

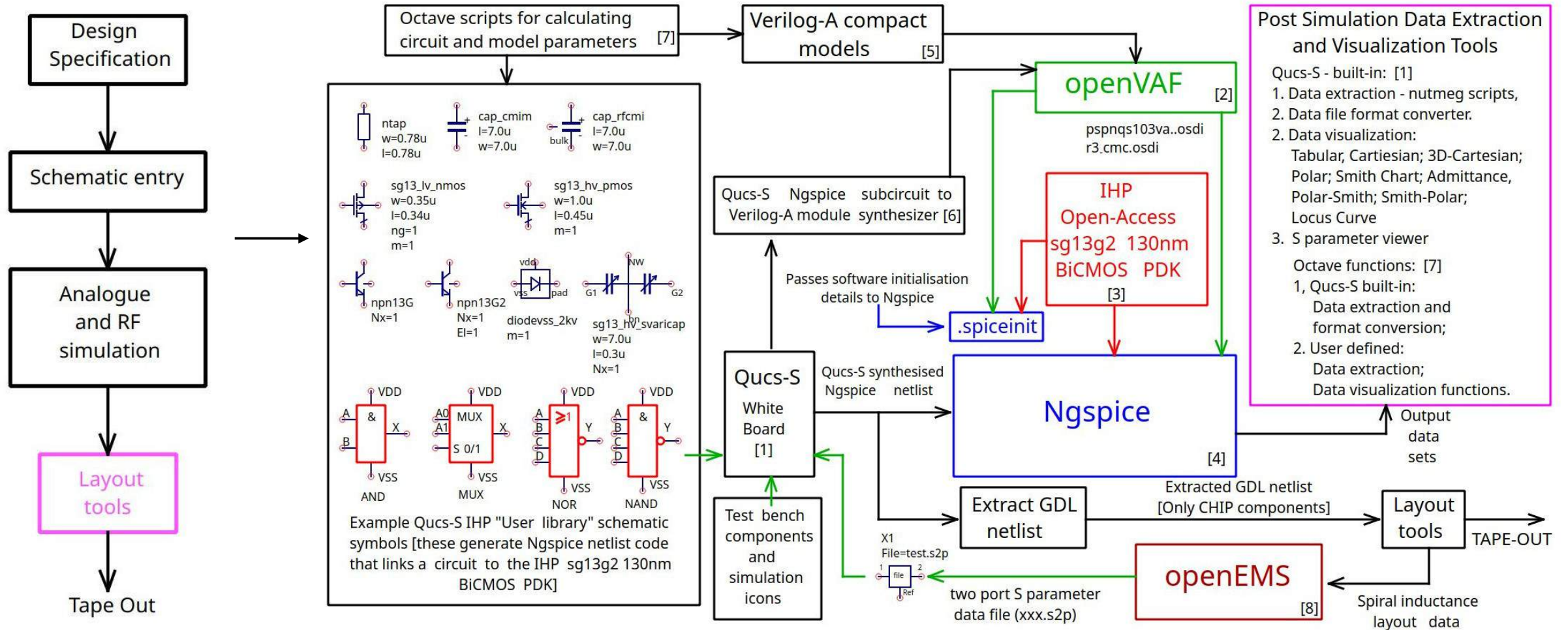
Building Component Libraries for Use with the IHP OpenPDK and FOSS Tools

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Outline

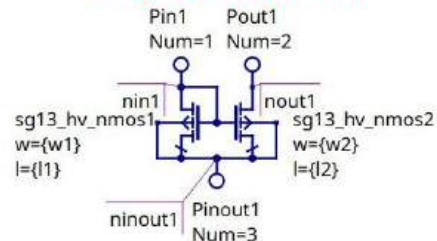
- Front-End FOSS/IHP RF IC Design Flow
- Constructing User Defined Subcircuits
- Building an RLCG Inductance Library
- Qucs-S IHP 130 nm HBT 60 GHz LNA
- Tuned Monte Carlo Simulation
- Monte Carlo Corner Simulation Data
- Monte Carlo Histogram Test Bench
- Data Conversion to Octave m Files
- Corner Simulation Histograms
- Improved RF Inductance Performance
- Summary
- References and Software Links

Front-End FOSS/IHP RF IC Design Flow



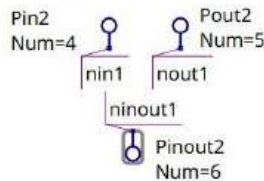
Constructing User Defined Subcircuits

Subcircuit Body
Schematic
Representation



OR

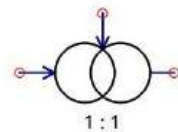
Ngspice Script
Representation



.INCLUDE SCRIPT

```
INCLSCR1
SpiceCode=* Basic 2 nMOS lv current mirror.
X1 nin1 nin1 ninout1 ninout1 sg13_lv_nmos w={w1} l={l1} ng={ng} m={m} as={as} ad={ad} pd={pd}
+ ps={ps} trise={trise} z1={z1} z2={z2} wmin={wmin} rfmode={rfmode} pre_layout={pre_layout} mlist={mlist}
*
X2 nout1 nin1 ninout1 ninout1 sg13_lv_nmos w={w2} l={l2} ng={ng} m={m} as={as} ad={ad} pd={pd}
+ ps={ps} trise={trise} z1={z1} z2={z2} wmin={wmin} rfmode={rfmode} pre_layout={pre_layout} mlist={mlist}
```

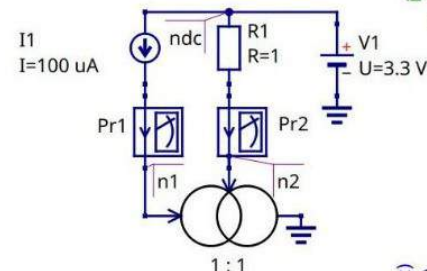
Qucs-S
Subcircuit
Symbol



```
CM_hv_nMOS_subcircuit_1
w1=1u
l1=1u
w2=1u
l2=1u
```

.INCLUDE SCRIPT

```
INCLSCR1
SpiceCode=
.PARAM mc_ok = 1.0
.LIB cornerMOShv.lib mos_tt
```



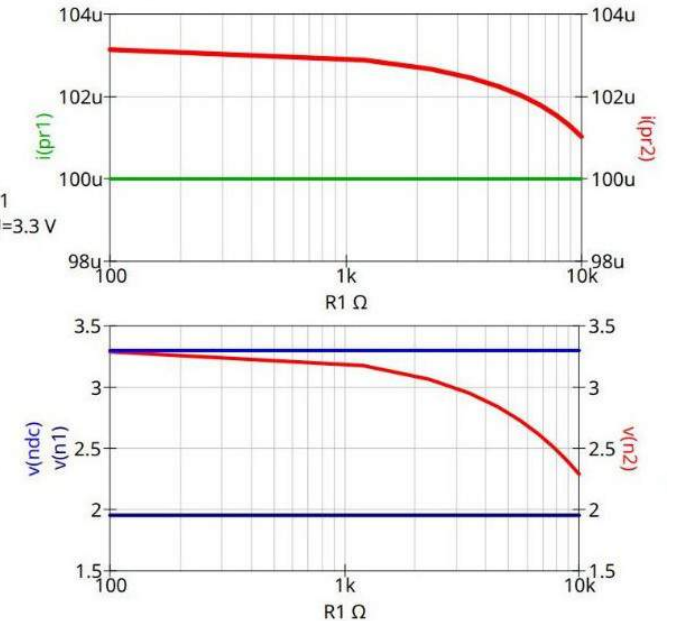
```
CM_hv_nMOS_subcircuit_1
w1=1u
l1=1u
w2=1u
l2=1u
```

dc simulation

DC1

Parameter sweep

```
SW1
Sim=DC1
Type=log
Param=R1
Start=100
Stop=10k
Points=10
```



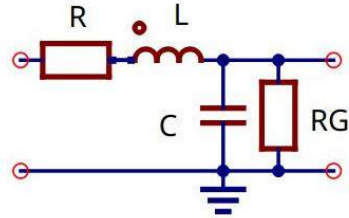
sw1.res-sweep	sw1.i(pr1)	sw1.i(pr2)	sw1.v(n1)	sw1.v(n2)
100	0.0001	0.000103138	1.9532	3.2897
1.2e3	0.0001	0.000102884	1.9531	3.1765
2.3e3	0.0001	0.000102664	1.9531	3.0639
3.4e3	0.0001	0.000102449	1.9531	2.9517
4.5e3	0.0001	0.000102234	1.9531	2.8399
5.6e3	0.0001	0.000102014	1.9531	2.7287
6.7e3	0.0001	0.000101787	1.9531	2.618
7.8e3	0.0001	0.000101548	1.9531	2.5079
8.9e3	0.0001	0.000101295	1.9531	2.3985
1e4	0.0001	0.000101025	1.9531	2.2897

Building an RLCG Inductance Library: 1



- **Assumptions:** 1. Transverse Electromagnetic (TEM) mode propagation; 2. Quasi-static behaviour (where the field distribution remains constant over one segment length); 3. Uniform distributed parameters (R, L, C and G) remain constant per length.
- **High frequency effects** (the above are no longer true): 1. Wavelength λ is similar to inductor physical dimensions: to achieve good performance the RLCG length $\ll \lambda/20$; at $f = 40\text{GHz}$, $\lambda = 7\text{ mm}$, implying that five segments are a reasonable starting approximation; 2. Parasitic physical effects become dominant; both the skin and proximity effects are frequency dependent; 3. ElectroMagnetic effects are significant, for example radiation, eddy current loss and capacitive coupling: radiation effects are not implemented in standard RLCG inductance models.

Building an RLCG Inductance Library: 2



Inductance resonance frequency F_R (Hz) and Q factor are specified as model parameters.

Here, $X_L = 2\pi \cdot F_R / Q$, $R_0 = X_L / Q$, and $C = 1 / (2\pi \cdot F_R)^2 L$.

Also, $R = R_{dc} + R_0 [(f/f_0)^{1/2} + K_1 \cdot f/f_0]$, where f_0 is a reference frequency (that is often set to the same, or lower, value as F_R and f is the signal frequency in Hertz. These frequency terms represent conductor skin effect and the inductance proximity effect respectively. In this basic inductance model dielectric loss is given by $RG = 1/G = 1/[2\pi \cdot f \cdot C \cdot \tan\delta]$.

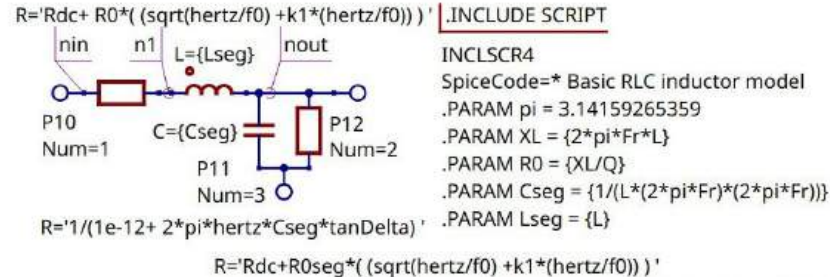
Practical Frequency Limits of RLCG Inductance Models

Frequency (GHz)	Model Accuracy	Notes
DC – 10	Excellent	Lumped component or RLCG OK;
10 – 40	Very good ≥ 3 segments	Segment-level tuning required;
40 – 80	Good with ≥ 5 segments	Substrate and skin effects increase;
80 – 120	Moderate: just usable	Only Near the self-resonant frequency;
> 40	Use EM simulation	Fails to capture radiation etc.

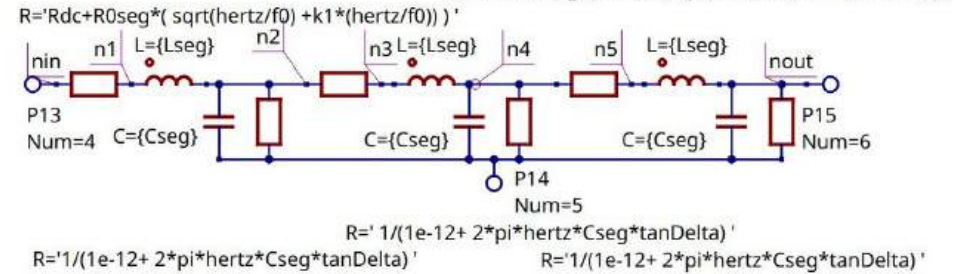
Building an RLCG Inductance Library: 3



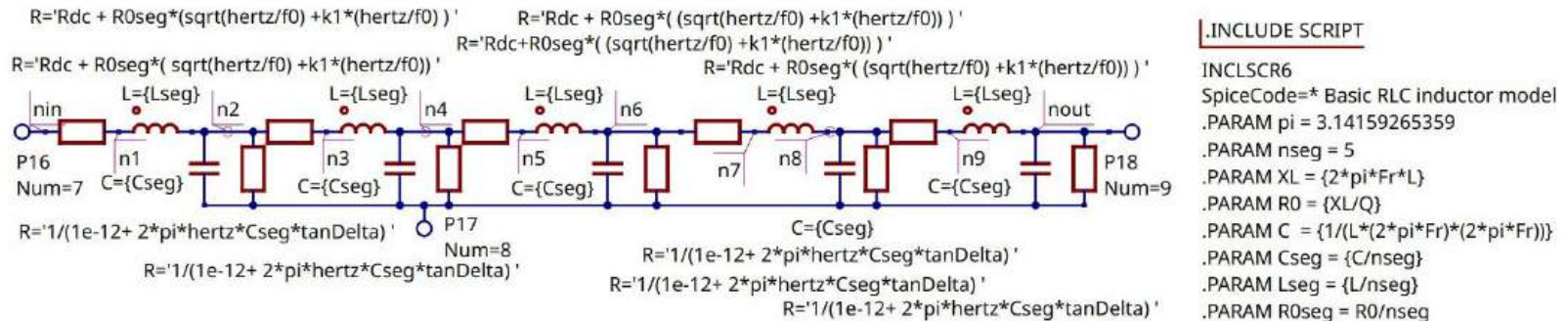
RF_L_seg1_1
Fr=50G
Q=12
L=100p
K1=0
f0=50G
tanDelta=0
Rdc=0.1



RF_L_seg3_1
Fr=50G
Q=12
L=100p
K1=0
f0=50G
tanDelta=0
Rdc=0.1

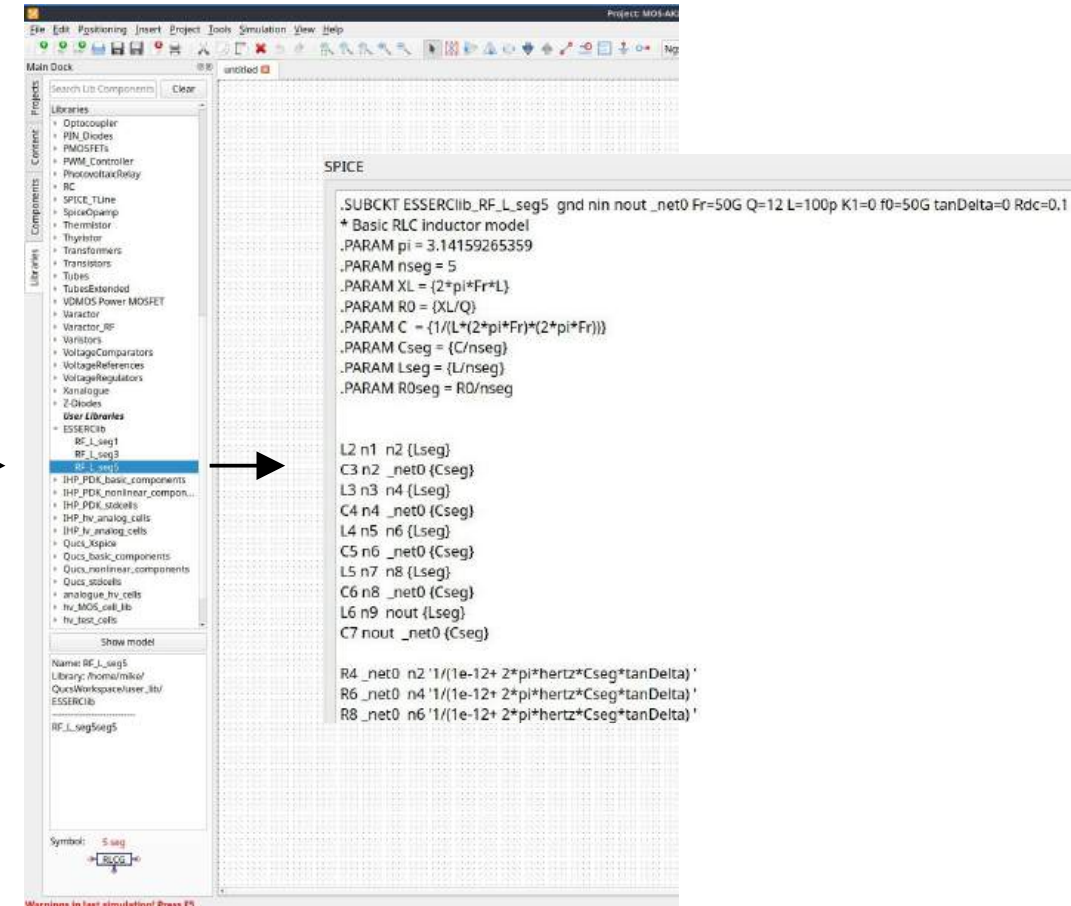
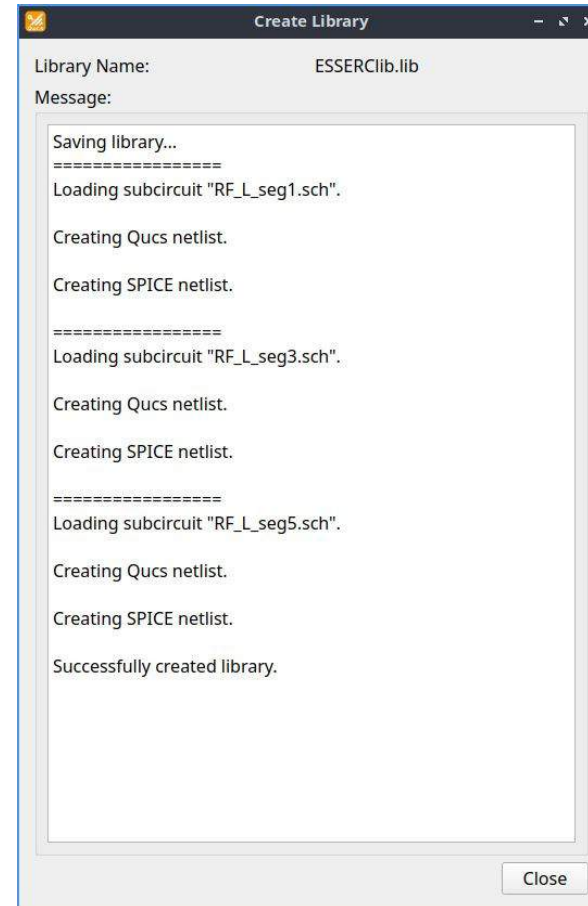
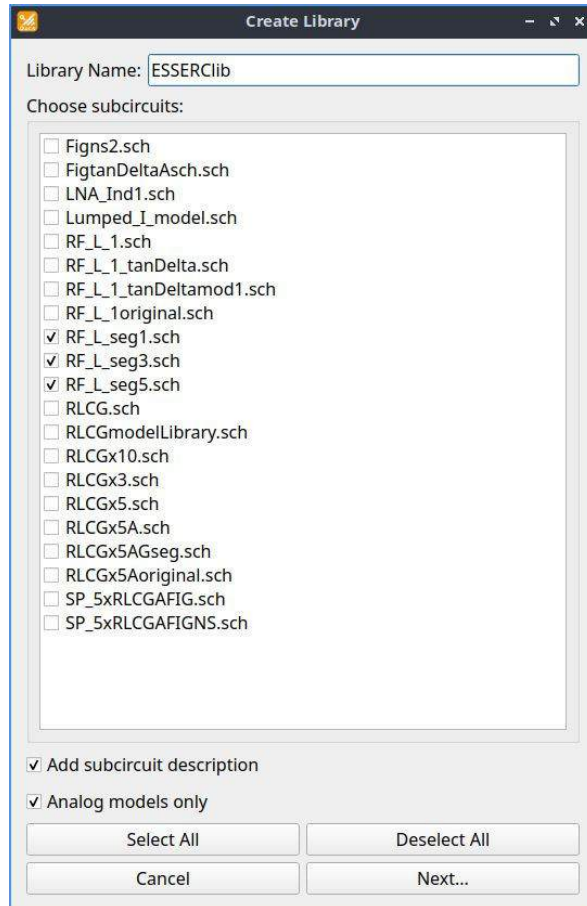


RF_L_seg5_1
Fr=50G
Q=12
L=100p
K1=0
f0=50G
tanDelta=0
Rdc=0.1



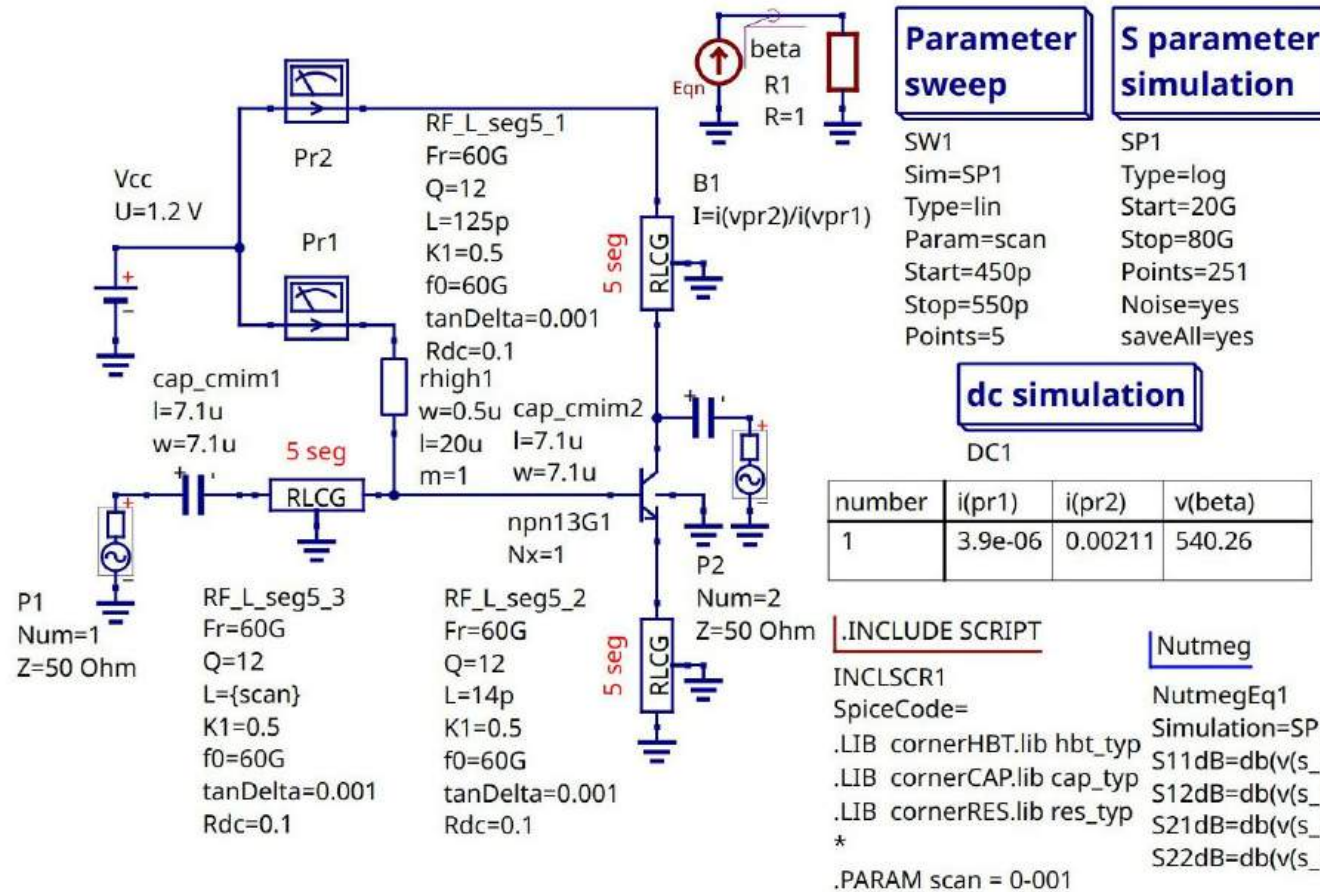
□ One, three and five segment RLCG non-linear behavioural RF inductance models

Building an RLCG Inductance Library: 4



Creation of a Qucs-S User Library called ESSERClib

Qucs-S IHP 130 nm HBT 60 GHz LNA: 1



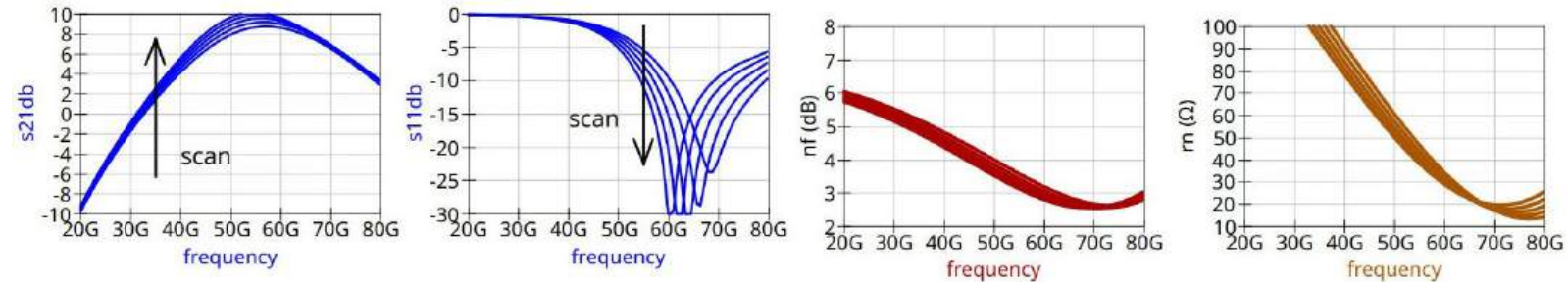
- S-parameter test bench schematic, illustrating the use of IHP the Open PDK and Qucs-S User Libraries

Qucs-S IHP 130 nm HBT 60 GHz LNA: 2

.INCLUDE SCRIPT

```

INCLSCR1
SpiceCode=
.LIB cornerHBT.lib hbt_bcs
.LIB cornerCAP.lib cap_bcs
.LIB cornerRES.lib res_bcs
  
```

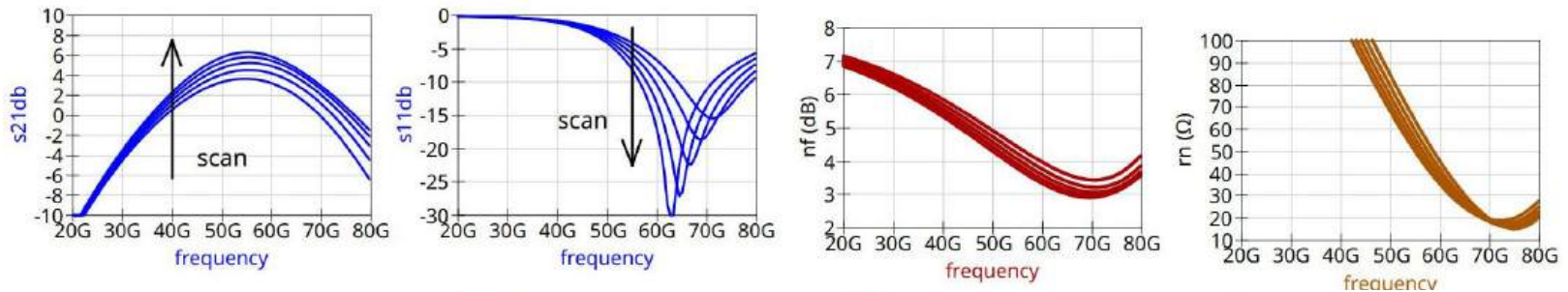


Best Case

.INCLUDE SCRIPT

```

INCLSCR1
SpiceCode=
.LIB cornerHBT.lib hbt_typ
.LIB cornerCAP.lib cap_typ
.LIB cornerRES.lib res_typ
  
```

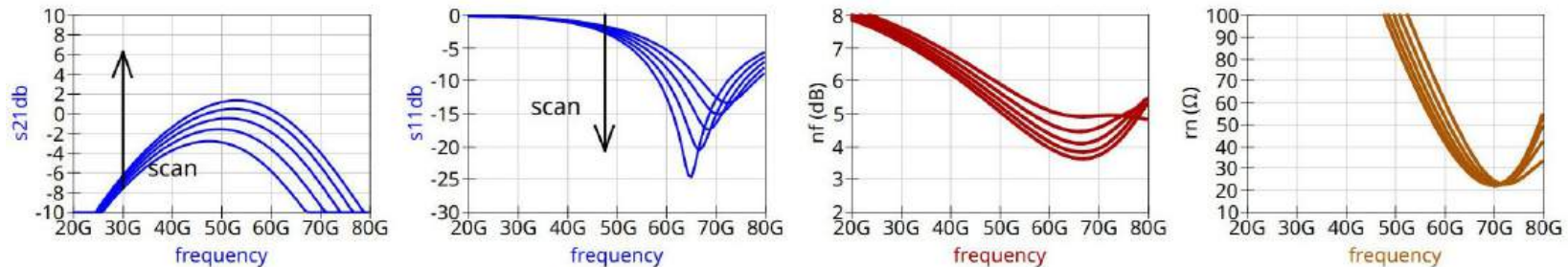


Typical

.INCLUDE SCRIPT

```

INCLSCR1
SpiceCode=
.LIB cornerHBT.lib hbt_wcs
.LIB cornerCAP.lib cap_wcs
.LIB cornerRES.lib res_wcs
  
```



Worst Case

□ S-parameter and noise simulation output data for bcs, typ and wcs PDK corners

Tuned Monte Carlo Simulation

Parameter sweep

SW1
Sim=SP1
Type=lin
Param=No_of_runs
Start=0
Stop=50
Points=51

S parameter simulation

SP1
Type=lin
Start=40G
Stop=80G
Points=201
Noise=yes
saveAll=yes

Vcc U=1.2 V

Nutmeg

NutmegEq1
Simulation=SP1
S11dB=db(v(s_1_1))
S12dB=db(v(s_1_2))
S21dB=db(v(s_2_1))
S22dB=db(v(s_2_2))

B1
I=i(vpr2)/i(vpr1)

INCLUDE SCRIPT

```
INCLSCR1
SpiceCode=
.LIB cornerHBT.lib hbt_typ_stat
.LIB cornerCAP.lib cap_typ_stat
.LIB cornerRES.lib res_typ_stat
*.PARAM No_of_runs = 100
```

dc simulation

DC1			
number	i(pr1)	i(pr2)	v(beta)
1	3.54e-06	0.00196	555.57

Reset Values RF_L_seg5_3:L RF_L_seg5_2:L RF_L_seg5_1:L

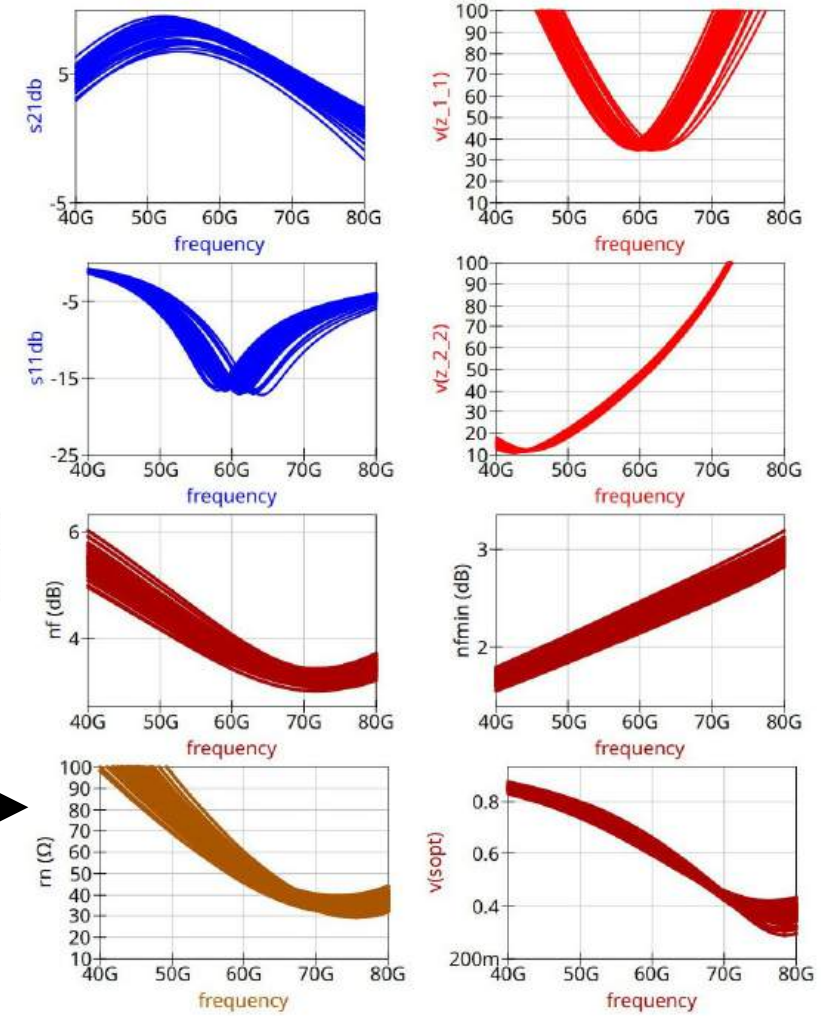
Update Values Max.: 700 Max.: 11 Max.: 300

Close

Min.: 400 Min.: 8 Min.: 100

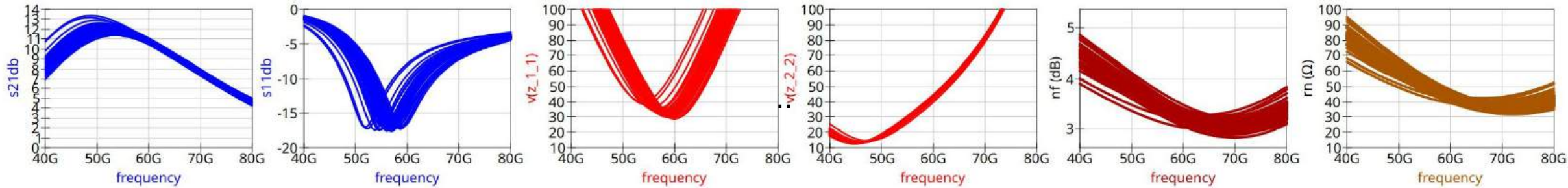
Val.: 670 Val.: 9.000 Val.: 1.45e+02

Step 10 Step 0.2 Step 5

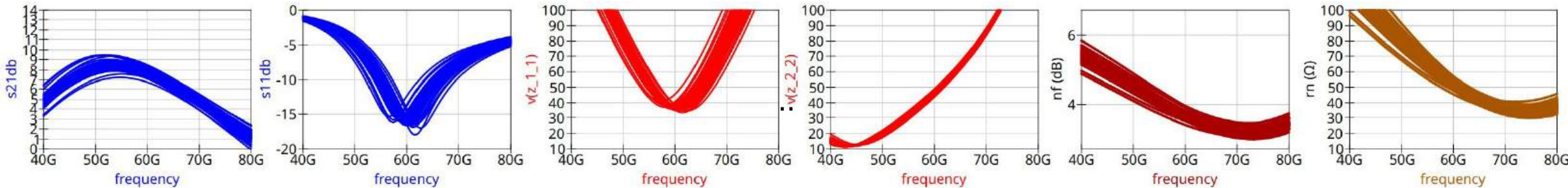


Monte Carlo Corner Simulation Data

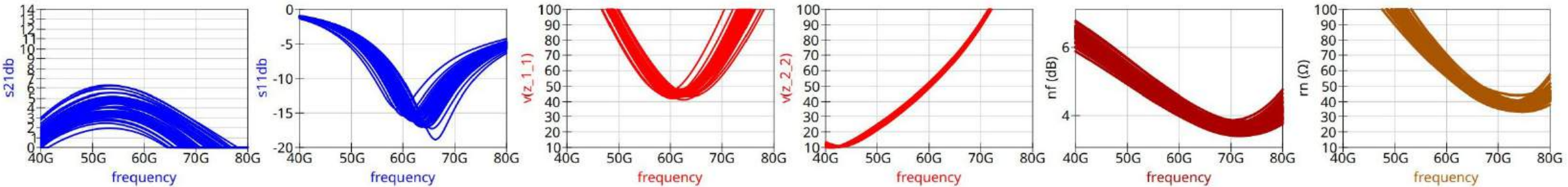
BCS



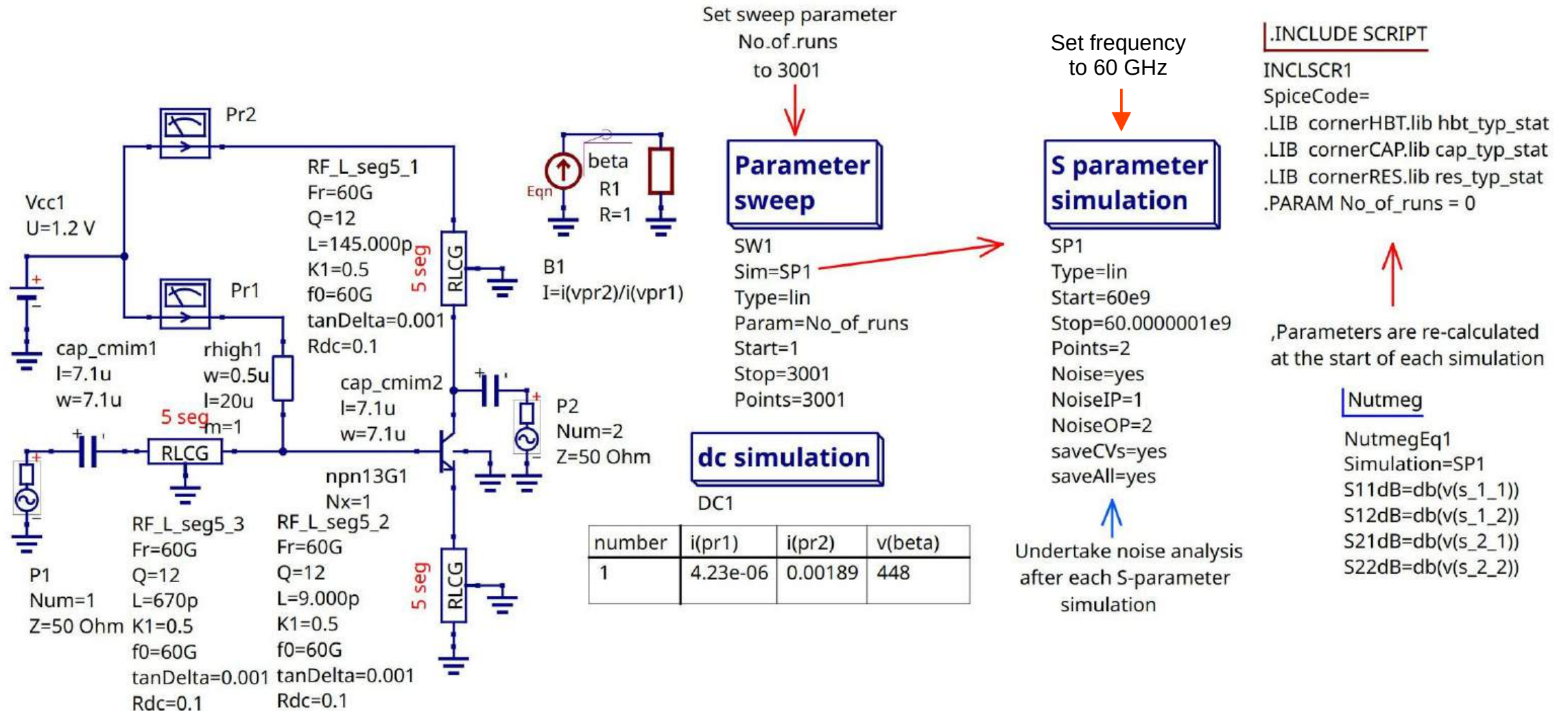
TYP



WCS

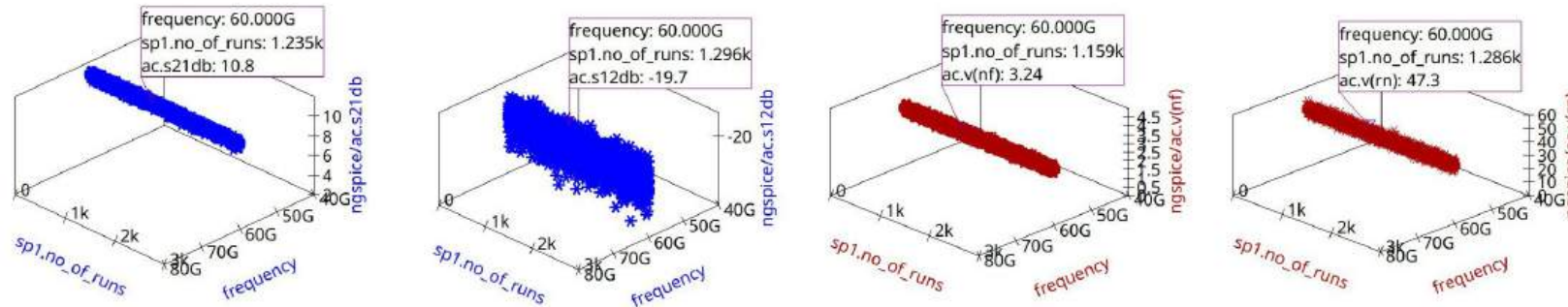


Monte Carlo Histogram Test Bench: 1

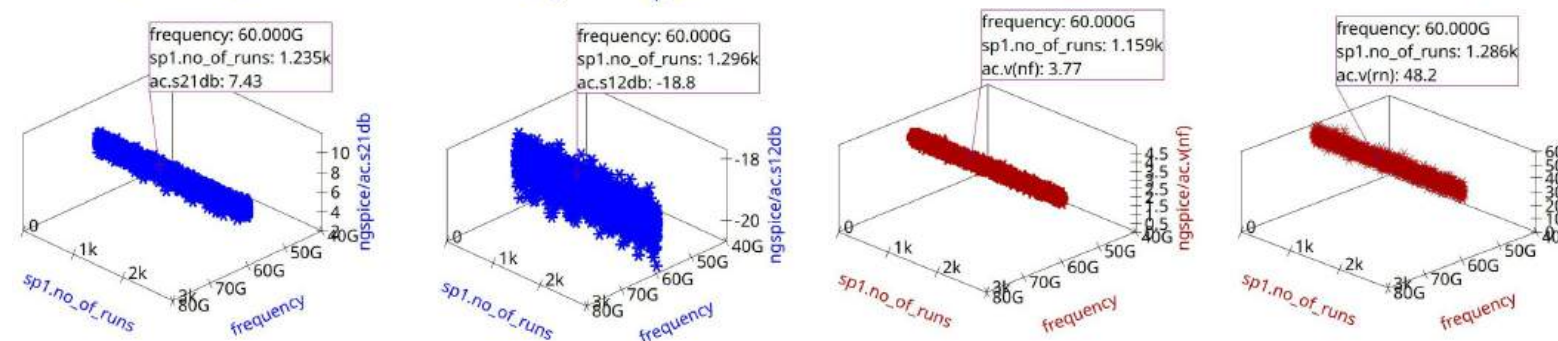


Monte Carlo Histogram Test Bench: 2

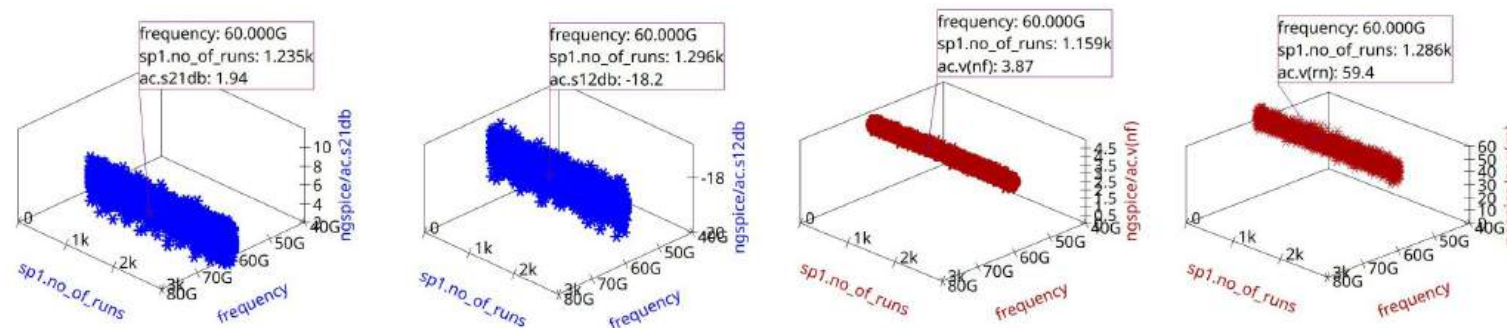
BCS



TYP



WCS



Data Conversion to Octave m Files

Convert Data File...

File specification

Input File: /home/mike/QucsWorkspace/MOS-AKLondon2025_prj/LNA_MC_Cornerbcs_HistgramsS23000.dat.ngspice

Input Format: Qucs dataset

Output File: /home/mike/QucsWorkspace/MOS-AKLondon2025_prj/LNA_MC_Cornerbcs_HistgramsS23000.m

Output Format: Matlab

Output Data: ac.v(s_1_1)

Library Name:

Messages

```

/usr/bin/qucsconv_rf -if qucsdata -of matlab -i /home/mike/QucsWorkspace/MOS-AKLondon2025_prj/LNA_MC_Cornerbcs_Histgrams

```

Successfully converted file!

```

octave:10>
load /home/mike/QucsWorkspace/MOS-AKLondon2025_prj/LNA_MC_Cornerbcs_HistgramsS23000.m
octave:11>

```

```

whos
Variables visible from the current scope:

```

variables in scope: top scope

Attr	Name	Size	Bytes	Class
====	====	====	=====	=====
	ac_s11db	3001x1	24008	double
	ac_s12db	3001x1	24008	double
	ac_s21db	3001x1	24008	double
	ac_s22db	3001x1	24008	double
	ac_v_cy_1_1_	3001x1	24008	double
c	ac_v_cy_1_2_	3001x1	48016	double
c	ac_v_cy_2_1_	3001x1	48016	double
	ac_v_cy_2_2_	3001x1	24008	double
	ac_v_nf_	3001x1	24008	double
	ac_v_nfln_	3001x1	24008	double
	ac_v_rn_	3001x1	24008	double
c	ac_v_s_1_1_	3001x1	48016	double
c	ac_v_s_1_2_	3001x1	48016	double
c	ac_v_s_2_1_	3001x1	48016	double
c	ac_v_s_2_2_	3001x1	48016	double
c	ac_v_sopt_	3001x1	48016	double
c	ac_v_y_1_1_	3001x1	48016	double
c	ac_v_y_1_2_	3001x1	48016	double
c	ac_v_y_2_1_	3001x1	48016	double
c	ac_v_y_2_2_	3001x1	48016	double
c	ac_v_z_1_1_	3001x1	48016	double
c	ac_v_z_1_2_	3001x1	48016	double
c	ac_v_z_2_1_	3001x1	48016	double
c	ac_v_z_2_2_	3001x1	48016	double
	ans	1x45	45	char
	frequency	1x1	8	double
	i_pr1_	1x1	8	double
	i_pr2_	1x1	8	double
	sp1_no_of_runs	3001x1	24008	double
	v_beta_	1x1	8	double

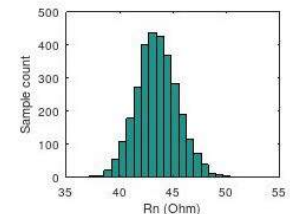
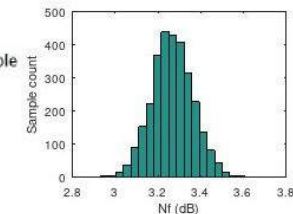
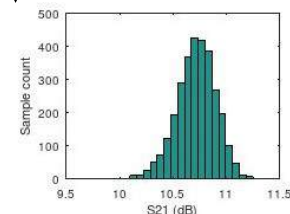
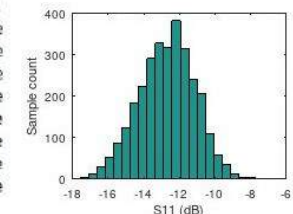
Total is 75074 elements using 960397 bytes

plotHistogramMike2.m

```

nbins = 21;
subplot(2,2,1);
hist(ac_s11db,nbins)
xlabel("S11 (dB)")
ylabel("Sample count")
%
subplot(2,2,2);
hist(ac_s21db,nbins)
xlabel("S21 (dB)")
ylabel("Sample count")
%
subplot(2,2,3);
hist(ac_v_nf_ ,nbins)
xlabel("Nf (dB)")
ylabel("Sample count")
%
subplot(2,2,4);
hist(ac_v_rn_ ,nbins)
xlabel("Rn (Ohm)")
ylabel("Sample count")

```

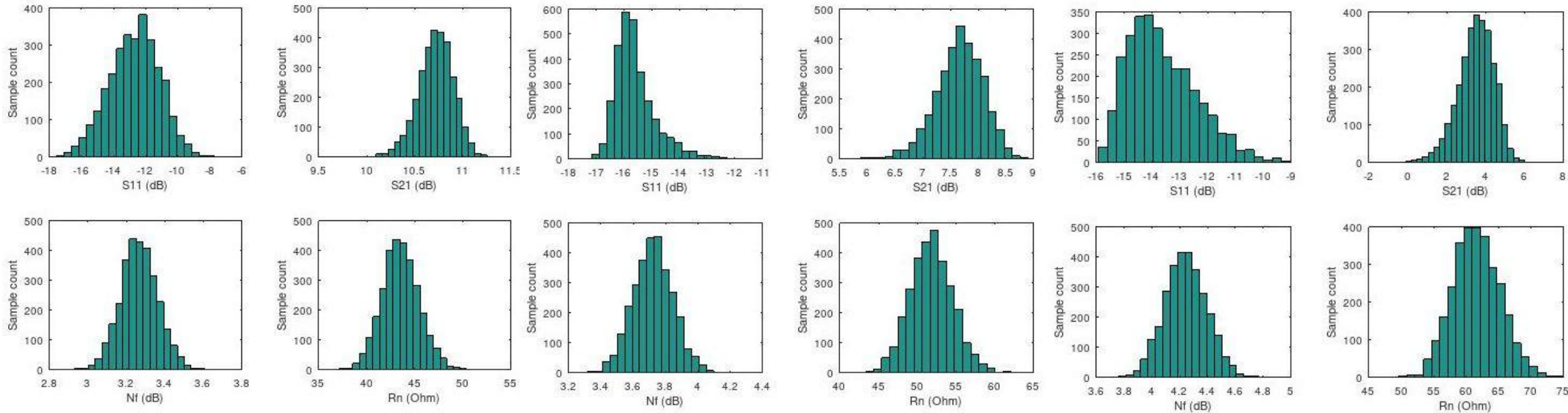


Corner Simulation Histograms

BCS

TYP

WCS



Improved RF Inductance Performance

RF
simulation

IC Layout

Octagonal Spiral Inductor

Use modified Wheeler model:

$$L = \frac{P1 \cdot \mu_0 \cdot n^2 \cdot d_{avg}}{1 + P2 \cdot \rho}$$

where:

L = inductance (H),

$\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m,

n is the number of turns,

$d_{avg} = \frac{d_{out} + d_{in}}{2}$ (the average diameter)

$\rho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}}$ (fill ratio), and

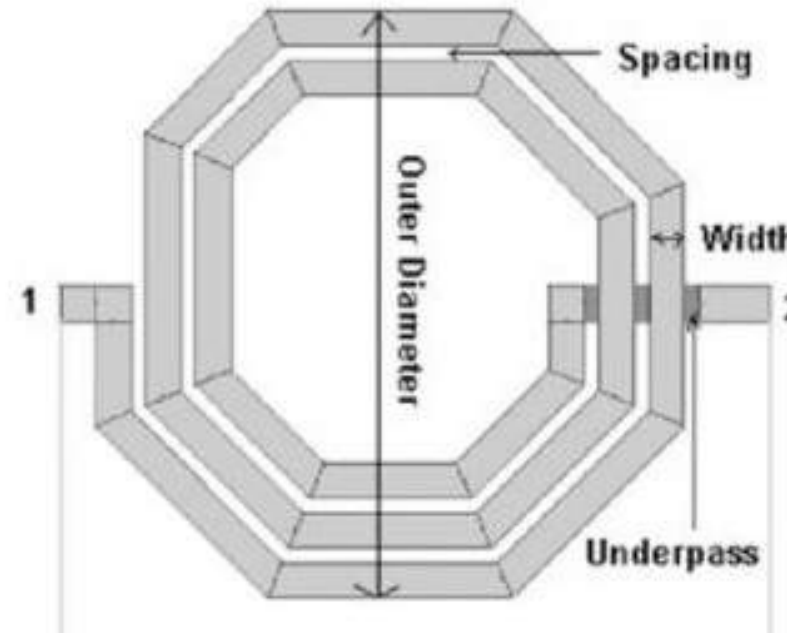
P1 = 2.34, P2 = 2.75 (typical values for an octagonal spiral)

For W = 5 μ m and S = 2 μ m

Dout = 50 μ m, Din = 20 μ m Davg = 35 μ m

and n = 1.5 turns, $\rho = 0.241$, giving

L = 133 pH.



→ openEMS

EM
simulation

XXXX.s2p



RF_L_1_tanDelta_1
Fr=100e9
Q=12
L=100p
K1=0
f0=40e9
tanDelta=0.005

Summary

- This presentation reports on the application of FOSS tools for RF IC design using the IHP open-access PDK for the SG13G2 130nm BiCMOS process node;
- Particular attention is given to illustrating how FOSS tools are applied in the construction user designed model libraries for RF IC design;
- A basic multi-section RLCG RF inductor model library, for the design of a 60GHz HBT LNA, is introduced and characterised;
- The LNA design is centred around a single HBT biased from a 1.2V d.c. voltage, and behavioural inductors employing RLCG transmission lines that include the effects of frequency dependant skin and proximity effects and substrate dielectric loss;
- The final section of the reported work introduces inductor design with octagonal spiral passive structures that are defined during IC layout, simulated by openEMS, characterised as s2p touchstone data and fed back to Qucs-S/Ngspice for simulation.
- Future work will continue the development of the topics presented at this workshop.

- [1] Brinson, Mike (2020) **The Qucs/QucsStudio and Qucs-S graphical user interface: an evolving “white-board” for compact device modeling and circuit simulation in the current era.** In the 27th International Conference on Mixed Design of Integrated Circuits and System (MIXDES), 25-27 June 2020, Lodz, Poland.
<https://doi.org/10.23919/MIXDES49814.2020.9155809>
- [2] **OpenVAF** a next-generation Verilog-A compiler that empowers the open source silicon revolution. <https://openvaf.semimod.de/>
- [3] **IHP-GmbH, Open Source PDK in 130nm BiCMOS**, developed for Analog/Digital, Mixed Signal and RF ASIC Design, <https://www.ihp-microelectronics.com/services/research-and-prototyping-service/fast-design-enablement/open-source-pdk>
- [4] **Ngspice** the next generation open source SPICE simulator.
<https://ngspice.sourceforge.io/>
- [5] **Si CMC** Standard Models. <https://si2.org/cmc-standard-models/>

References and software links : 2

[6] Brinson, Mike and Kuznetsov, Vadim (2016) **A new approach to compact semiconductor device modelling with Qucs Verilog-A analogue module synthesis**. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields. pp. 1-19. <http://onlinelibrary.wiley.com/doi/10.1002/jnm.216...>

[7] **GNU Octave** scientific programming language. <https://www.octave.org/>

[8] **OpenEMS** is a free and open electromagnetic field solver using the FDTD method. <https://www.openems.de/>

For more background on the use of open-access FOSS tools for IHP SG13G2 130nm BiCMOS IC design, see

Brinson, M. (2024, September 9). **QUCS-S - a central tool in the openPDK IC design flow**. 21 Zenodo. <https://doi.org/10.5281/zenodo.14178763>