A high-level VHDL-AMS model design methodology for analog RF LNA and Mixer

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Outline

- Introduction
- Design Approach
- Model Validation In The Case of LNA
- Conclusion

Introduction

- Mixed signal System On Chip
  - Rapidly increasing transistors density
  - The booming market of wireless applications
- Gap between
  - need of rapid time-to-market
  - complex design and verification procedure of the SOCs
- Need for SoC model library
  - A need exists to create a SoC model library include RF models
  - Support Top down design for the SoCs.

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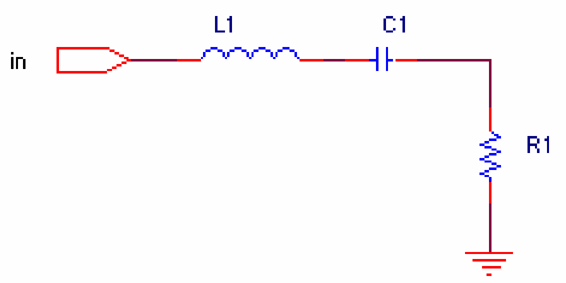
Design Approach

- Modeling the impedance matching
- Modeling the function of the RF block
- Modeling the bandwidth
- Modeling the noise
- Modeling the non-linearity
- Design flow

Modeling the impedance matching

- LRC network is chosen to be the basic frame.



$$\omega_0 = \frac{1}{\sqrt{LC}}$$

- R1 equals to 50Ω matching with the input 50Ω source impedance.
- L1 and C1 are resonant at designed frequency ω_0 .
- The value of L1 is set to an experienced value. according to the designed frequency ω_0.

Modeling the function of RF block

- LNA
  - Function:
    - Gain
  - Model expression:
    - The input signal is multiplied by a constant
- MIXER
  - Function:
    - Provide frequency translation and/or gain.
  - Model expression:

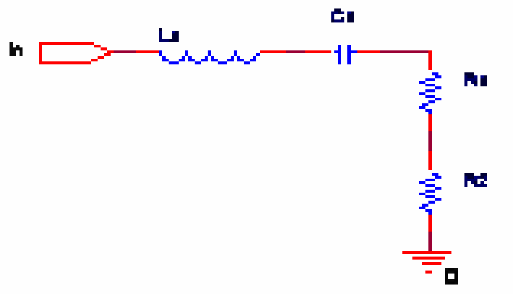
$$(A\cos\omega_1 t)(B\cos\omega_2 t) = \frac{AB}{2}[\cos(\omega_1 - \omega_2)t][\cos(\omega_1 + \omega_2)t] -- (1)$$

Modeling the bandwidth

- Behavioral model of filter in VHDL-AMS
    - Restriction to model a user-specified filter in VHDL-AMS.
        - VHDL-AMS supports Laplace transforms by providing the predefined ‘LTF attribute of a quantity.
        - The ‘LTF attribute requires both numerator and denominator coefficient lists that are required to be static expressions.
    - Overcome this difficulty.
        - Exploited a filter model generator to produce models from dynamic model parameters [7].
- Butterworth bandpass filter is chosen to model the bandwidth of RF components.
    - Use 0.2dB instead of 3dB as the attenuation limit.

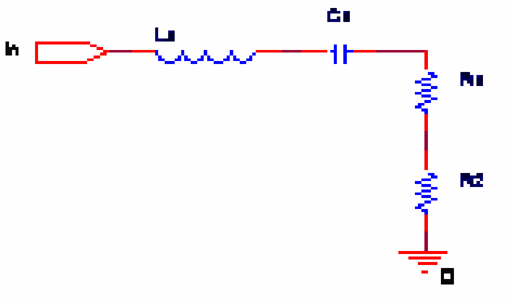
Modeling the noise

- Noise Figure
  - A very important specification of LNA and Mixer.
  - Is chosen to be the one of the specifications of the model.
- Solution
  - Two parallel connected resistors are used instead of one resistor in the input RLC network.



Modeling the noise

- Solution (continued)
  - R1 is a noisy resistor.
  - R2 is a ideal/non-noisy resistor.
  - The value of R1 is initialized to be 25ohm.
  - According to the specified noise figure, the design tool optimized the value of R1 by bisection algorithm.
  - To keep the model's input impedance matching at the designed frequency, R2 equals 50 minus the value of R1.



Modeling the non-linearity

- IIP3
  - A very important characteristic of LNA and Mixer.
  - Is chosen to be the one of the specifications of the model.
- Solution
  - Assume the non-linear behavior of the RF circuit is $y(t) \approx \alpha_1 x(t) + \alpha_2 x(t)^2 + \alpha_3 x(t)^3 ---(2)$

    when x(t) are the input signals with different frequency and assume

    $x(t) = A_1 \cos\omega_1 t + A_2 \cos\omega_2 t ---(3)$

Modeling the non-linearity

- Solution(continued)
  - Y(t) has the following intermodulation products[6]:

$$\omega = \omega_1 \pm \omega_2 : \alpha_2 A_1 A_2 \cos(\omega_1 + \omega_2)t + \alpha_2 A_1 A_2 \cos(\omega_1 - \omega_2)t$$

$$= 2\omega_1 \pm \omega_2 : \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 + \omega_2)t + \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 - \omega_2)t$$

$$= 2\omega_2 \pm \omega_1 : \frac{3\alpha_3 A_2^2 A_1}{4} \cos(2\omega_2 + \omega_1)t + \frac{3\alpha_3 A_2^2 A_1}{4} \cos(2\omega_2 - \omega_1)t$$

and fundamental components[6]:

$$\omega = \omega_1 : (\alpha_1 A_1 + \frac{3}{4}\alpha_3 A_1^3 + \frac{3}{2}\alpha_3 A_1 A_2^2) \cos \omega_1 t$$

$$\omega_2 : (\alpha_1 A_2 + \frac{3}{4}\alpha_3 A_2^3 + \frac{3}{2}\alpha_3 A_2 A_1^2) \cos \omega_2 t$$

Modeling the non-linearity

- Solution(continued)
  - Since other frequency in inter-modulation products of the two tone signal are not big concern, the equation (2) is enough to model non-linearity.

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x(t)^2 + \alpha_3 x(t)^3 ---(2)$$

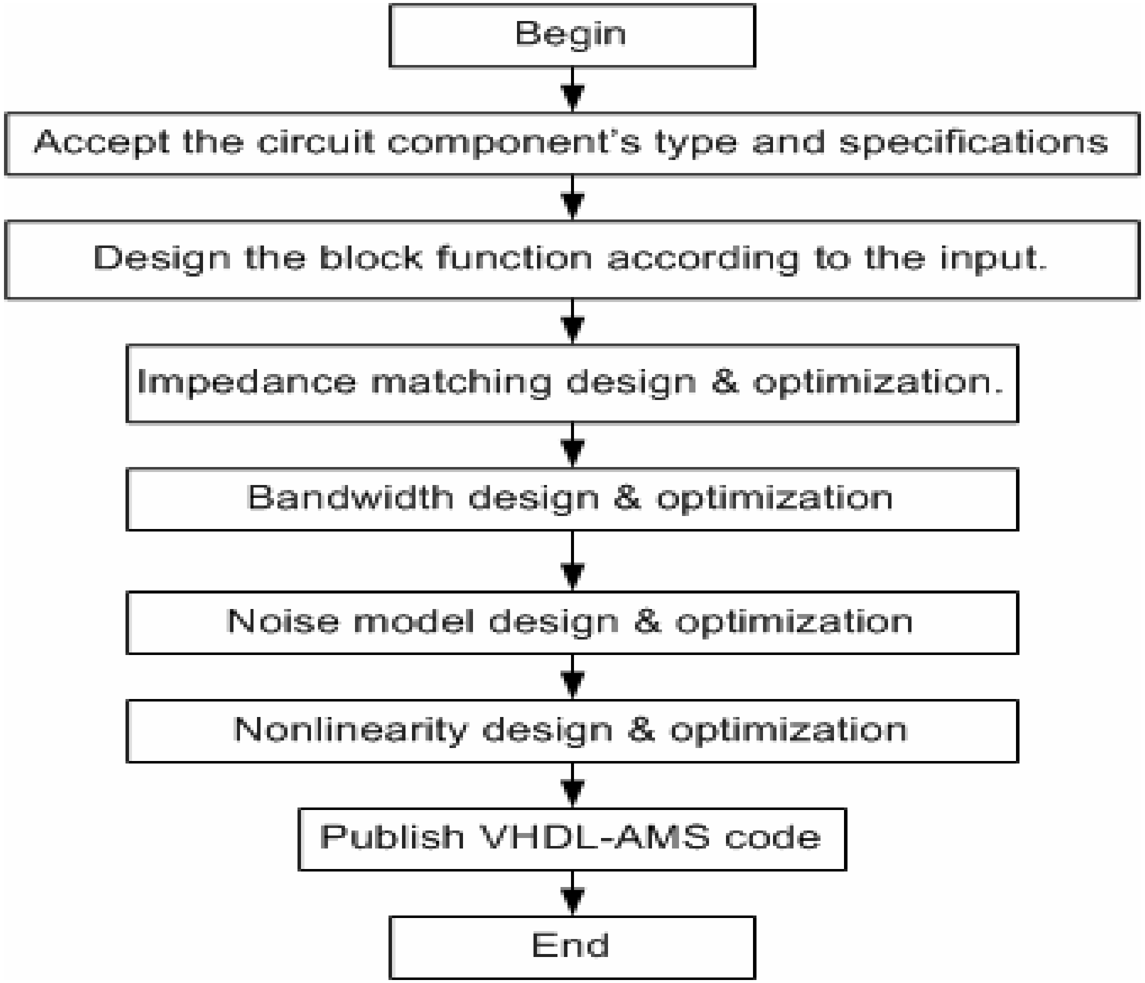
  - IMD (IM Distortion)[6]:

    The ratio of the amplitude of the output third-order products to $\alpha_1 A$.
  - Compute IIP3[6]: $IIP_3 |_{dBm} = \frac{IMD}{2} + P_{in} |_{dBm}$

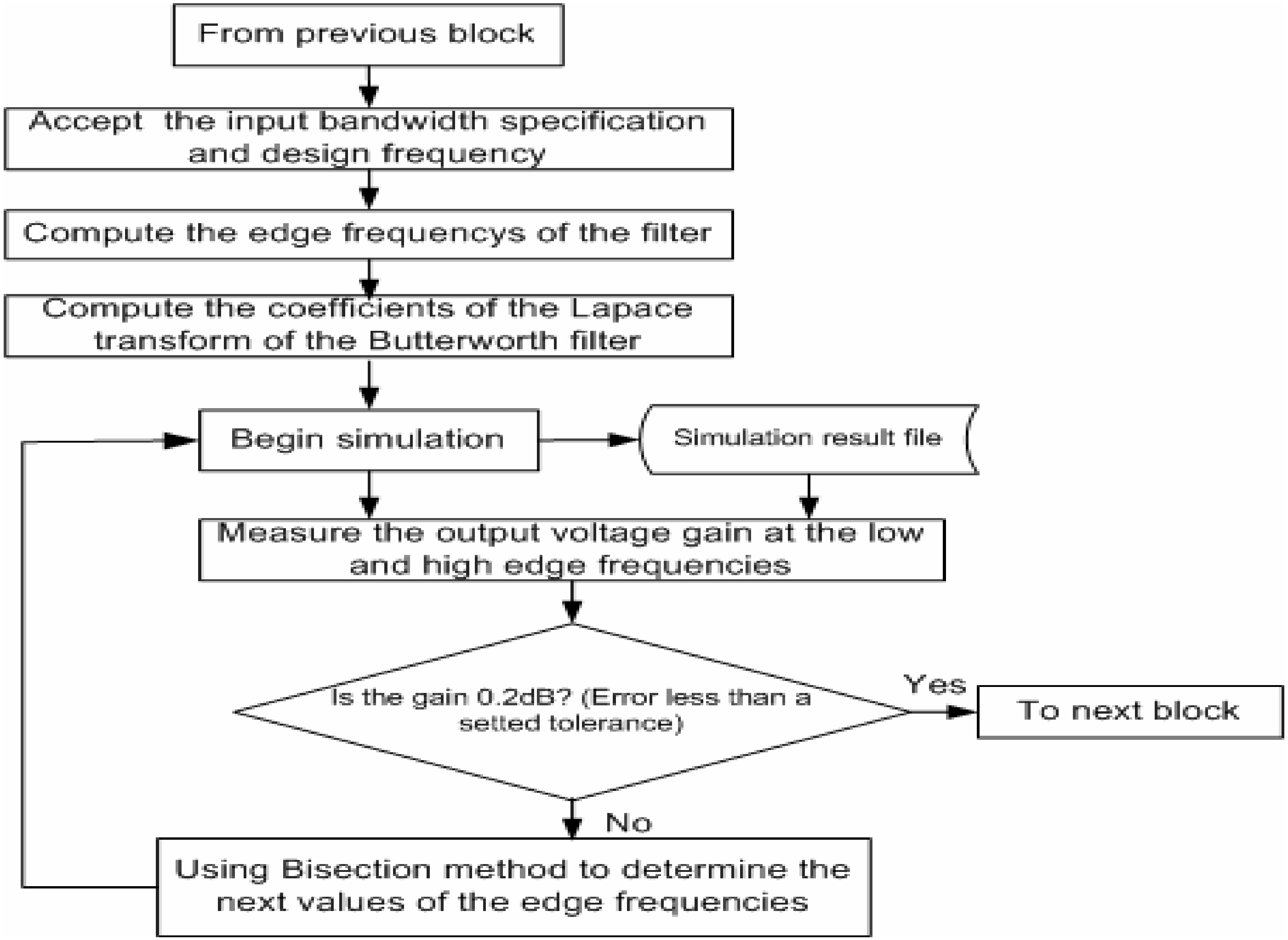
Modeling the non-linearity

- Solution (continued)
  - Parameters optimization
    - α_1 is set to be 1 to fulfill the gain specification.
    - For α_2, Since the intermodulation product of $\omega_1 \pm \omega_2$ is not the concern, α_2 is set to be 1.
    - For α_3, according to the specified IIP3, the design tool optimized the value of α_3 by bisection algorithm.

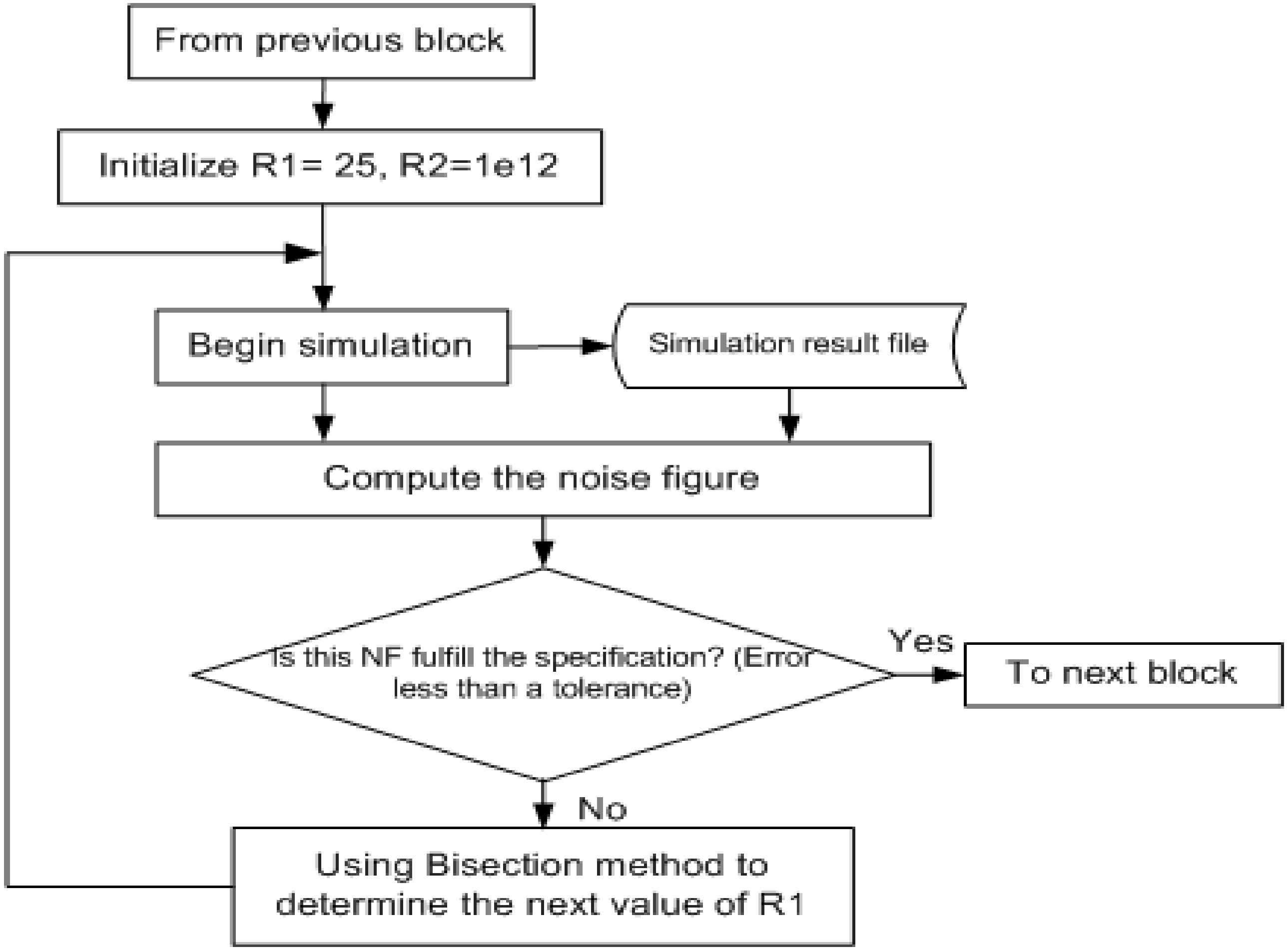
Design Flow


Begin
Accept the circuit component's type and specifications
Design the block function according to the input.
Impedance matching design & optimization.
Bandwidth design & optimization
Noise model design & optimization
Nonlinearity design & optimization
Publish VHDL-AMS code
End

Design Flow of the bandwidth modeling



Design Flow of the noise modeling



From previous block

Initialize R1= 25, R2=1e12

Begin simulation

Simulation result file

Compute the noise figure

Is this NF fulfill the specification? (Error less than a tolerance)

Yes

To next block

No

Using Bisection method to determine the next value of R1

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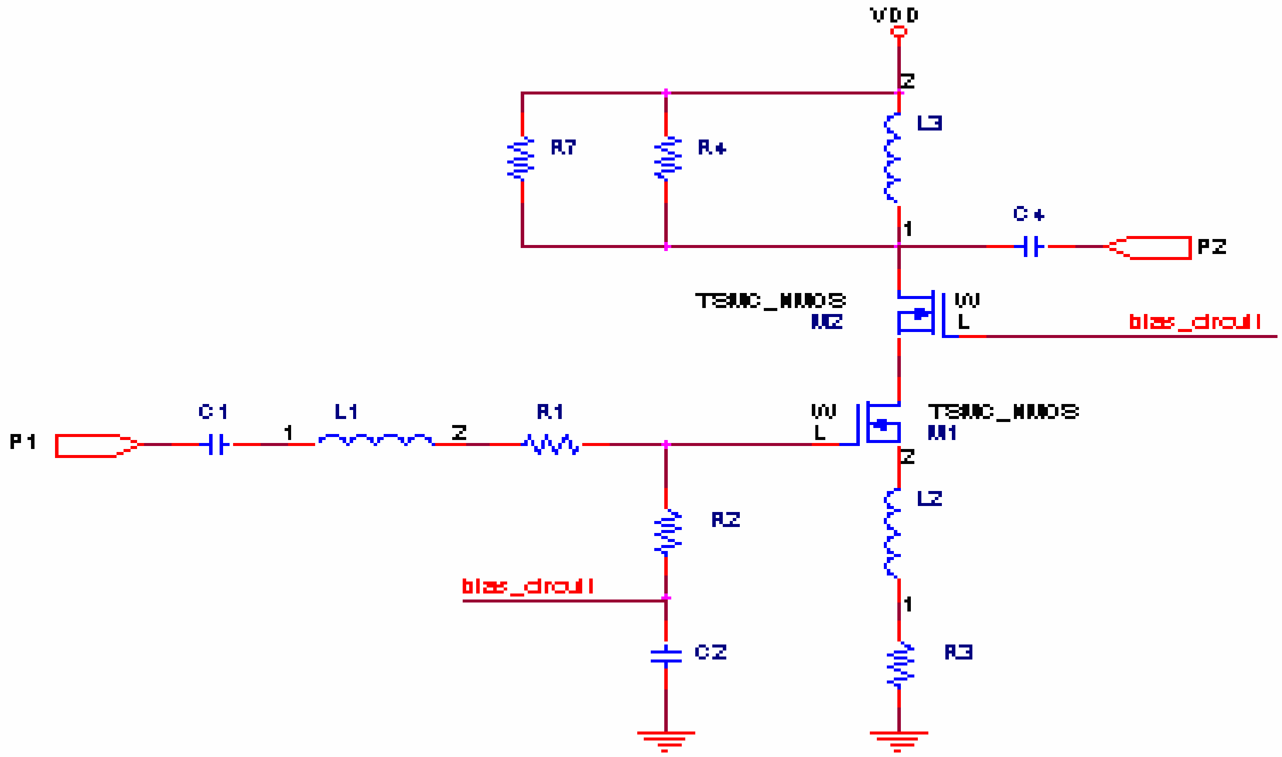
Model Validation of LNA

- Design Specifications

Gain	17.1dB
Bandwidth	>25M
Noise Figure	0.775dB
IIP3	3.6dBm

Model Validation of LNA

- Transistor- level 1.9GHz LNA in TSMC25 technology



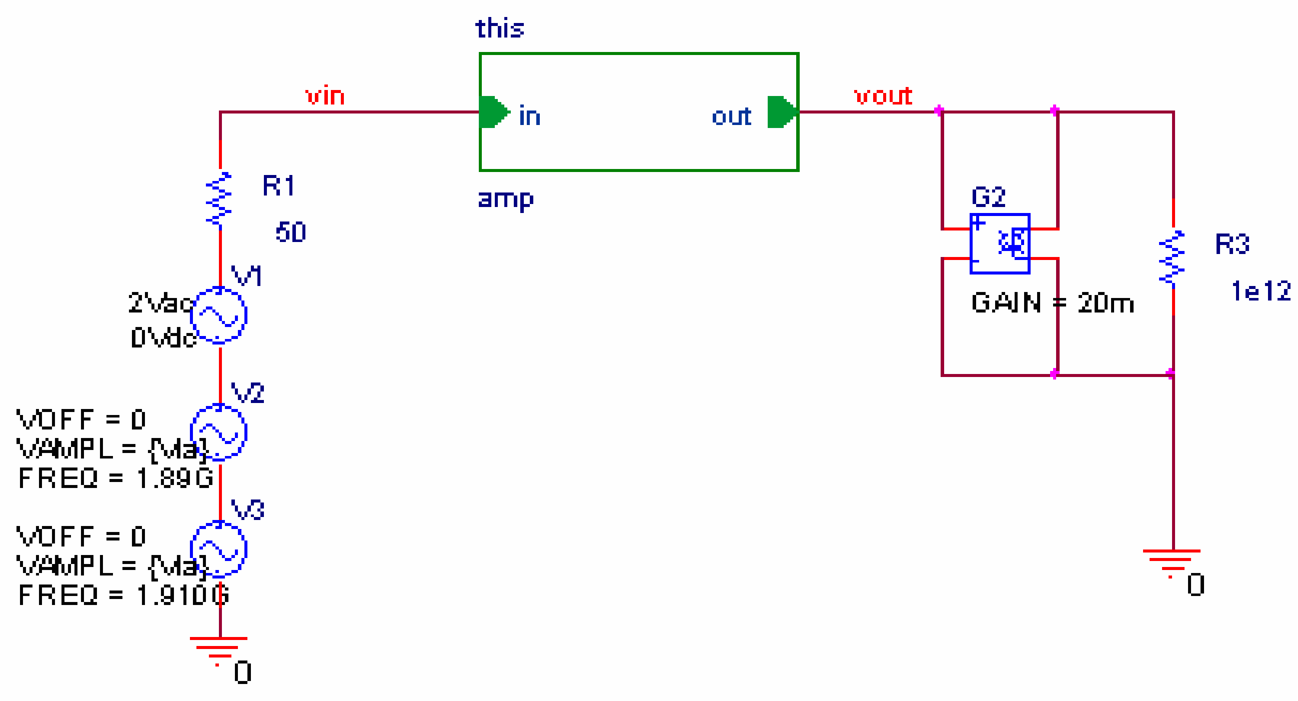
Model Validation of LNA

- Parameters in the behavioral LNA model

L1	10nH
C1	701.67fF
R1	9.75ohm
R2	40.25ohm
Laplace transfer function	$\frac{3769911040.0s}{142517087507302055936.0+3769911040.0s+s^2}$
Coefficients for the non-linearity expression	$\alpha_1=1,\alpha_2=1,\alpha_3=0.1183$

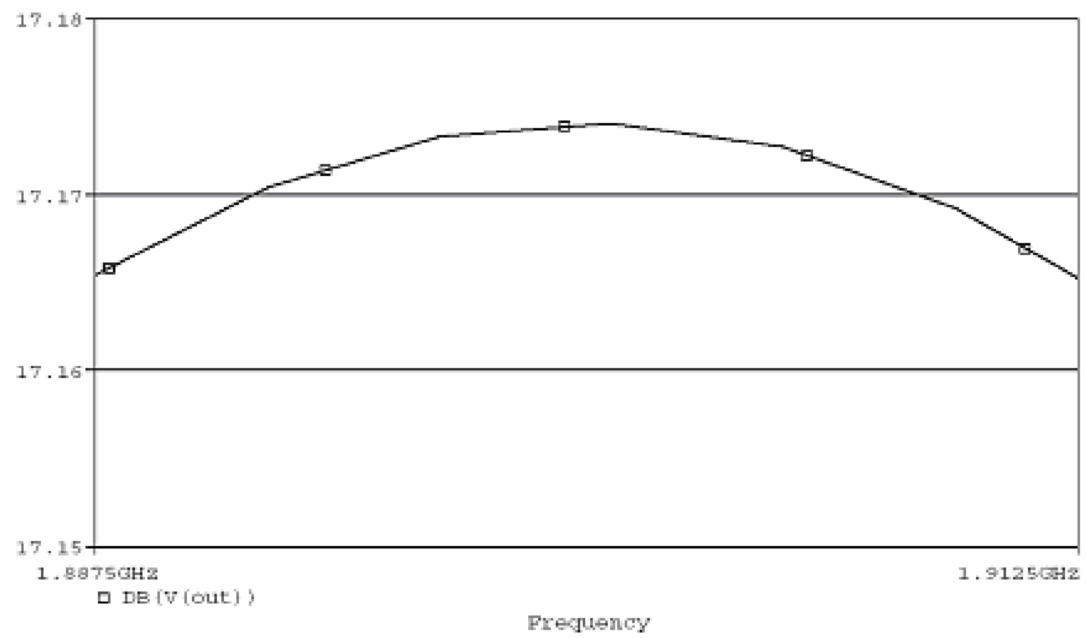
Model Validation of LNA

- Test circuit of LNA



Model Validation of LNA

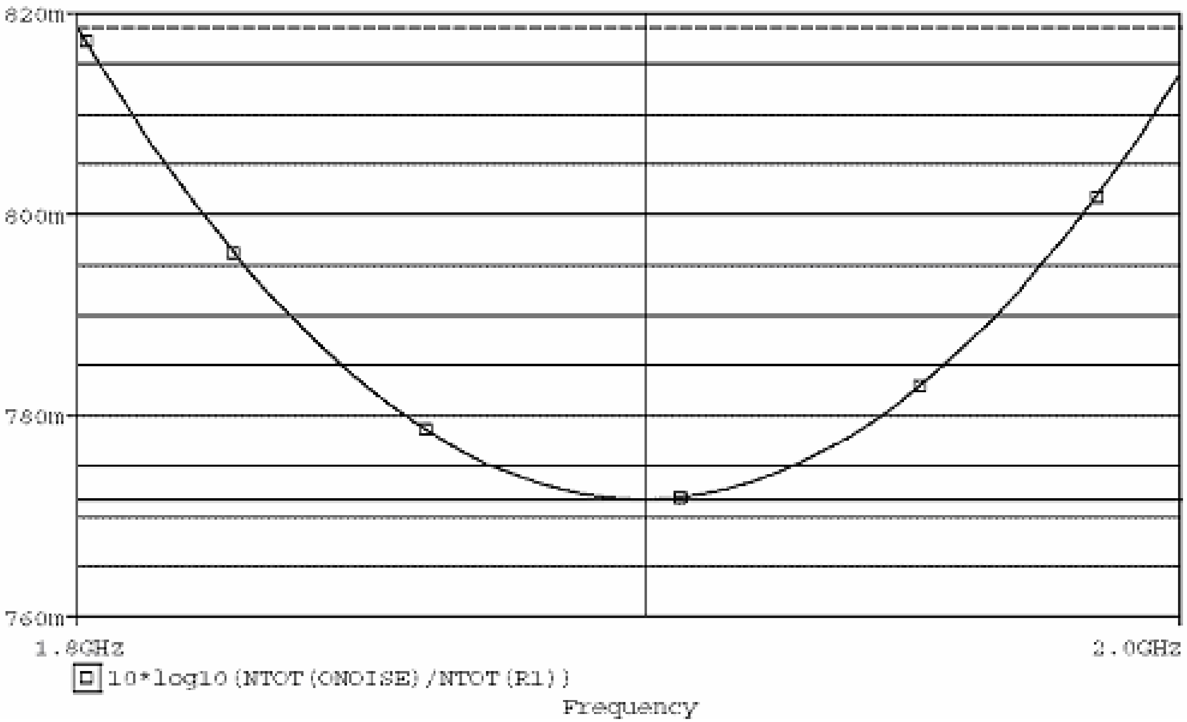
- Gain and Bandwidth Simulation for behavioral LNA model



- The gain variation between 1.8875Ghz and 1.9125Ghz is 0.01db, the bandwidth requirement is met.

Model Validation of LNA

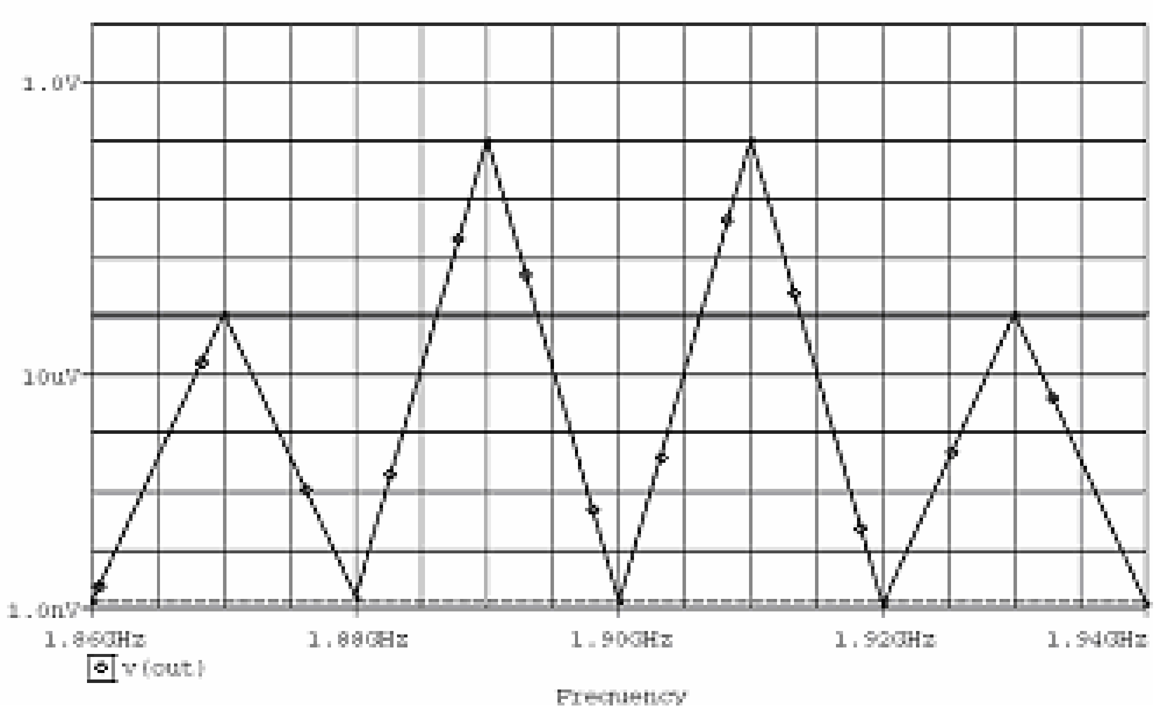
- Noise Figure Simulation for behavioral LNA model



- the noise figure at 1.9Ghz is 0.772dB.

Model Validation of LNA

- Two-tone analysis for for behavioral LNA model



- IIP3 equals to 3.52dBm

Model Validation of LNA

- Comparison between the design specification and the simulation result of the behavioral model.

	Design specification	Simulation result of behavioral model
Gain	17.1dB	17.174dB
Bandwidth	>25M	>25M
Noise figure	0.775dB	0.772dB
IIP3	3.6dBm	3.52dBm

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Conclusion

- The methodology is not necessarily general for all RF components, but is applicable to LNA and MIXER.
- In the future, this methodology will be extended to design oscillators and PLLs.
- To support RF circuit and system simulation and verification, harmonic analysis or FFT function and noise simulation must be supported by the VHDL-AMS simulator.

Reference

- [1] Sida, M.; Ahola, R.; Wallner, D., *Bluetooth transceiver design and simulation with VHDL-AMS,* Circuits and Devices Magazine, IEEE , Volume: 19 Issue: 2 , March 2003 Page(s): 11 -14
- [2] Murthy N. Revanuru, *Modeling and simulation of an FM Receiver using VHDL-AMS*, Master Thesis of ECECS, University of Cincinnati, 2001
- [3] Jinsong Zhao , *Behavioral modeling of RF circuits in Spectre*, http://www.cadence.com/datasheets/dat_pdf/rf_behavioral.pdf
- [4] N.Milet-Lewis, G.Monnerie, A.Fakhfakh, D.Geoffroy, Y.Herve, H.Levi, *A VHDL-AMS Library of RF Blocks Models*, Behavioral Modeling and Simulation, 2001. BMAS 2001. Proceedings of the Fifth IEEE International Workshop on , 10-12 Oct. 2001 Pages:12 – 14
- [5] Thomas H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*, Cambridge University Press 1998
- [6] Behzad Razavi, *RF microelectronics*, Upper Saddle River, NJ: Prentice Hall, c1998
- [7] Wei Yang, Hal. Carter, *An Approach to VHDL-AMS Model Generator*, Ohio Graduate Student Symposium on Computer and Information Science & Engineering (OGSS-CISE) , *2004*
- [8] Sponsors, Design Automation Standards Committee of the IEEE Computer Society, *IEEE standard VHDL language reference manual (Integrated with VHDL-AMS changes),* August 1, 1998

Thank you.

Questions and Answers.