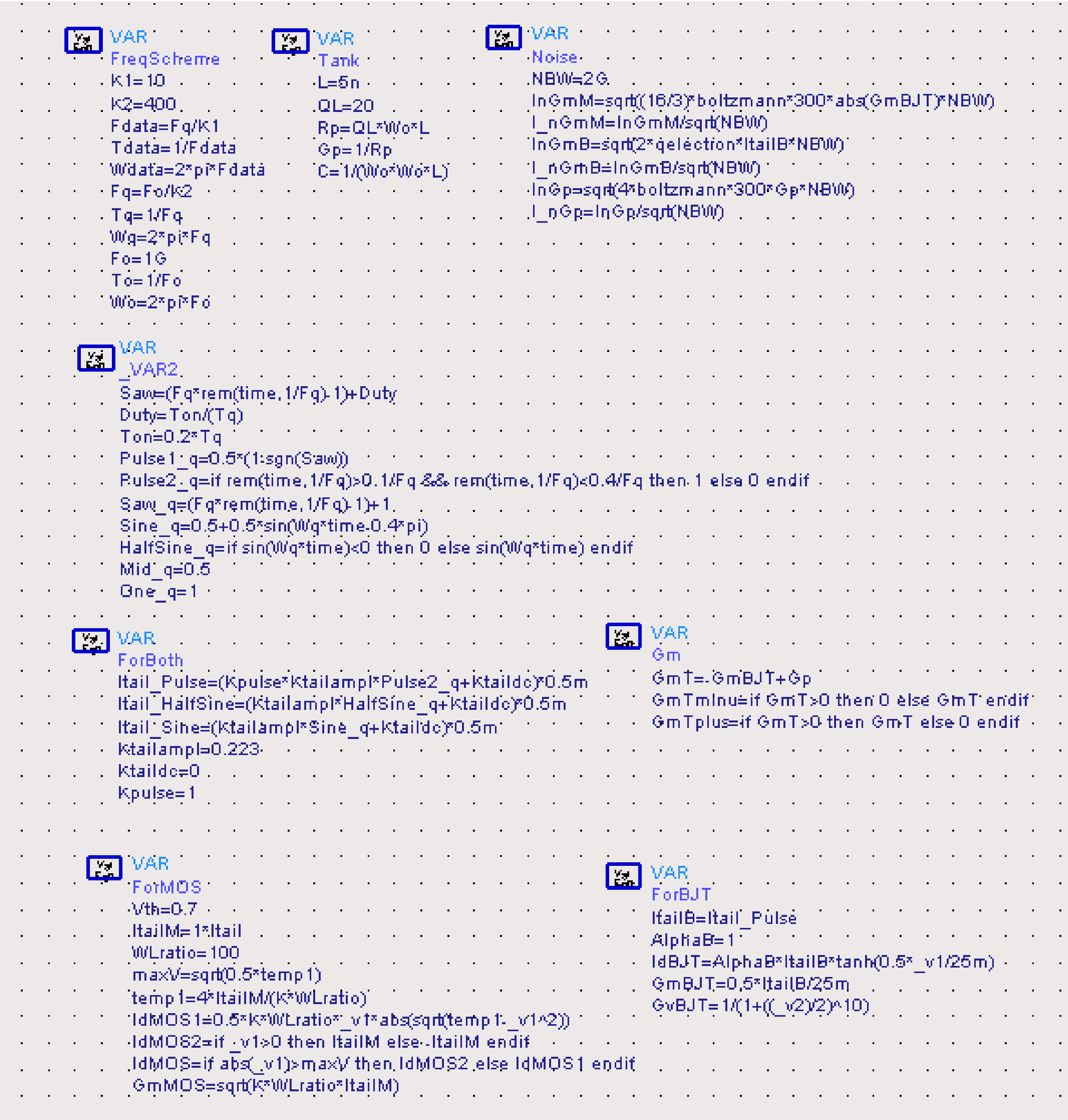
The validation of the two equations for linear-mode is done.

To carry on the work, the steps could be:

1. Perform circuit simulation using envelope simulator instead of transient simulator. Transient simulator is not possible for large circuit. Thus far, the elements used in the circuit simulation are only simple R, L and C. They are only four of them. With more elements, envelope simulator has to be used.
2. With envelope simulator, design the oscillator. Then investigate its performance for linear and logarithmic mode. Quenching signal generator must also be designed.
3. With the knowledge gained in step 2, studied the necessity of AGC and design it.

With those steps completed, the essential or the more difficult and uncertain part of the super-regenerative receiver design is completed.

7 Simulation Setup (ADS)



```
VAR
FreqScheme
K1=10
K2=400
Fdata=Fq/K1
Tdata=1/Fdata
Wdata=2*pi*Fdata
Fq=Fo/K2
Tq=1/Fq
Wq=2*pi*Fq
Fo=1G
To=1/Fo
Wo=2*pi*Fo
```

```
VAR
Tank
L=5n
QL=20
Rp=QL*Wo*L
Gp=1/Rp
C=1/(Wo*Wo*L)
```

```
VAR
Noise
NBW=2G
InGmM=sqrt((16/3)*boltzmann*300*abs(GmBJT)*NBW)
I_nGmM=InGmM/sqrt(NBW)
InGmB=sqrt(2*qelectron*ItailB*NBW)
I_nGmB=InGmB/sqrt(NBW)
InGp=sqrt(4*boltzmann*300*Gp*NBW)
I_nGp=InGp/sqrt(NBW)
```

```
VAR
_VAR2
Saw=(Fq*rem(time,1/Fq)-1)+Duty
Duty=Ton/(Tq)
Ton=0.2*Tq
Pulse1_q=0.5*(1-sgn(Saw))
Pulse2_q=if rem(time,1/Fq)>0.1/Fq && rem(time,1/Fq)<0.4/Fq then 1 else 0 endif
Saw_q=(Fq*rem(time,1/Fq)-1)+1
Sine_q=0.5+0.5*sin(Wq*time-0.4*pi)
HalfSine_q=if sin(Wq*time)<0 then 0 else sin(Wq*time) endif
Mid_q=0.5
One_q=1
```

```
VAR
ForBoth
Itail_Pulse=(Kpulse*Ktailampl*Pulse2_q+Ktaildc)*0.5m
Itail_HalfSine=(Ktailampl*HalfSine_q+Ktaildc)*0.5m
Itail_Sine=(Ktailampl*Sine_q+Ktaildc)*0.5m
Ktailampl=0.223
Ktaildc=0
Kpulse=1
```

```
VAR
Gm
GmT=-GmBJT+Gp
GmTminu=if GmT>0 then 0 else GmT endif
GmTplus=if GmT>0 then GmT else 0 endif
```

```
VAR
ForMOS
Vth=0.7
ItailM=1*Itail
WLratio=100
maxV=sqrt(0.5*temp1)
temp1=4*ItailM/(K*WLratio)
IdMOS1=0.5*K*WLratio*_v1*abs(sqrt(temp1-_v1^2))
IdMOS2=if _v1>0 then ItailM else -ItailM endif
IdMOS=if abs(_v1)>maxV then IdMOS2 else IdMOS1 endif
GmMOS=sqrt(K*WLratio*ItailM)
```

```
VAR
ForBJT
ItailB=Itail_Pulse
AlphaB=1
IdBJT=AlphaB*ItailB*tanh(0.5*_v1/25m)
GmBJT=0.5*ItailB/25m
GvBJT=1/(1+((_v2)/2)^10)
```

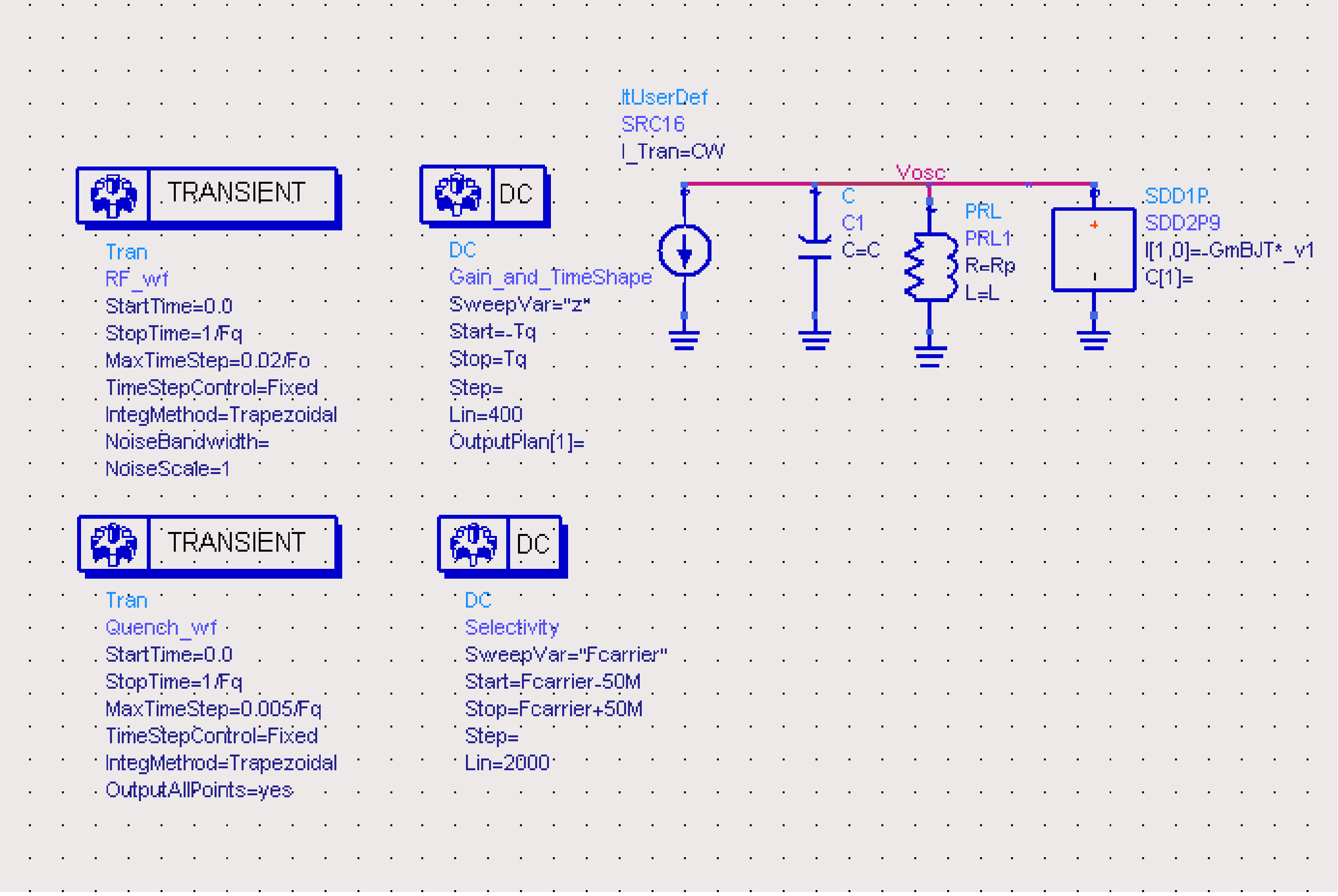
```
VAR
RFIN
AM=sin(Wdata*time) + (1/3)*sin(3*Wdata*time) + (1/5)*sin(5*Wdata*time) + (1/7)*sin(7*Wdata*time)
Fcarrier=1G
OOK1=(1+AM)*sin(2*pi*Fcarrier*time)
OOK2=if abs(OOK1)>0.5 then OOK1 else 0 endif
OOK=A*OOK2
CW=A*sin(2*pi*Fcarrier*time)
```

```
VAR
EitherSlope
t0=0
t1=44n
t2=156n
T1=t1-t0
T2=t2-t0
Greg=Go*sqrt(pi/(C*abs(Gpr_T1)))
Aminu=67p
Aplus=385p
Gsr=exp(Aminu/(2*C))
Gtot=Greg*Gsr
SHAPEsr=Gsr*exp(-Gpr_T2*z^2/(4*C))
Sf=(Wcarrier/Wo)*exp(-(C*((Wcarrier-Wo)^2)/abs(Gpr_T1)))
TimeShift=t0
Vo_slope=Vs*Greg*Gsr*exp(-(Gpr_T2*(time-TimeShift-T2)^2/(4*C)))*Sf*sin(Wo*(time-TimeShift)+(Wcarrier-Wo)*T1)
Vo_cond_t1mustlargethan=(6/pi)*Qo*To
```

```
VAR
BothSlopeStep
A=1u
Vs=A/Go
Go=Gp
G1=638.5u
Wcarrier=2*pi*Fcarrier
z=0
Af=Go/(4*pi*C*sqrt((Fcarrier-Fo)^2+(Go/(4*pi*C))^2))
Qo=QL
Gpr_T1=-30K
Gpr_T2=abs(Gpr_T1)
```

```
VAR
othFspecEnv
Fspec_slope1=2*sqrt(pi*C/Gpr_T2)*exp(-4*pi*pi*F*F*C/Gpr_T2)
Fspec_slope2=Fspec_q*Fspec_slope1
Fs1=Go/(2*C)
Fs2=G1/(2*C)
Fspec_step1=2*(Fs1+Fs2)*(Fs1*Fs2+(2*pi*F)^2)/(((2*pi*F)^2+Fs1*Fs1)*((2*pi*F)^2+Fs2*Fs2))
Fspec_step2=Fspec_q*Fspec_step1
F=0
Fspec_q=if rem(F,Fq)=0 then 1 else 1e-12 endif
```

```
VAR
EitherStep
t0=42n
tb=156n
Tb=tb-t0
Greg=(Go+G1)/G1
Aminu=75.34p
Aplus=448.8p
Gsr=exp(Aminu/(2*C))
Gtot=Greg*Gsr
SHAPEsr=if z<0 then exp(G1*Tb/(2*C))*exp(G1*(z)/(2*C)) else exp(G1*Tb/(2*C)*exp(-Go*(z)/(2*C))) endif
Sf=Go*G1/(4*C*C*sqrt((Wcarrier-Wo)^2+(Go/(2*C))^2)*sqrt((Wcarrier-Wo)^2+(G1/(2*C))^2))
TimeShift=t0
Vo_slope_shape=if time-tb<0 then exp(G1*(time-tb)/(2*C)) else exp(-Go*(time-tb)/(2*C)) endif
Vo_slope=Vs*Greg*exp(G1*Tb/(2*C))*Vo_slope_shape*Sf*sin(Wo*(time-TimeShift))
q_cond_mustlargethan_q_cond1=Aplus/(2*C)
q_cond1=(Aminu/2*C)+0.5*ln(Greg)+3
```



Tran
RF_wf
StartTime=0.0
StopTime=1/Fq
MaxTimeStep=0.02/Fo
TimeStepControl=Fixed
IntegMethod=Trapezoidal
NoiseBandwidth=
NoiseScale=1

DC
Gain_and_TimeShape
SweepVar="z"
Start=-Tq
Stop=Tq
Step=
Lin=400
OutputPlan[1]=

Tran
Quench_wf
StartTime=0.0
StopTime=1/Fq
MaxTimeStep=0.005/Fq
TimeStepControl=Fixed
IntegMethod=Trapezoidal
OutputAllPoints=yes

DC
Selectivity
SweepVar="Fcarrier"
Start=Fcarrier-50M
Stop=Fcarrier+50M
Step=
Lin=2000

8 Reference

[1] "A Low-Power CMOS Super-Regenerative Receiver at 1GHz," IEEE Journal of Solid-state circuits, Vol. 36, No. 3, March 2001.

[2] "A 2V 600uA 1GHz BiCMOS Super-Regenerative Receiver for ISM Applications", IEEE Journal of Solid-state circuits, Vol. 33, No. 12, Dec. 1998.

[3] "A Low-Power 1GHz Super-Regenerative Transceiver with Time-Shared PLL Control", IEEE Journal of Solid-state circuits, Vol. 36, No. 7, July 2001.

[4] "Super-Regenerative Receivers," Whitehead J. R., Cambridge University Press, 1950.