April 2, 2019

Introduction to Surface Acoustic Wave (SAW) Devices

Part 7: Basics of RF Circuits

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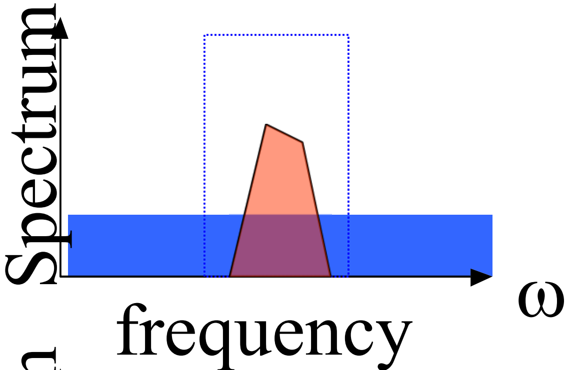
Contents

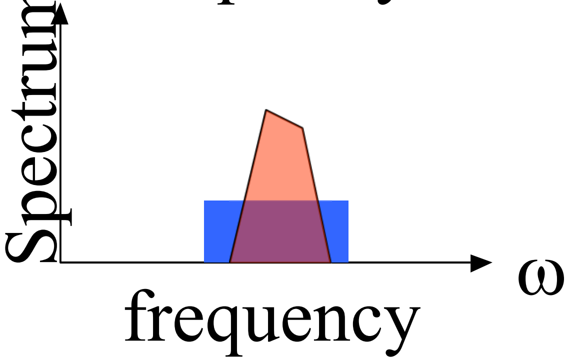
Contents

- Noise Figure and Non-Linearities

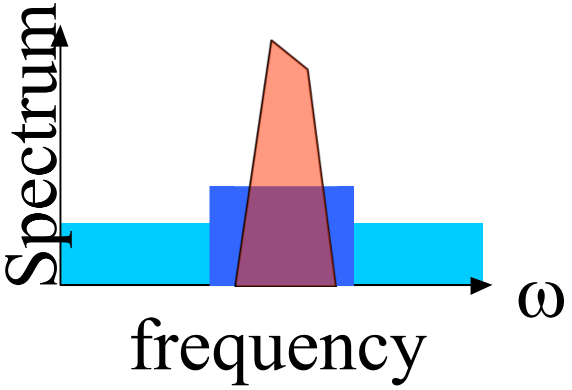
Signal to Noise Ratio (SNR)



(a) Signal +Noise



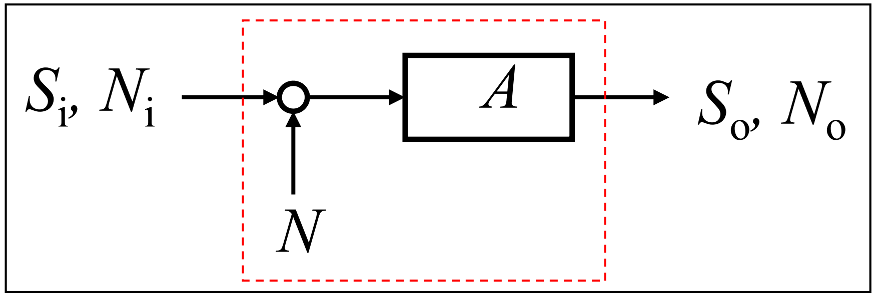
(b) After Front End Filtering



(c) After Front End
Amplifying

Noise Figure, NF

$$F = \frac{S_i / N_i}{S_o / N_o} = 1 + \frac{N}{N_i}$$ [Power Ratio] $$NF = 10\log F$$



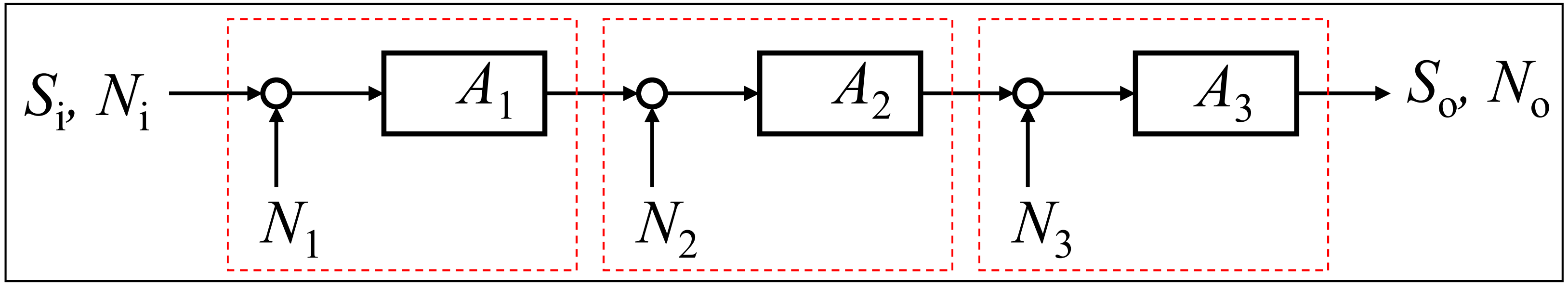
N_i: Input Noise Power

N_o: Output Noise Power

N: Thermal Noise

A: Power Gain

Cascade Connection



$$P_{\text{output}} = A_3(A_2(A_1(S_i + N_i + N_1) + N_2) + N_3)$$

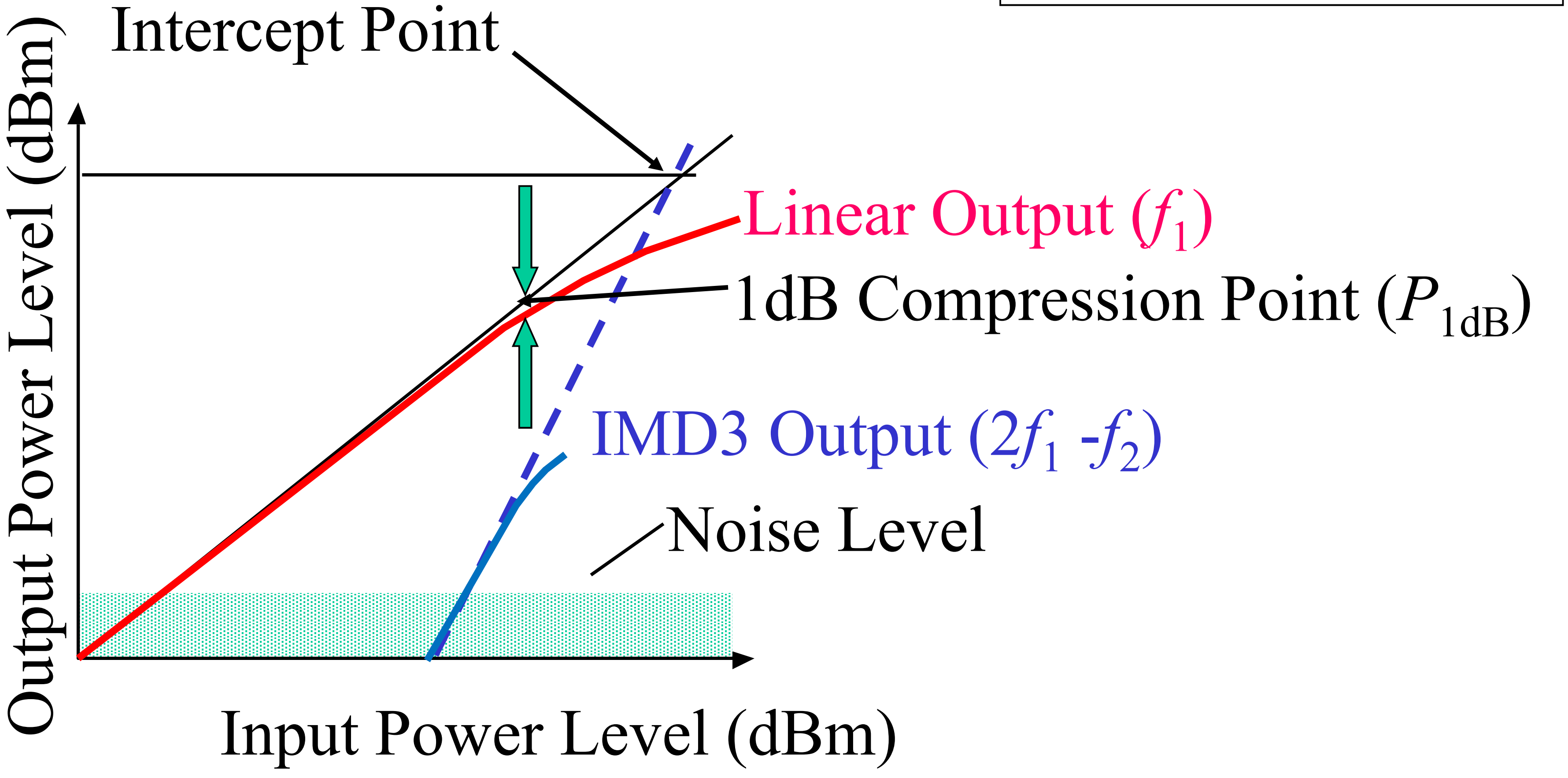
$$F = 1 + \frac{N_1}{N_i} + \frac{N_2}{N_i A_1} + \frac{N_3}{N_i A_1 A_2} = \boxed{F_1 +} \frac{F_2 - 1}{A_1} + \frac{F_3 - 1}{A_1 A_2}$$

Most Significant!

3rd order Intercept Point (IP3)

Generation of Jammer signals by Intermodulation

$\mathrm{IIP3} \approx P_{1\mathrm{dB}} + 9.6$ [dB]



Intercept Point

Linear Output (f_1)

1dB Compression Point ($P_{1\mathrm{dB}}$)

IMD3 Output ($2f_1 - f_2$)

Noise Level

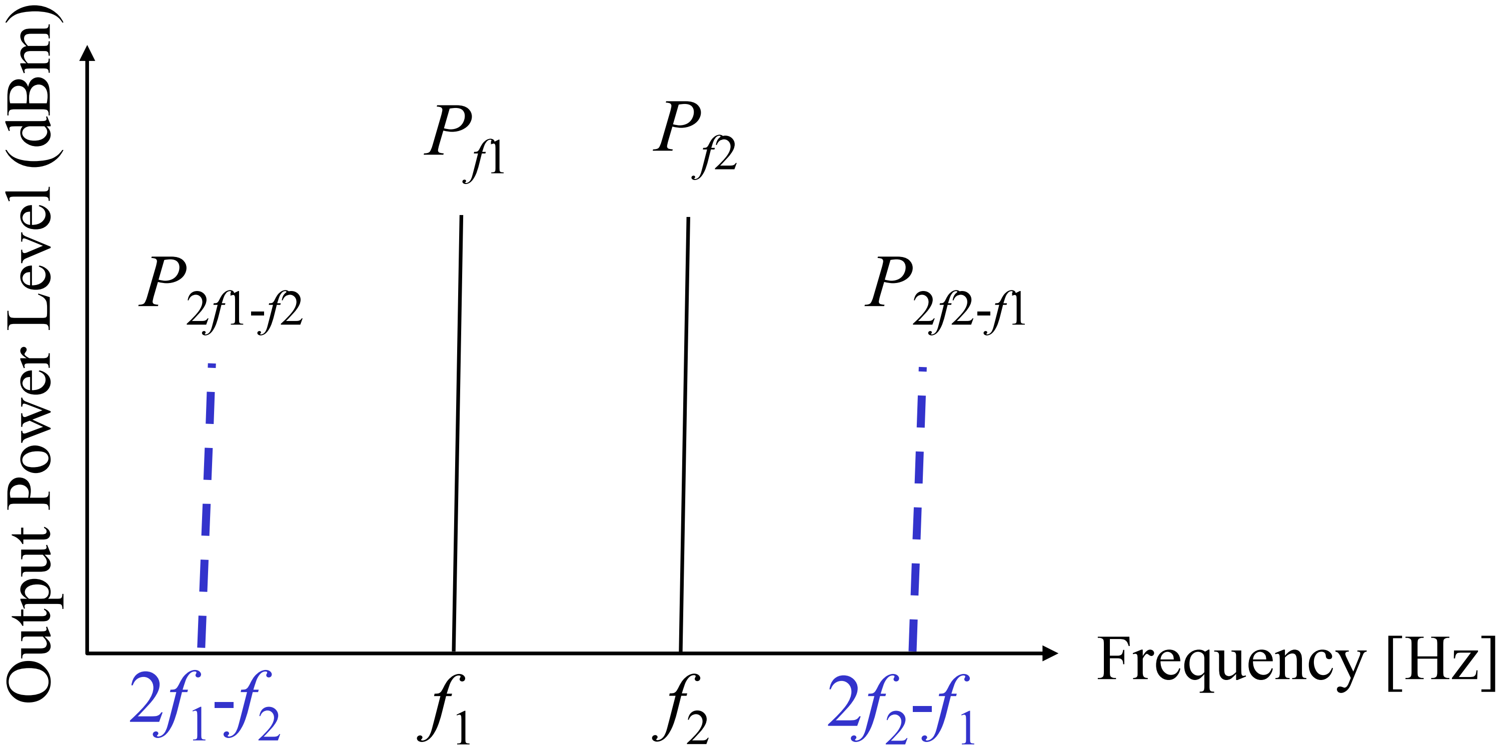
Output Power Level (dBm)

Input Power Level (dBm)

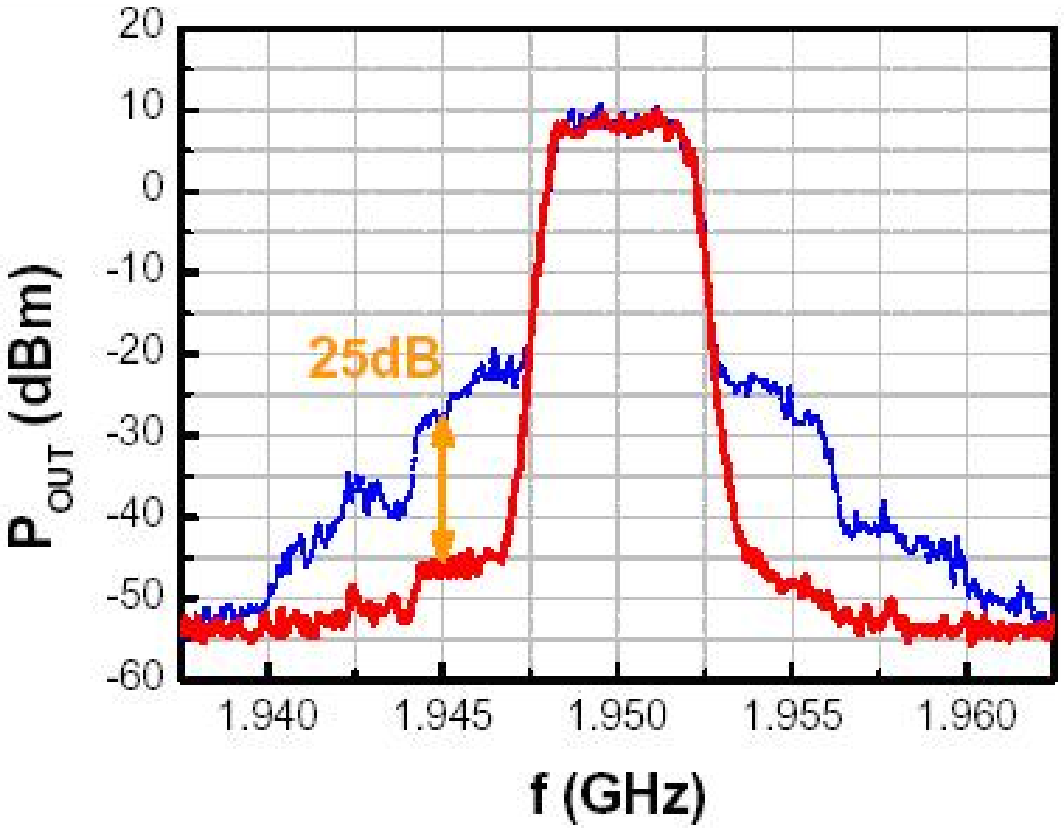
3rd order Intercept Point (IP3)

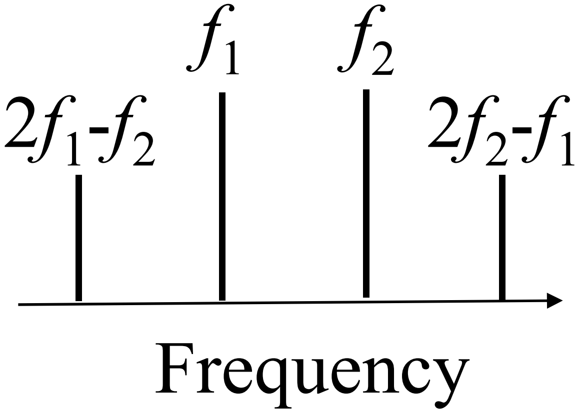
$$P_{2f1\text{-}f2}\ [\mathrm{dBm}] = 2P_{f1}\ [\mathrm{dBm}] + P_{f2}\ [\mathrm{dBm}] - 2\times \mathrm{IP3}\ [\mathrm{dBm}]$$

$$P_{2f2\text{-}f1}\ [\mathrm{dBm}] = 2P_{f2}\ [\mathrm{dBm}] + P_{f1}\ [\mathrm{dBm}] - 2\times \mathrm{IP3}\ [\mathrm{dBm}]$$



Spectrum Regrowth in PA and DPX = Self Mixing of Tx Signals

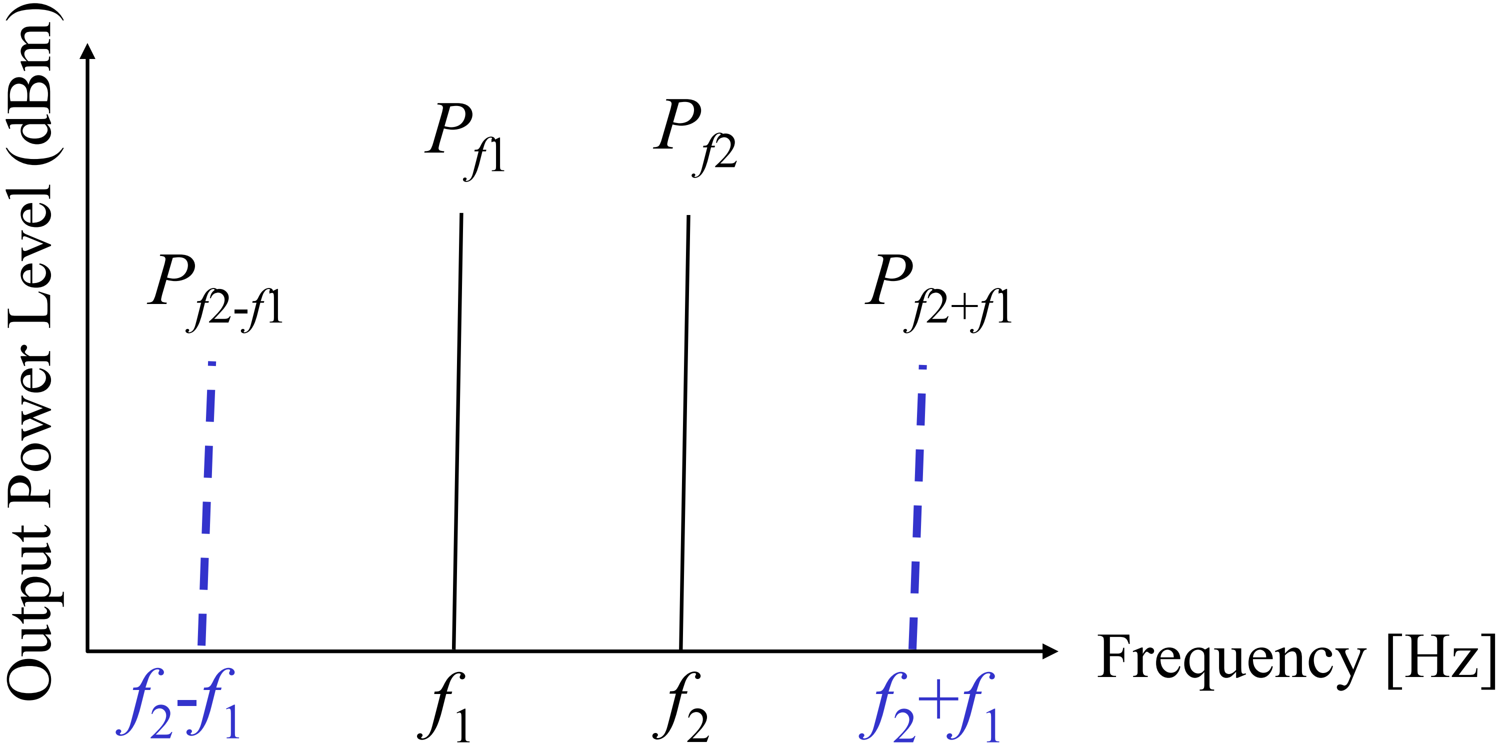




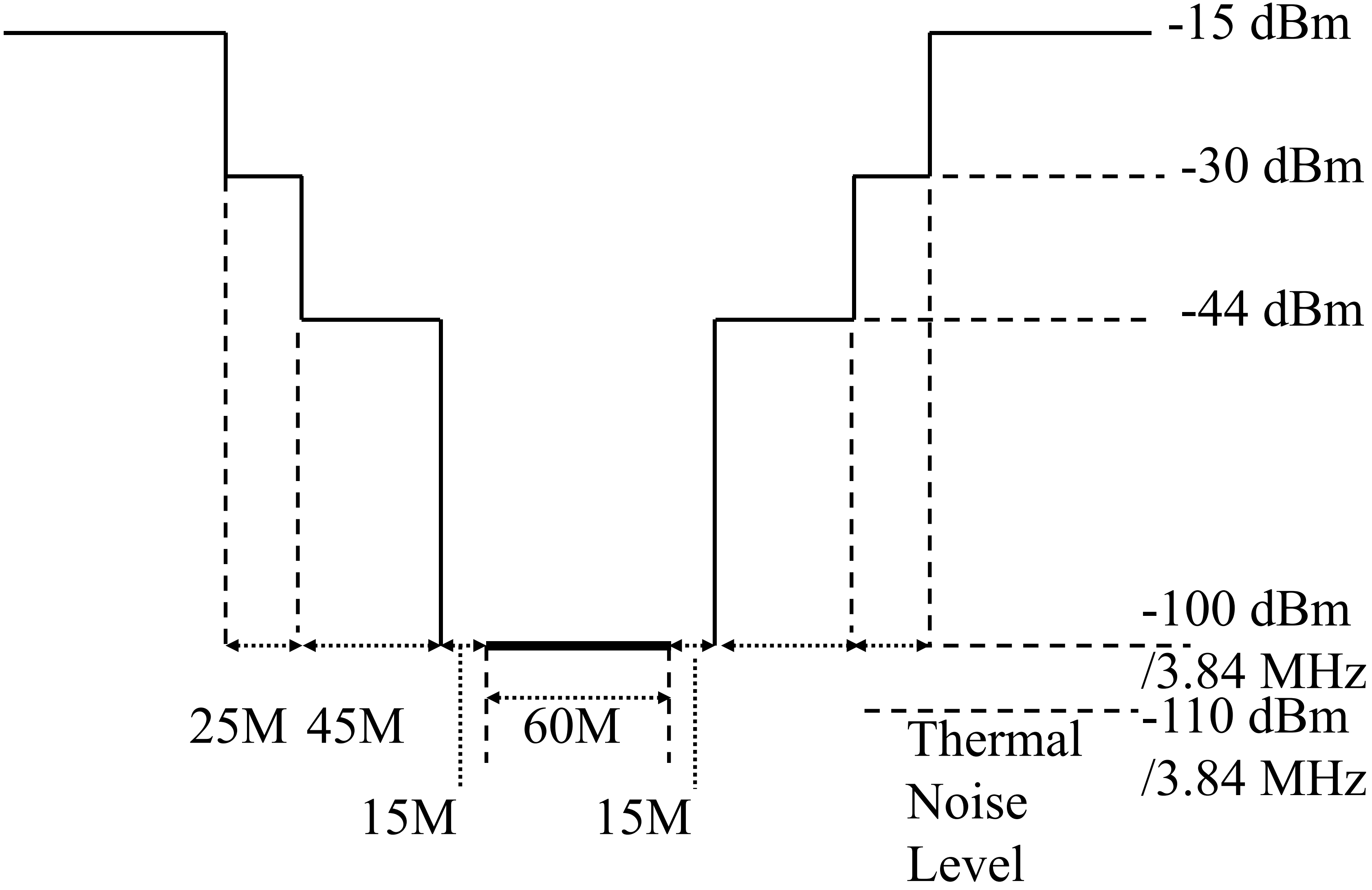
Jammer Signal Emission to Adjacent Channels

2nd order Intercept Point (IP2)

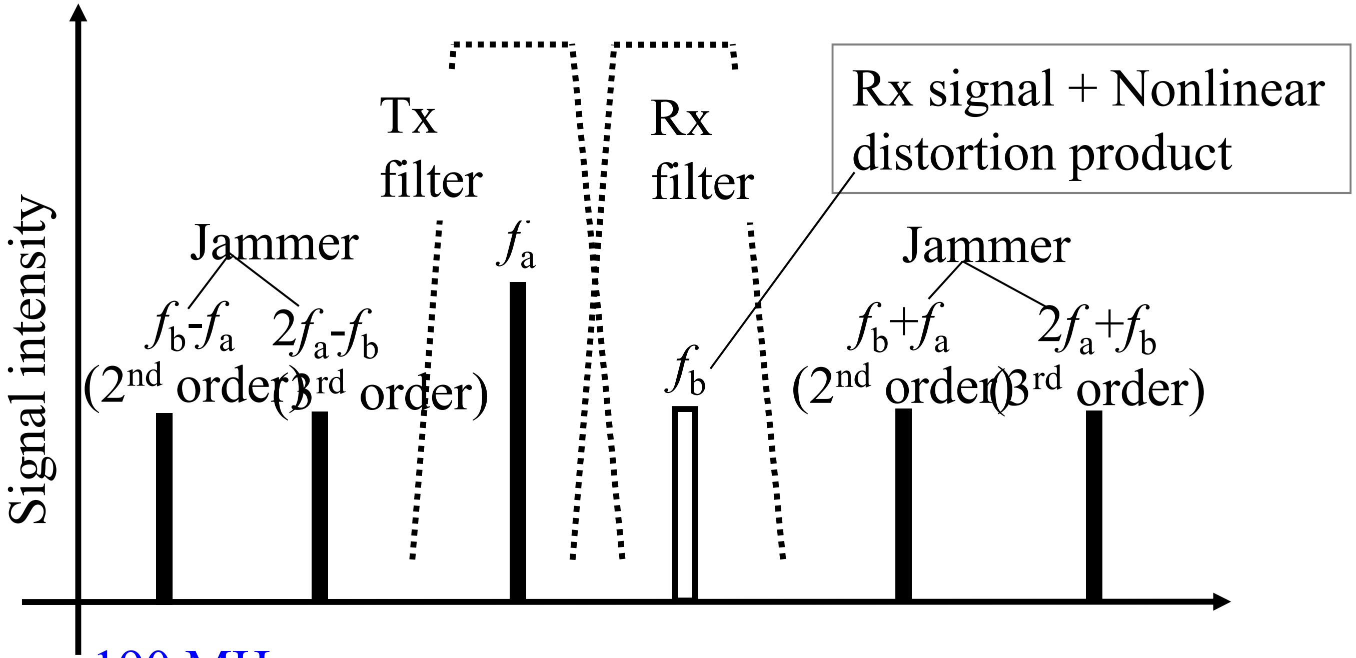
$$P_{f2\pm f1}\ [\text{dBm}] = P_{f2}\ [\text{dBm}] + P_{f1}\ [\text{dBm}] - \text{IP2}\ [\text{dBm}]$$



Blocking Test Example（W-CDMA Band II）



Inter Modulation Distortion in Nonlinear Circuit for WCDMA System



Band1
Tx: 1920 - 1980 MHz
Rx: 2110 - 2170 MHz

190 MHz

1730 - 1790 MHz

4030 - 4150 MHz

5950 - 6010 MHz

Jammer Frequency

Band2
Tx: 1850 - 1910 MHz
Rx: 1930 - 1990 MHz

80 MHz

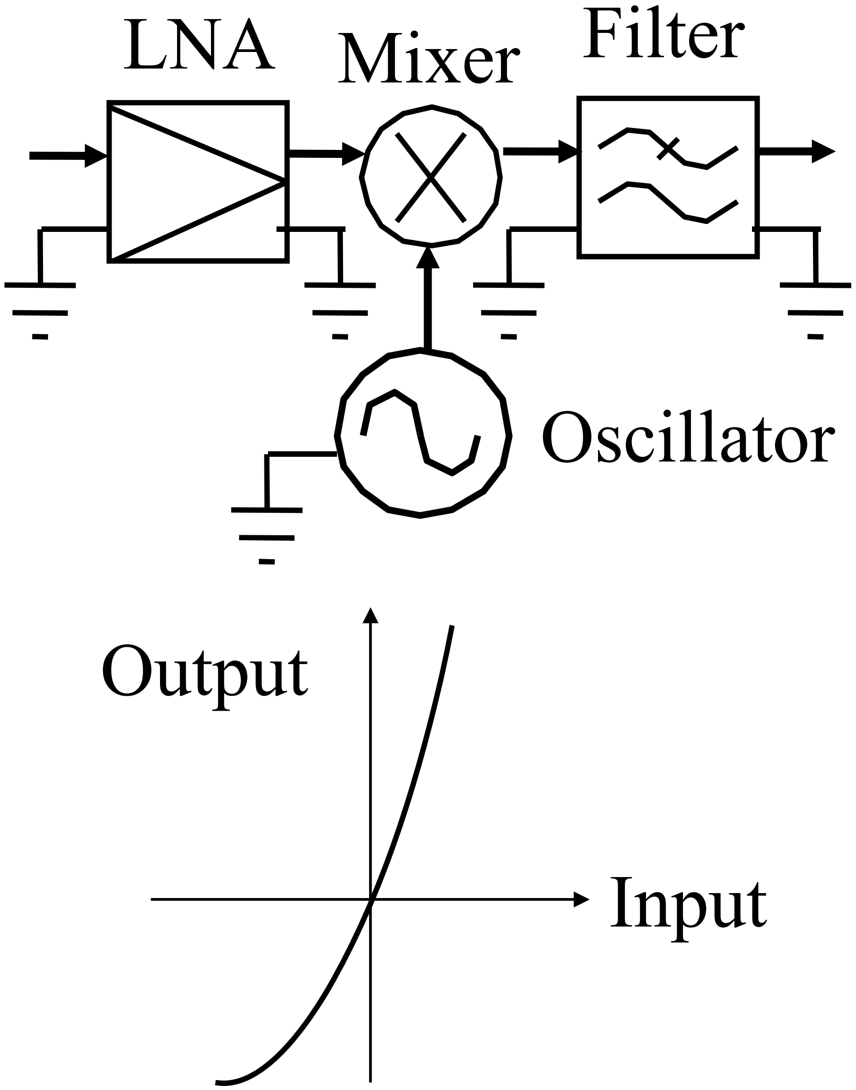
1770 - 1830 MHz

3780 - 3900 MHz

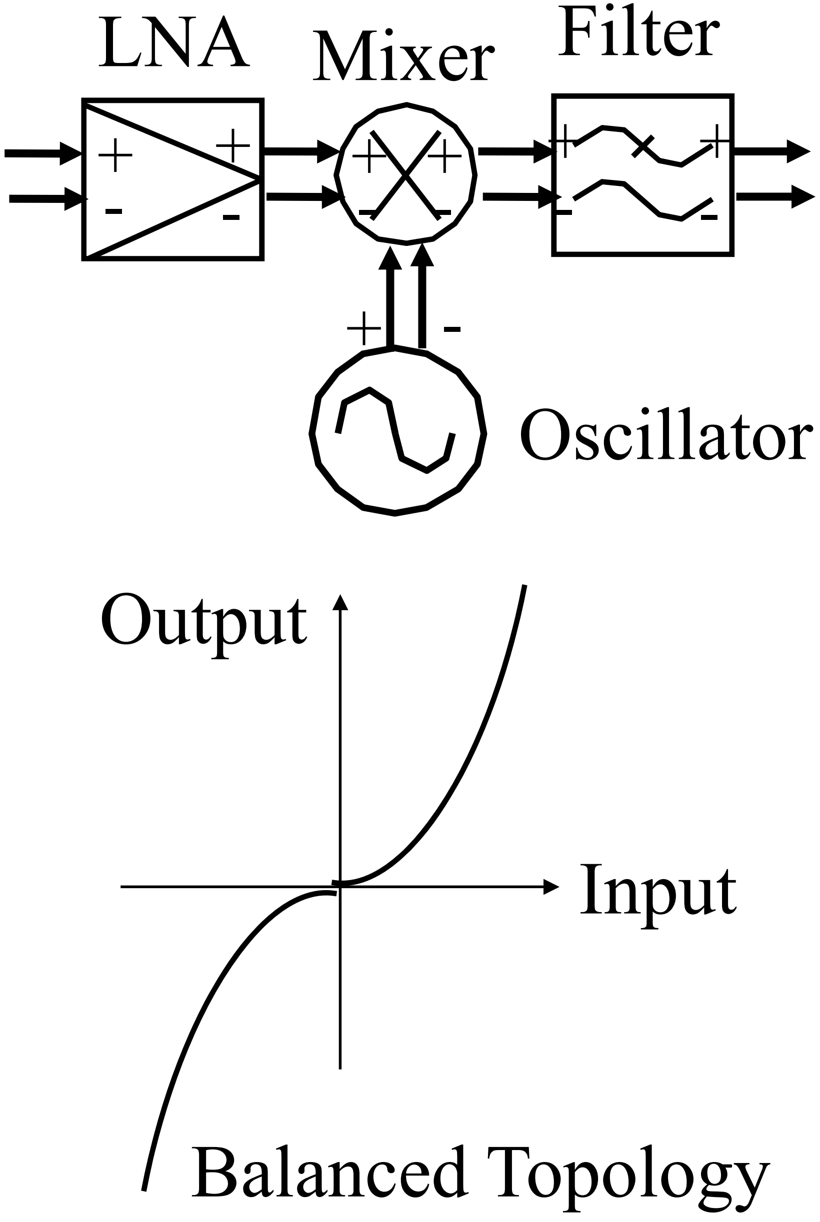
5630 - 5810 MHz

Jammer Frequency

IP2 Suppression by Balanced Topology



Unbalanced Topology

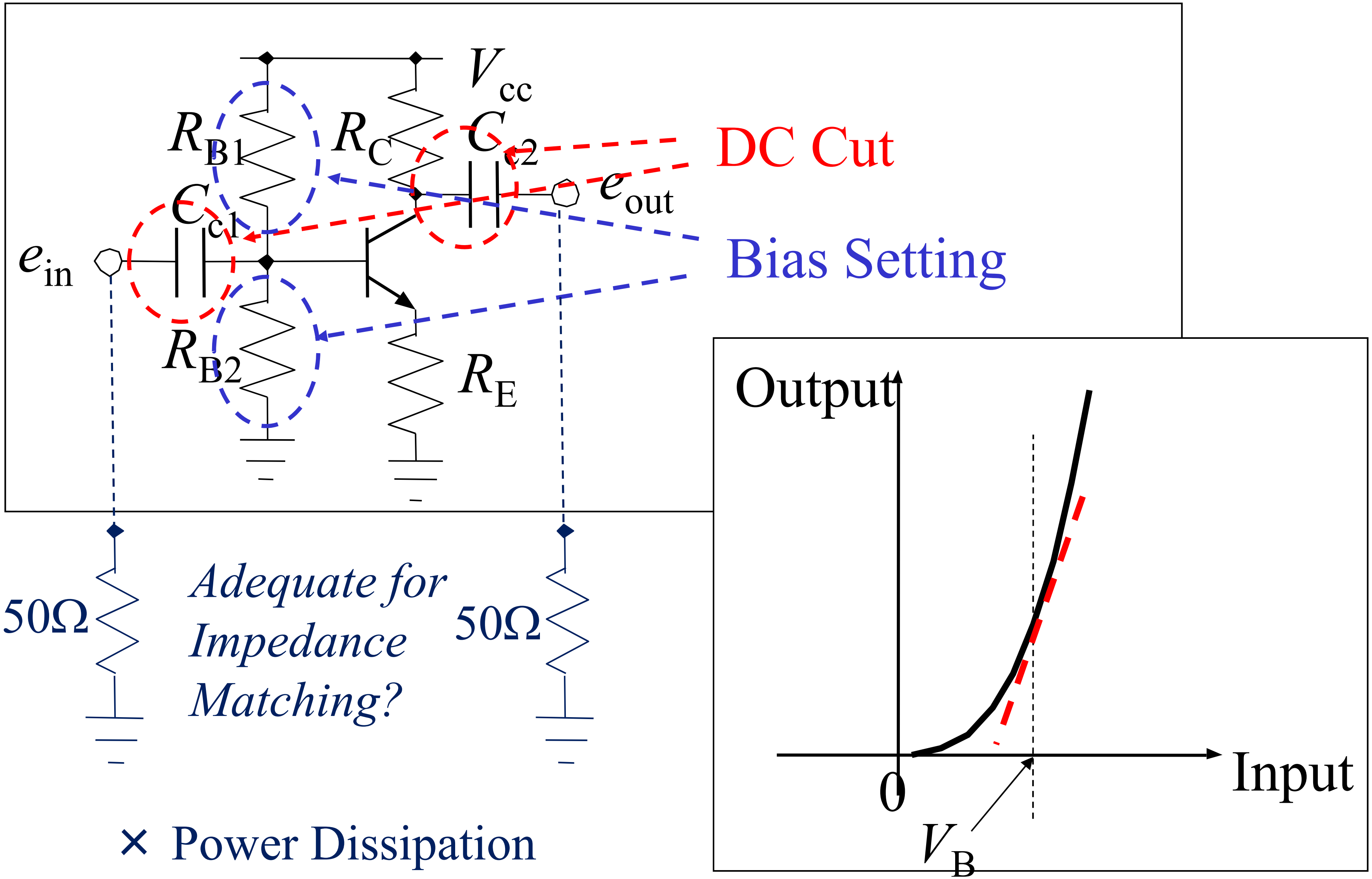


Balanced Topology

Contents

- RF Amplifier

Capacitor Coupled LF Amplifier



DC Cut

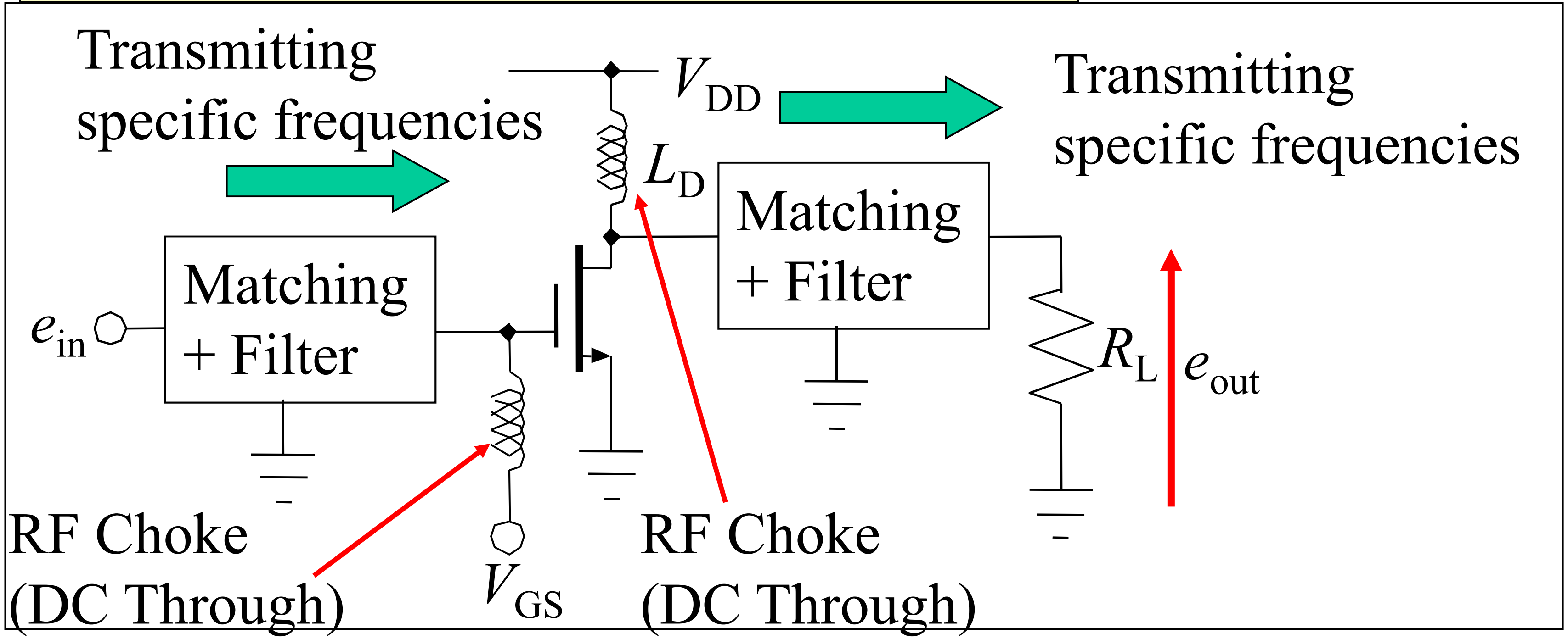
Bias Setting

Adequate for Impedance Matching?

× Power Dissipation
× Noise Generation

Vias Voltage

RF Amplifier Configuration



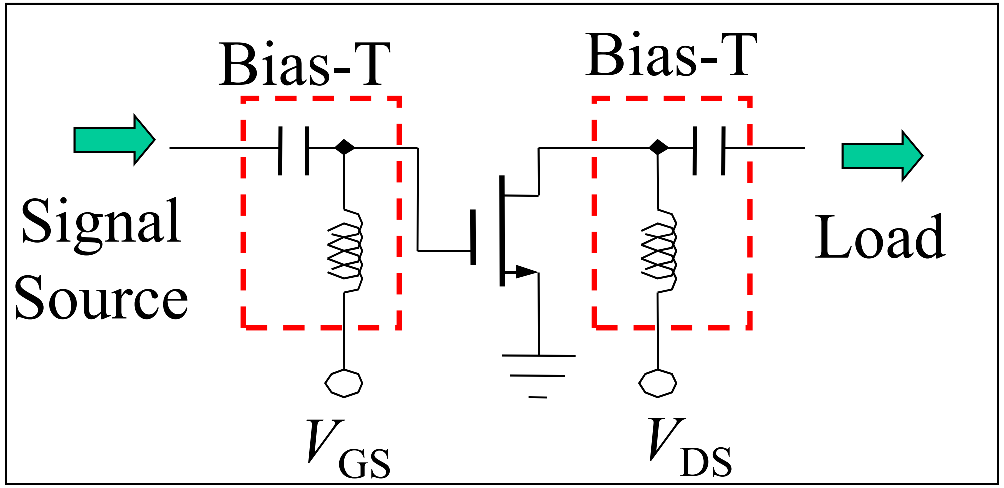
Transmitting specific frequencies

Transmitting specific frequencies

RF Choke (DC Through)

RF Choke (DC Through)

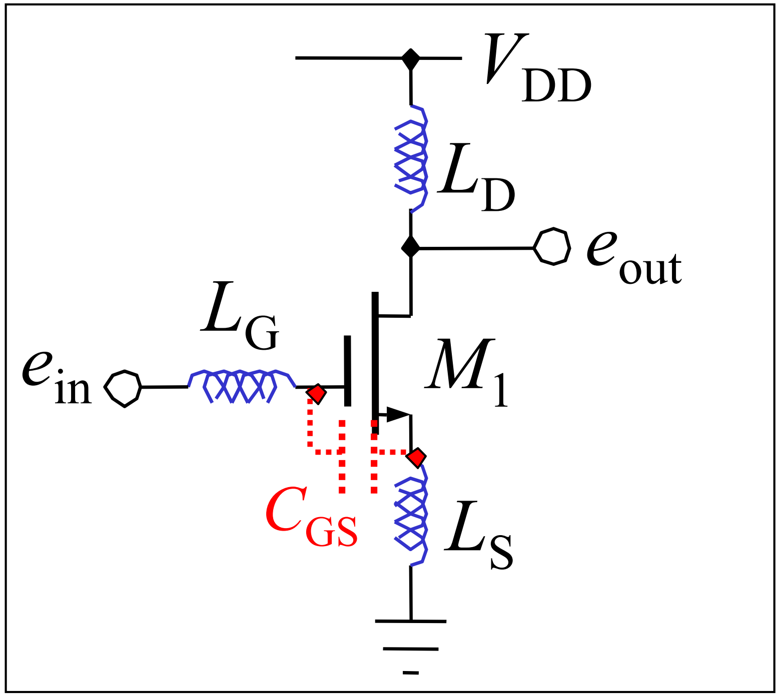
Measurement of Transistor *S* Parameters



Small Signal Measurement for Given Bias Condition

(For R_0=50 Ω)

Common Source Amplifier



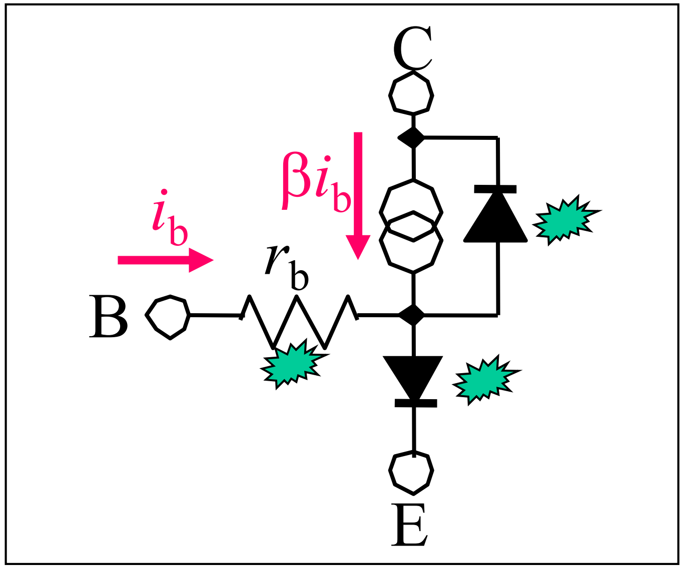
L_{G}, L_{S} → Impedance Matching

L_{D} → RF Choke

Large Voltage Gain

$$Z_{\mathrm{in}} = i\omega L_{\mathrm{G}} + \frac{1}{i\omega C_{\mathrm{GS}}} + i\omega L_{\mathrm{S}}\left[1 + \frac{g_{\mathrm{m}}}{i\omega C_{\mathrm{GS}}}\right]$$

$$= \underbrace{\boxed{\frac{L_S g_m}{C_{GS}}}}_{\rightarrow 50\Omega} + \boxed{i\omega(L_{\mathrm{G}} + L_{\mathrm{S}}) + \frac{1}{i\omega C_{\mathrm{GS}}}} \rightarrow 0$$

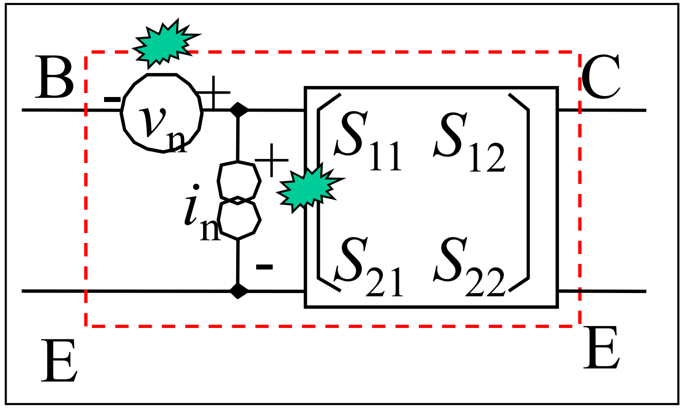


Noise Generation

Thermal Noise (Resistance Origin)

+ Shot Noise (Junction Origin)

Small Signal Model (Linearize)



Input Referred Noise

$i_n = i_c + i_u$

i_c: correlated with v_n ($\equiv \boxed{Y_c} v_n$)

i_u: not-correlated with v_n

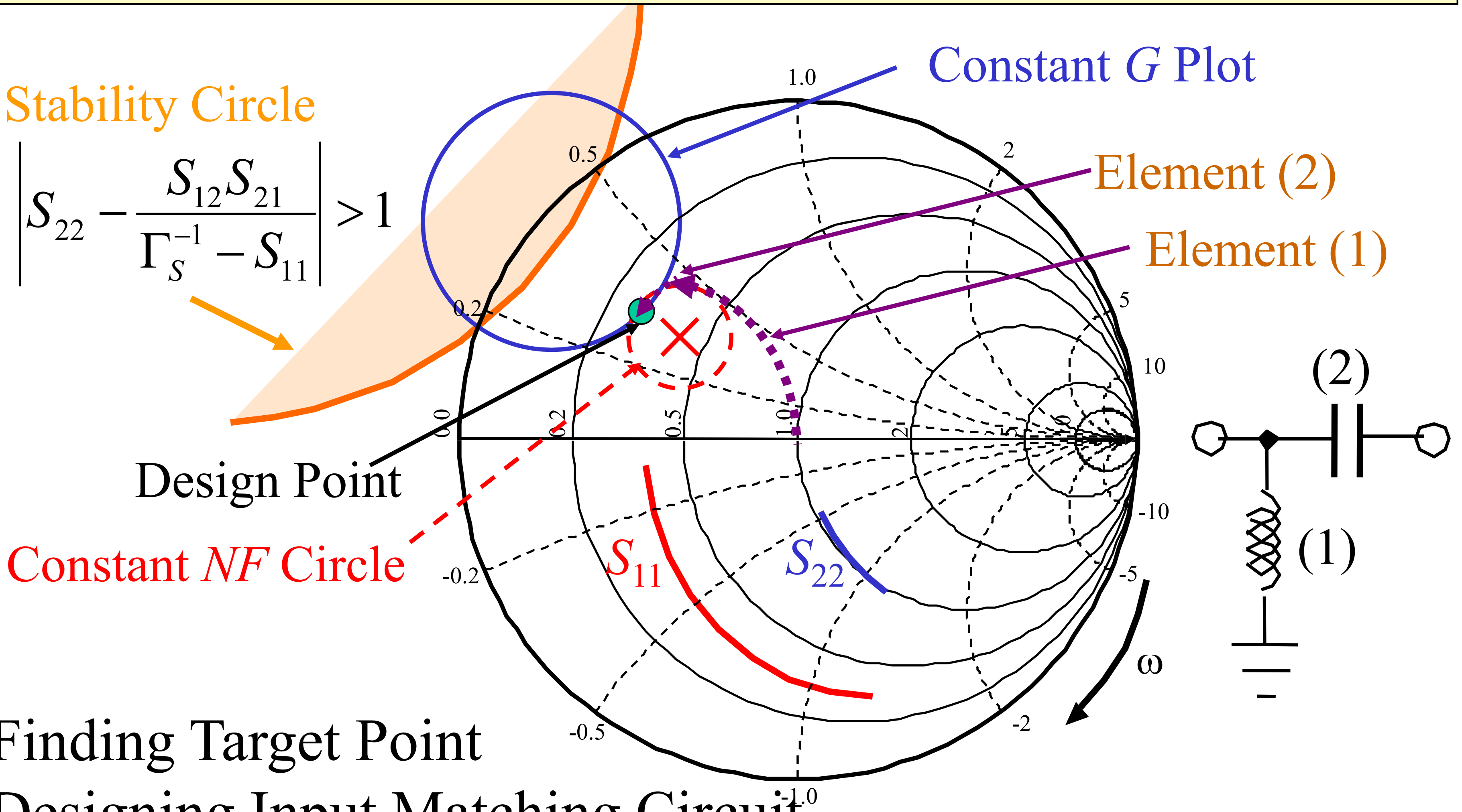
$$\left.\begin{aligned} \overline{v_n^2} &= 4kTB\boxed{R_n} \\ \overline{i_u^2} &= 4kTB\boxed{G_u} \end{aligned}\right\} \quad B\text{: Frequency Bandwidth}$$

Rollet Stability (*K*) Factor

Unconditionally Stable When $K>1$

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|^2}{2|S_{21}S_{12}|}$$

Matching Circuit Design Using Smith Chart



$$\left| S_{22} - \frac{S_{12}S_{21}}{\Gamma_S^{-1} - S_{11}} \right| > 1$$

•Finding Target Point

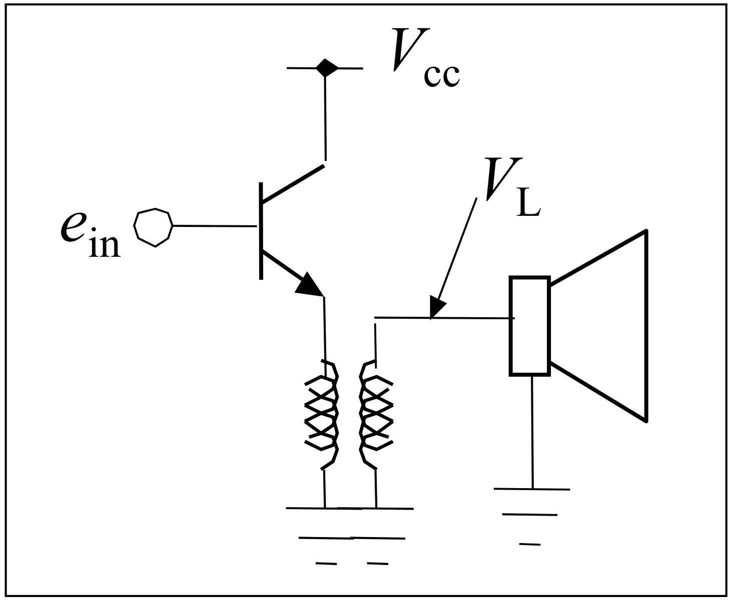
•Designing Input Matching Circuit

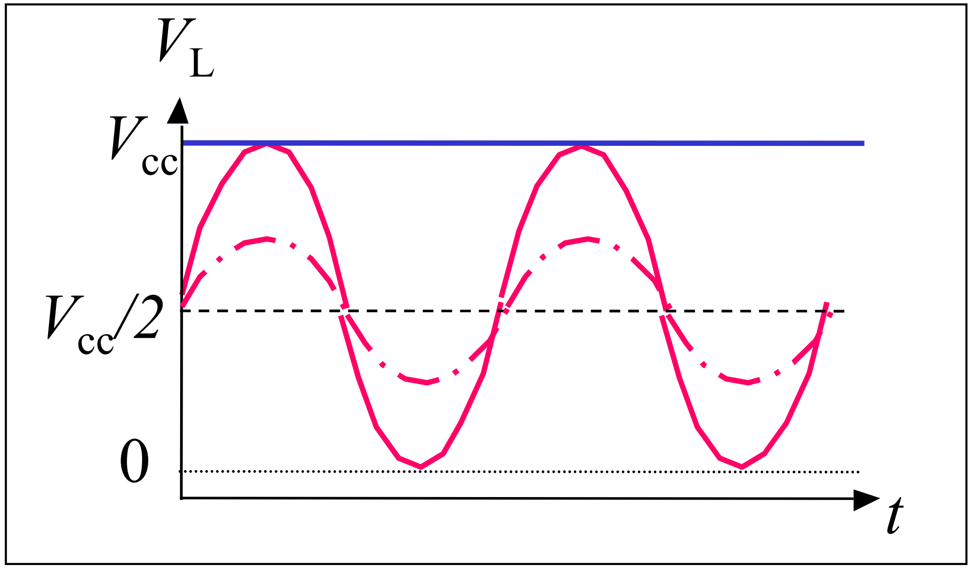
•Designing Output Matching Circuit

•Verification (Often S_{11} and S_{22} are NOT acceptable

Gain and *NF* are Dependent on Bias Current (Voltage)

Power Efficiency η of Class A Amplifier

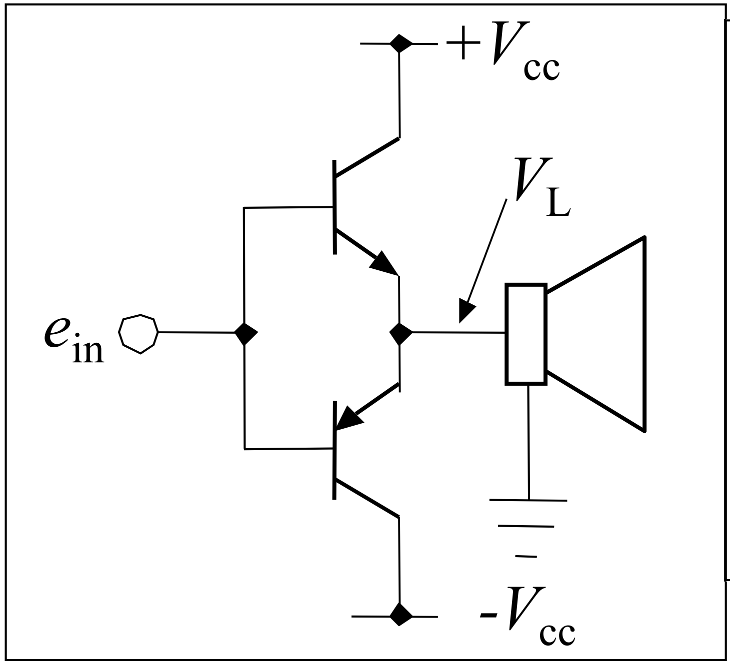


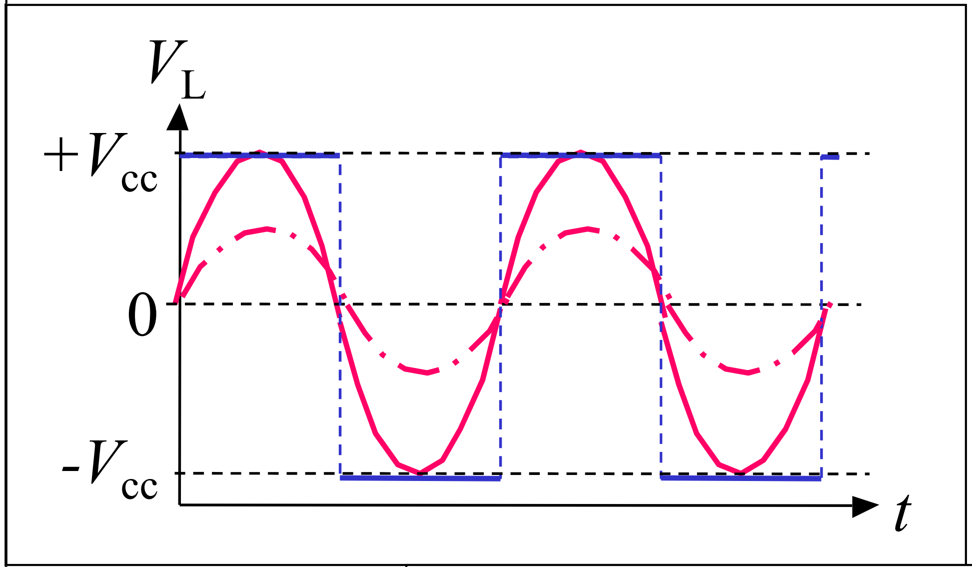


$$\eta = \frac{\frac{1}{R_L}\frac{1}{T}\int_0^T [V_o \sin(2\pi t/T)]^2 dt}{\frac{1}{R_L}\frac{1}{T}\int_0^T V_{cc}\left[\frac{V_{cc}}{2} + V_o \sin(2\pi t/T)\right]dt} = \left[\frac{V_o}{V_{cc}}\right]^2$$

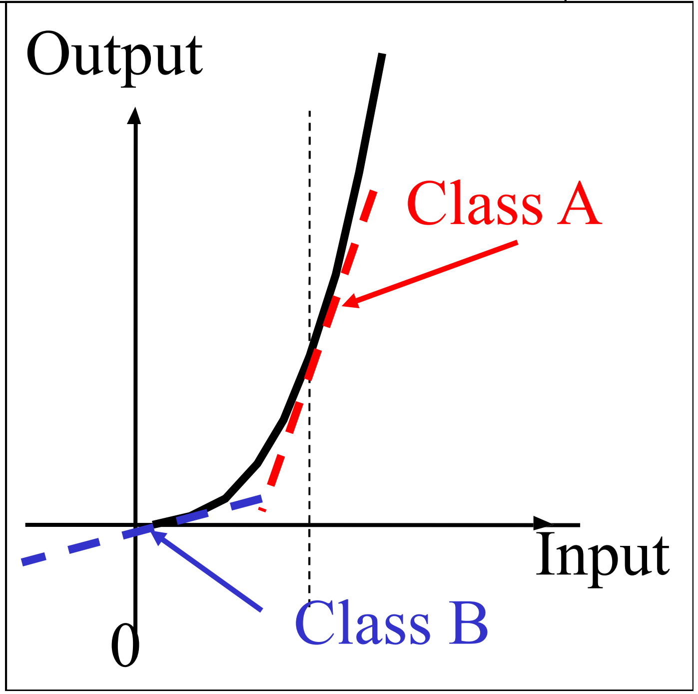
Maximum η 25% (at $V_o = V_{cc}/2$)

Power Efficiency η of Class B Amplifier

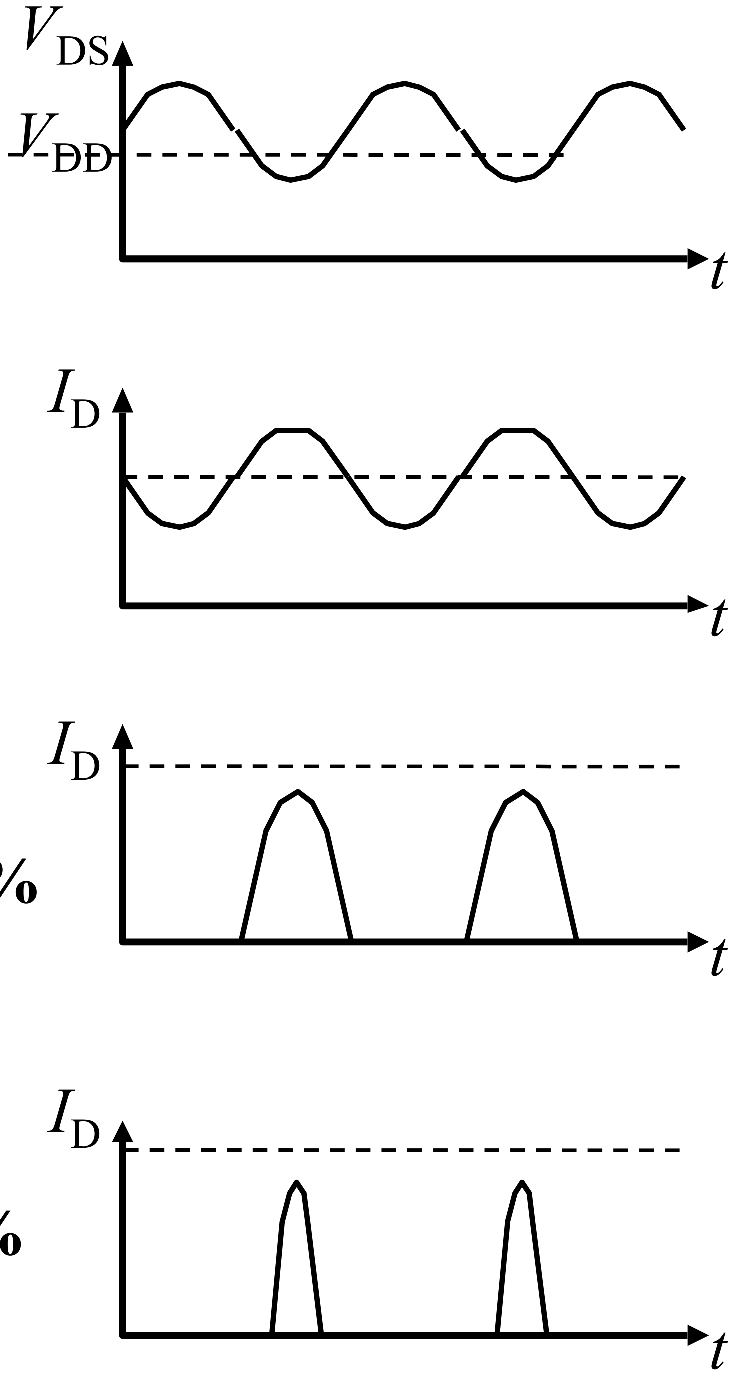




$$\eta = \frac{\frac{1}{R_L}\frac{2}{T}\int_0^{T/2}\left[V_o \sin(2\pi t/T)\right]^2 dt}{\frac{1}{R_L}\frac{2}{T}\int_0^{T/2}V_{cc}\left[V_o \sin(2\pi t/T)\right]dt} = \frac{\pi}{4}\left[\frac{V_o}{V_{cc}}\right]$$



Maximum η 78.5% (at V_o=V_{cc})



Class A

η_{max}=50% for RF

Class B

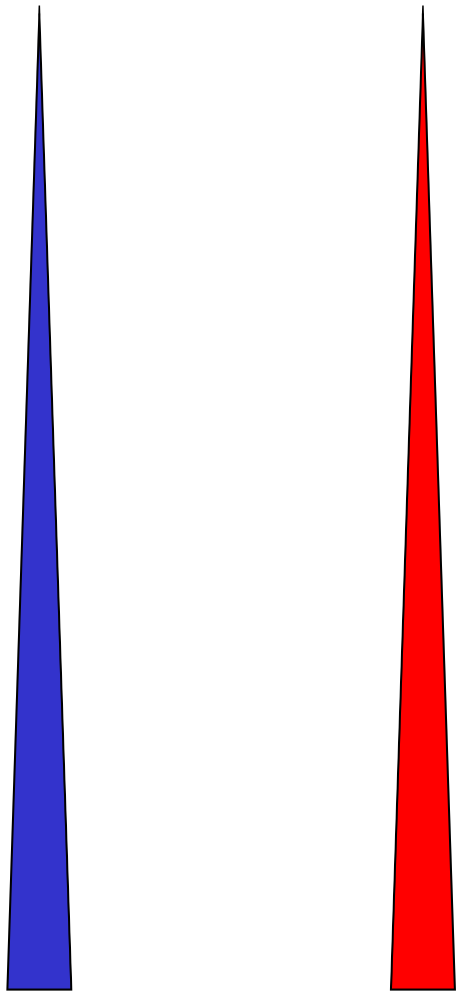
η_{max}=78.5%

Class C

η_{max}=100%

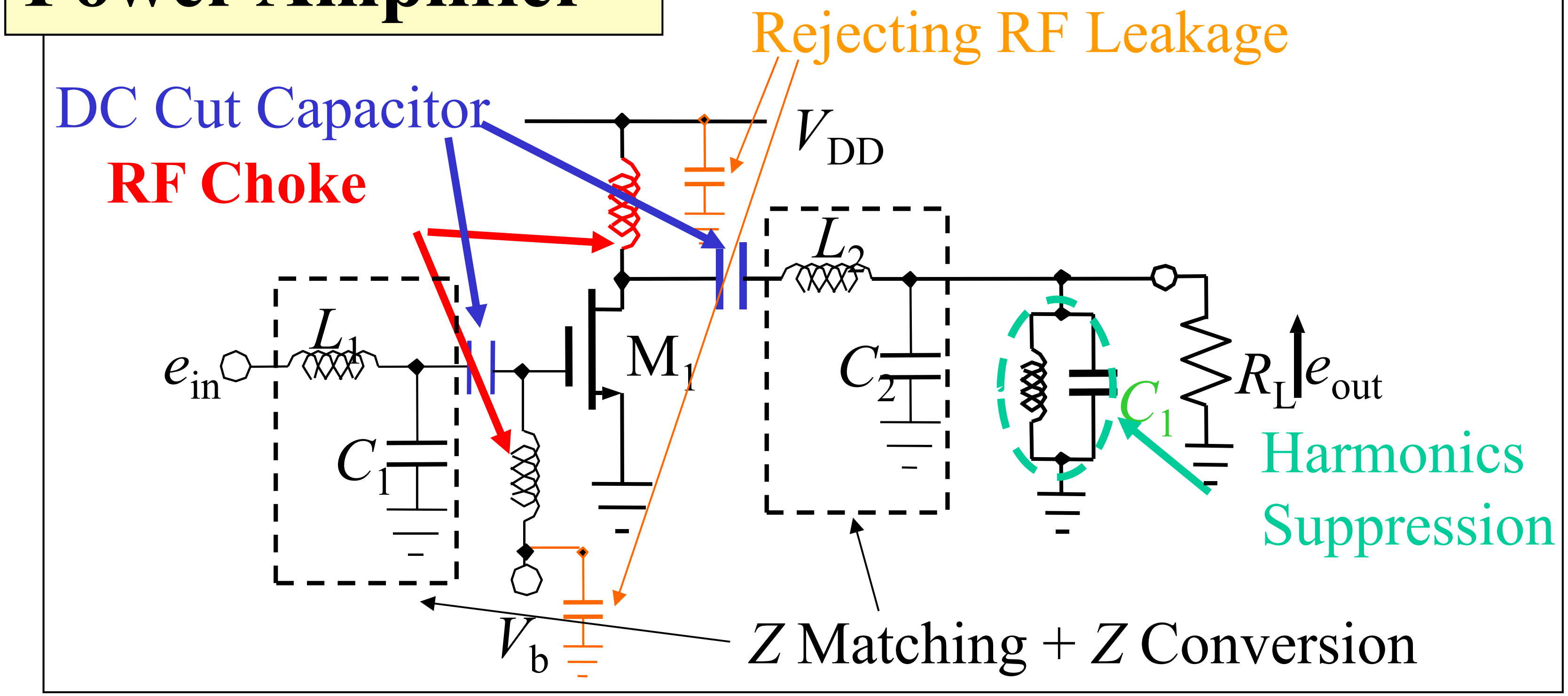
(At P=0)

Efficiency **Distortion**



Good **Bad**

Power Amplifier



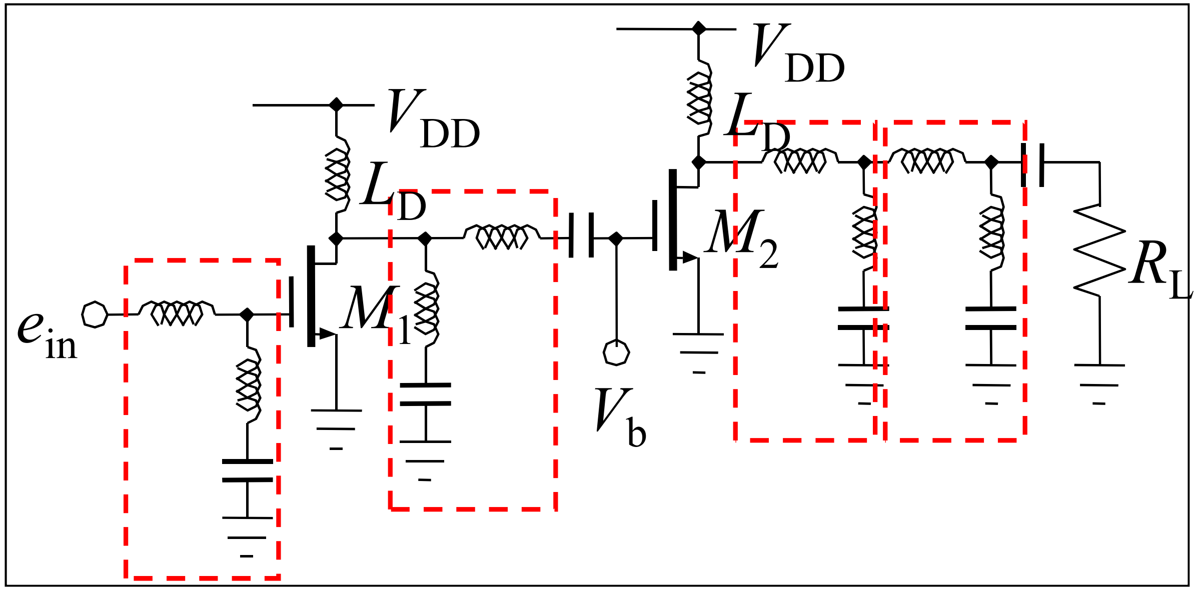
DC Cut Capacitor

RF Choke

Rejecting RF Leakage

Harmonics Suppression

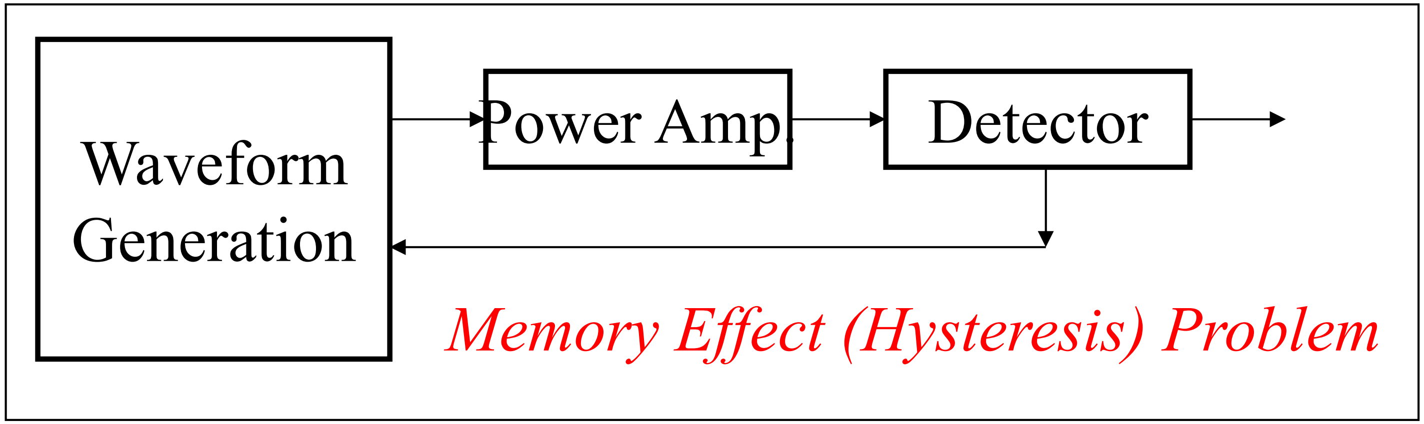
Z Matching + *Z* Conversion



Driver + Main Amplifier

Linear High Efficiency PA

Pre-distortion Feedback Compensation



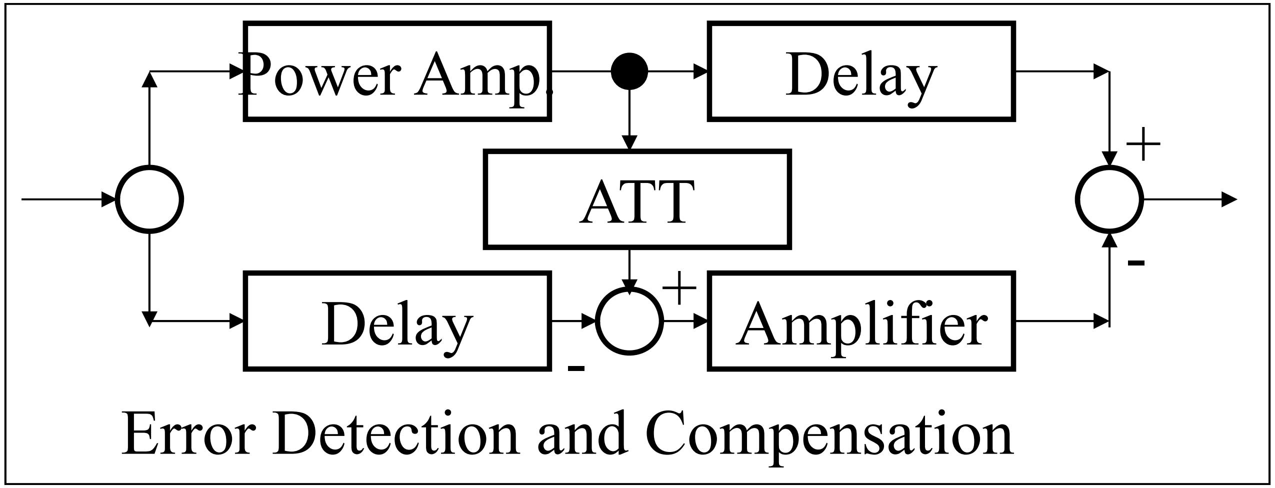
Waveform Generation

Power Amp

Detector

Memory Effect (Hysteresis) Problem

Feed-Forward PA



Power Amp

Delay

ATT

Delay

Amplifier

+

-

+

-

Error Detection and Compensation

Linear Amplifier with Non-linear Components (LINC)

$$E(t) = A(t)\sin(\omega_c t + \varphi(t))$$

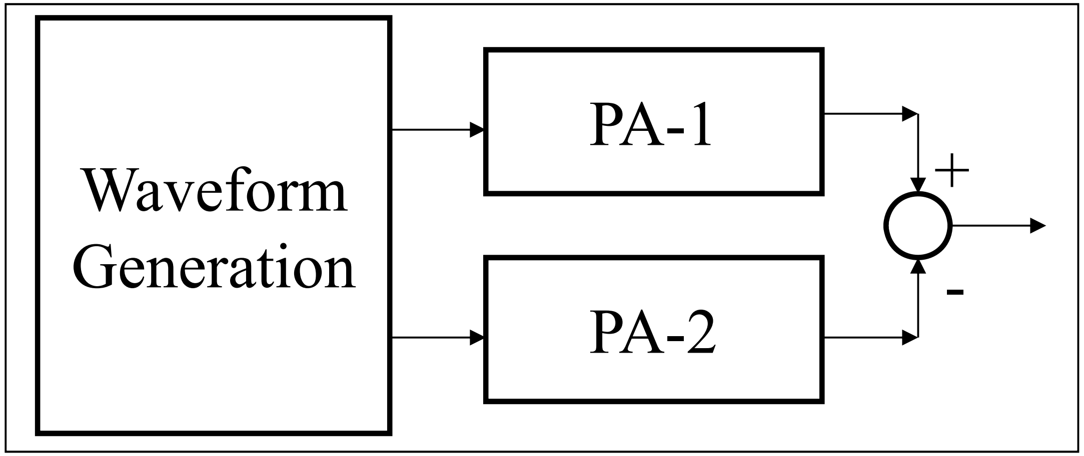
$$= \frac{A_{\max}}{2}[\underline{\cos(\omega_c t + \varphi(t) - \theta(t))} - \underline{\cos(\omega_c t + \varphi(t) + \theta(t))}]$$

where $\theta(t)=\cos^{-1}(A(t)/A_{\max})$

Constant Amplitude

⬇

Non-Linear PA Applicable

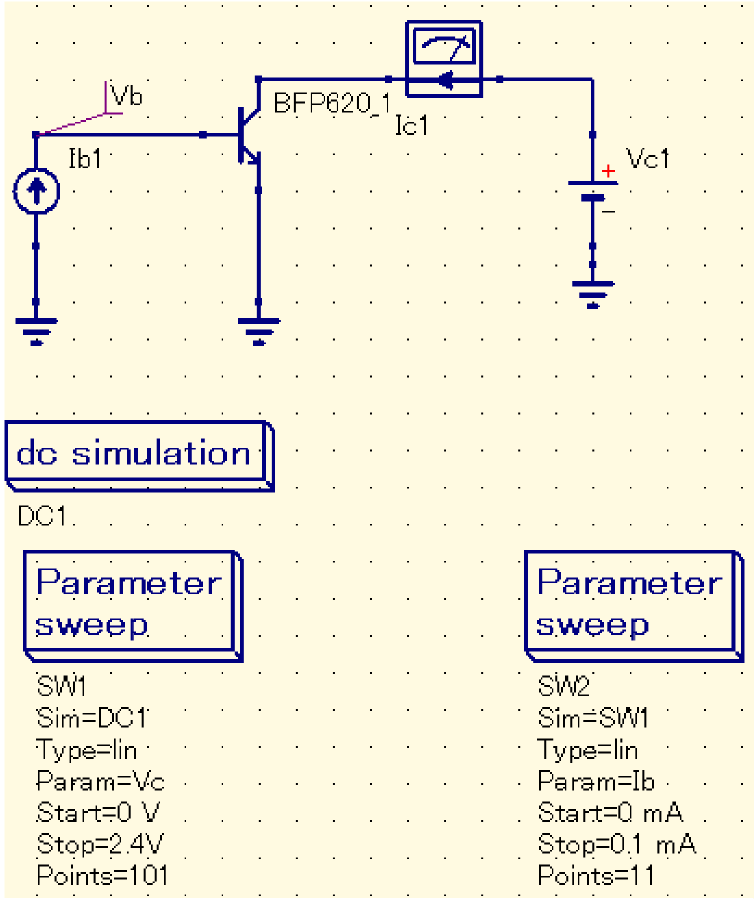


Contents

- Low Noise Amplifier Design Example

Use of High Speed Transistor BFP620

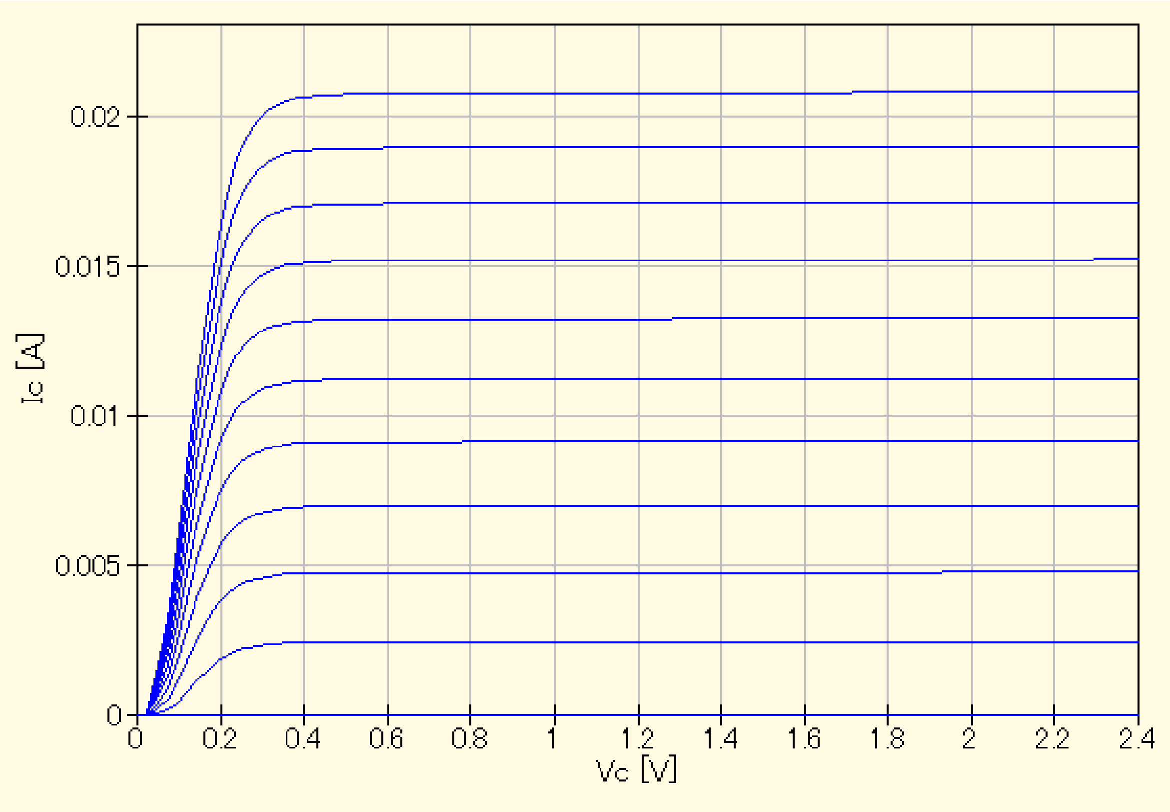
Design Low Noise Amplifier at 2.488 GHz. V_{cc}=1.5 V and I_c=5 mA. Low NF and Return Suppression Mandatory. How High Gain Achievable?



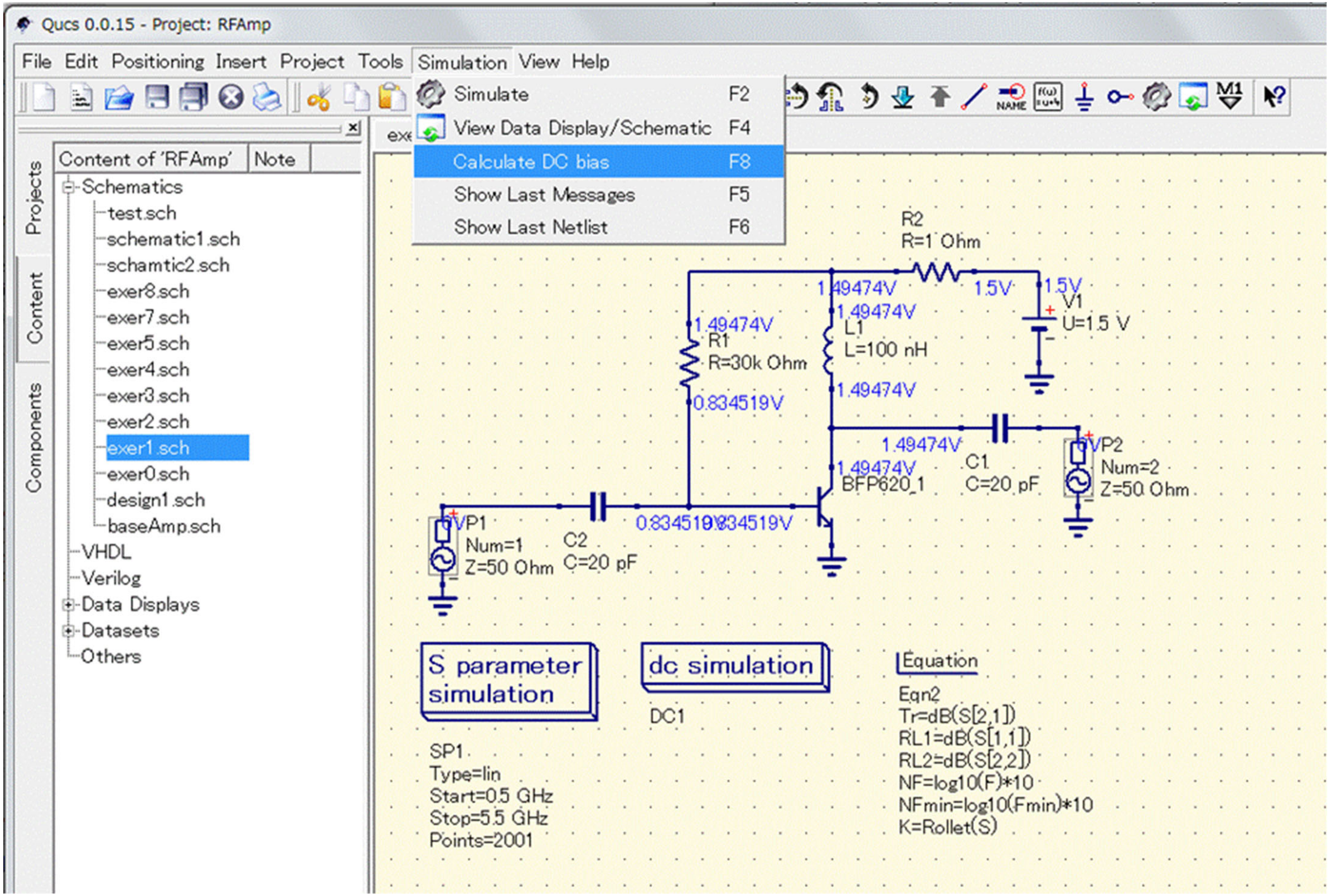
DC1

SW1
Sim=DC1
Type=lin
Param=Vc
Start=0 V
Stop=2.4V
Points=101

SW2
Sim=SW1
Type=lin
Param=Ib
Start=0 mA
Stop=0.1 mA
Points=11



Step 1 Bias Circuit Design



R2
R=1 Ohm

V1
U=1.5 V

R1
R=30k Ohm

L1
L=100 nH

C1
C=20 pF

BFP620_1

P2
Num=2
Z=50 Ohm

P1
Num=1
Z=50 Ohm

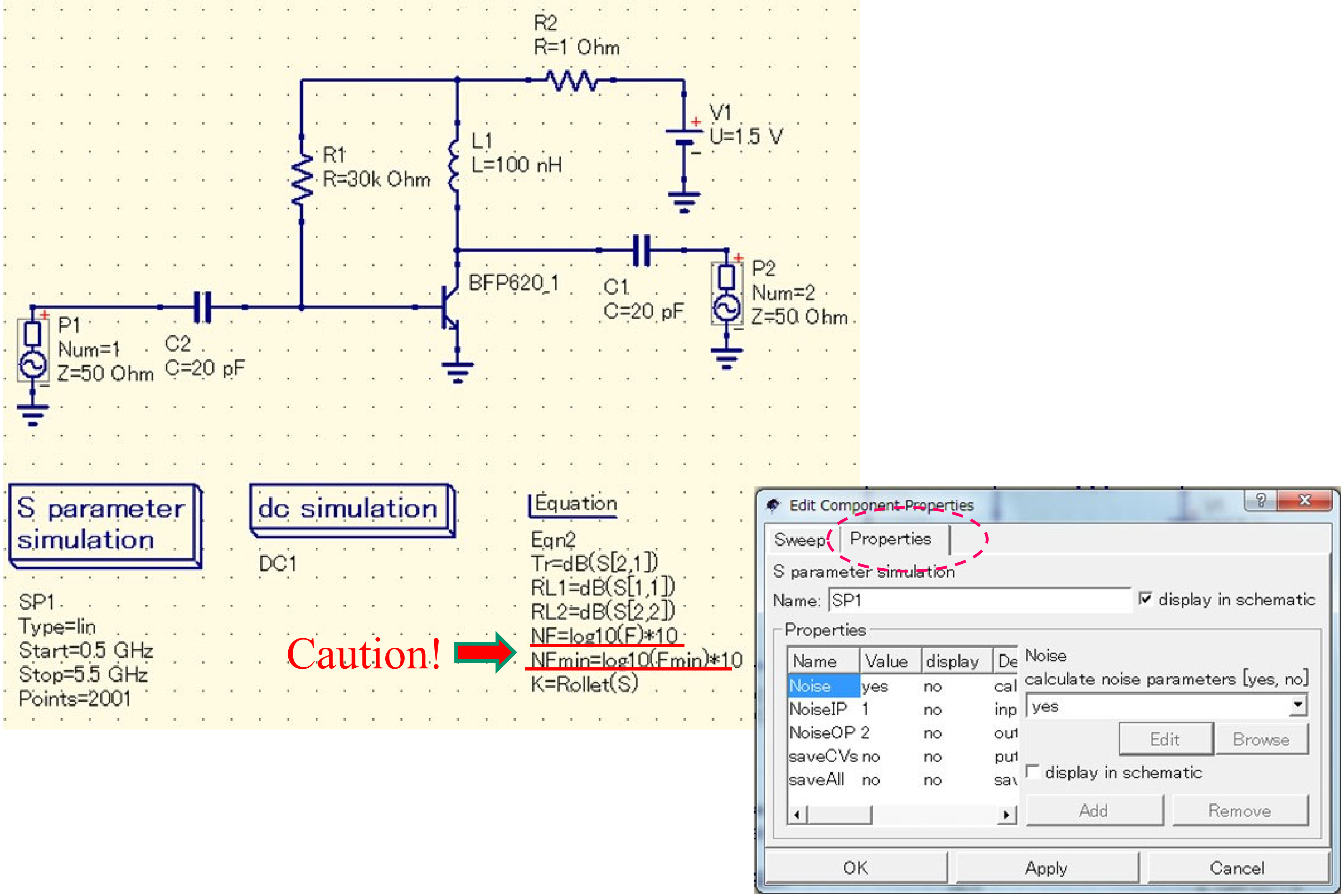
C2
C=20 pF

SP1
Type=lin
Start=0.5 GHz
Stop=5.5 GHz
Points=2001

DC1

Eqn2
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10
K=Rollet(S)

Step 2 *S* Parameter Simulation



SP1
Type=lin
Start=0.5 GHz
Stop=5.5 GHz
Points=2001

Eqn2
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10
K=Rollet(S)

Caution!

S parameter simulation

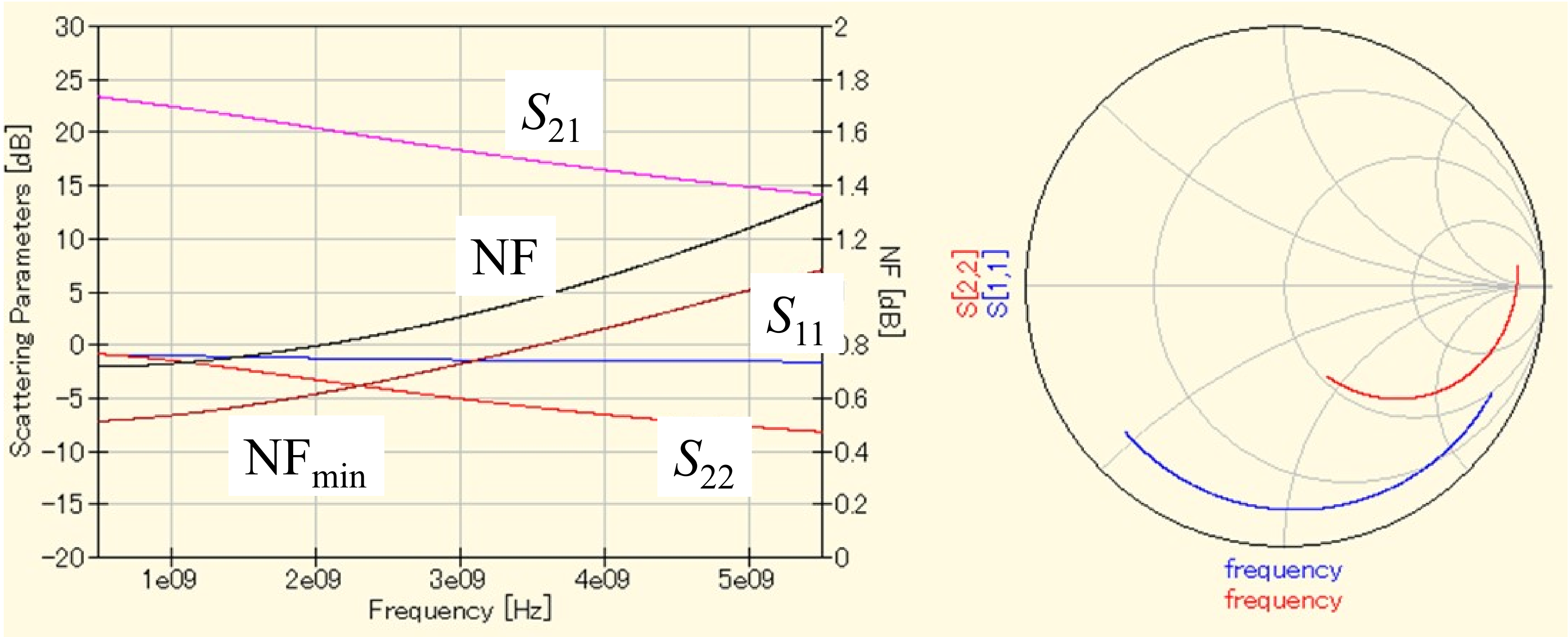
Name: SP1 ☑ display in schematic

Properties

Name	Value	display	De
Noise	yes	no	cal
NoiseIP	1	no	inp
NoiseOP	2	no	out
saveCVs	no	no	put
saveAll	no	no	sav

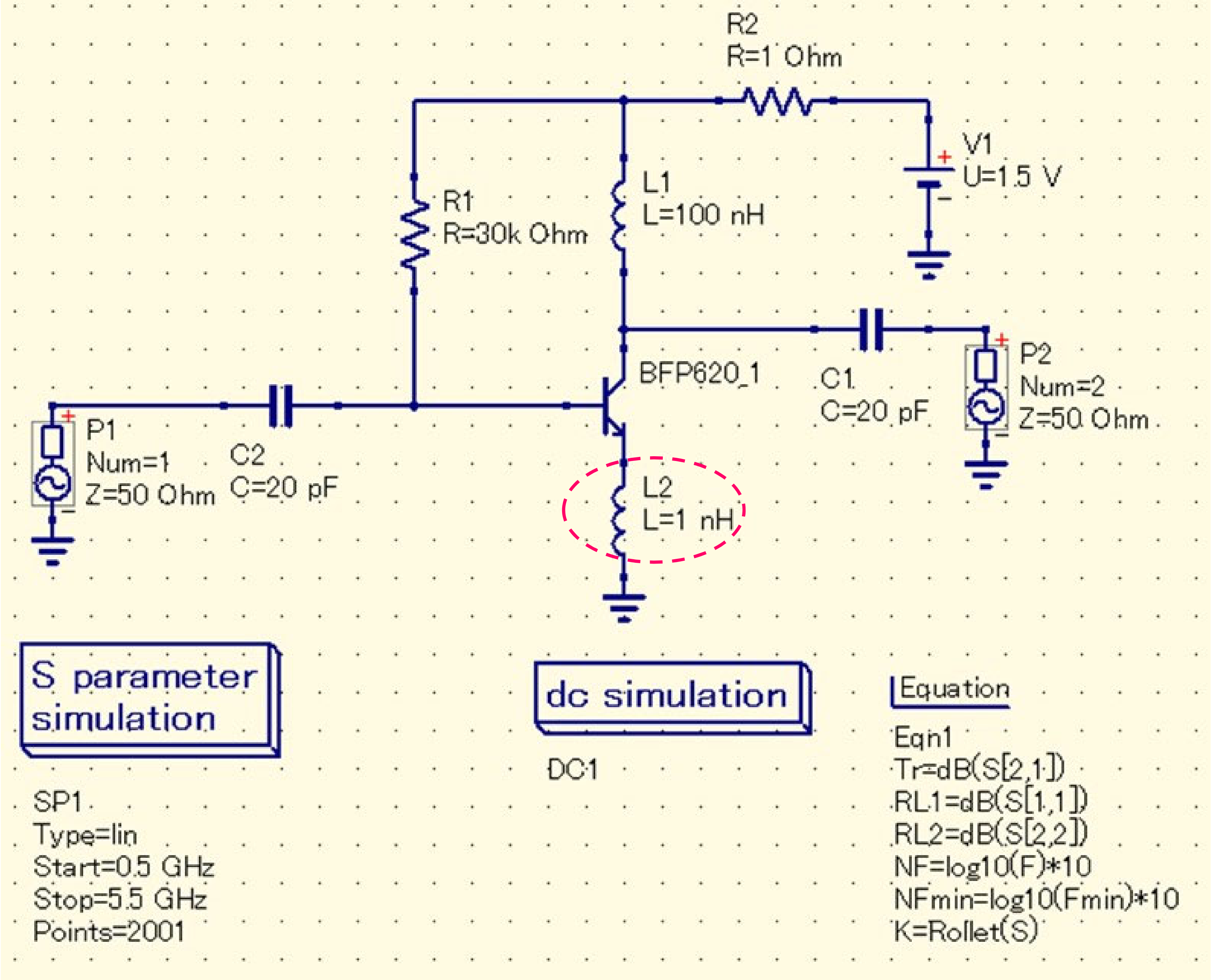
Noise
calculate noise parameters [yes, no]
yes
☐ display in schematic

S Simulation Result



$\mathrm{NF}_{\mathrm{min}}$: Achievable minimum NF at the given frequency

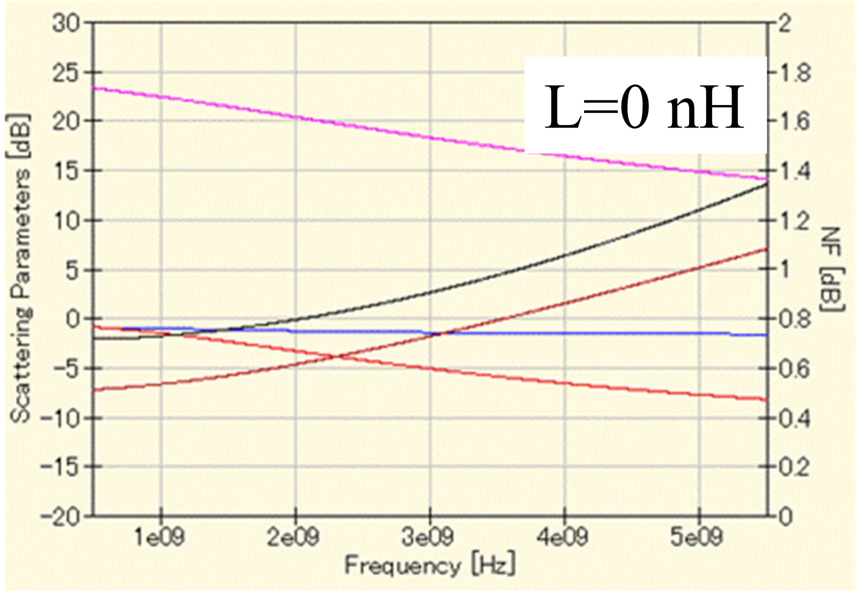
Impact of Emitter Degeneration Inductor

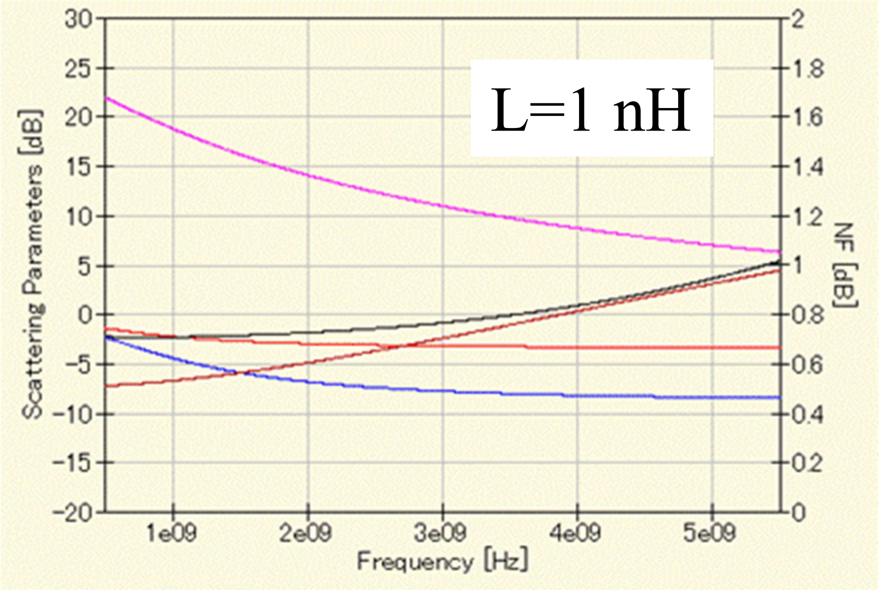


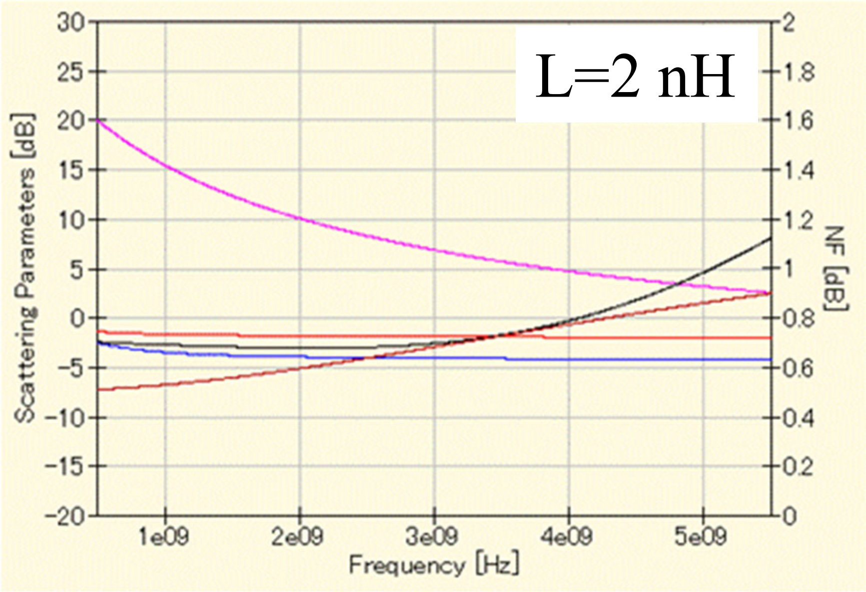
SP1
Type=lin
Start=0.5 GHz
Stop=5.5 GHz
Points=2001

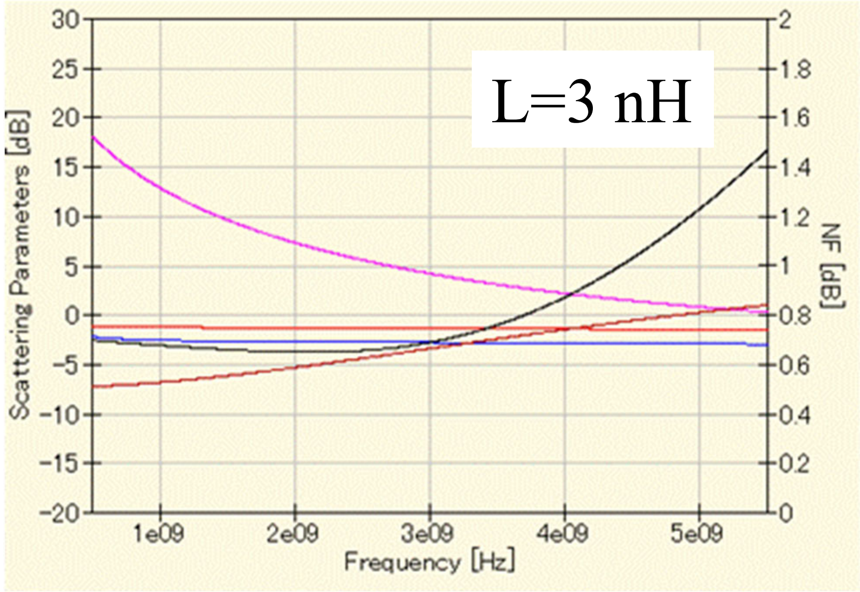
Eqn1
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10
K=Rollet(S)

Simulation Results

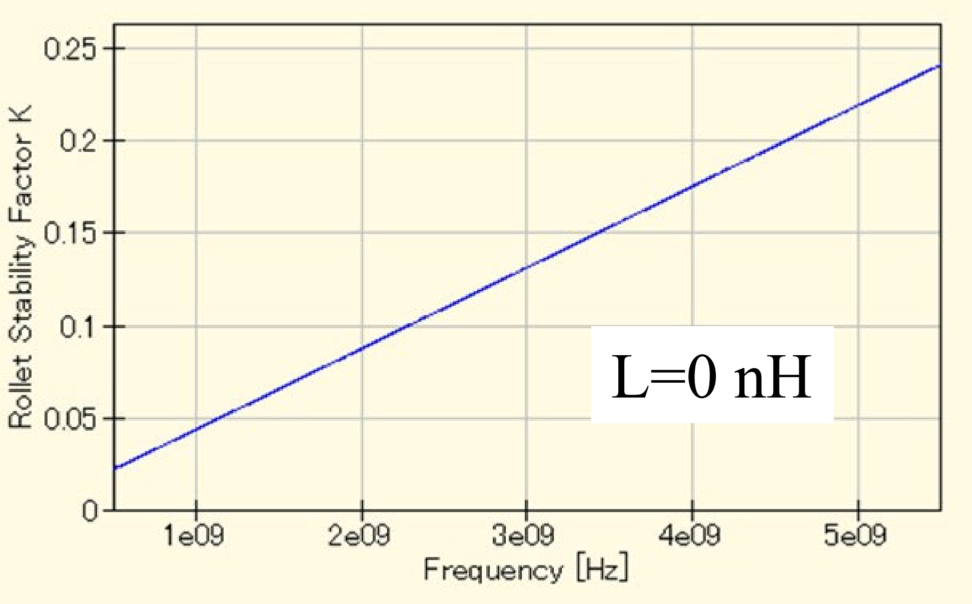

L=0 nH

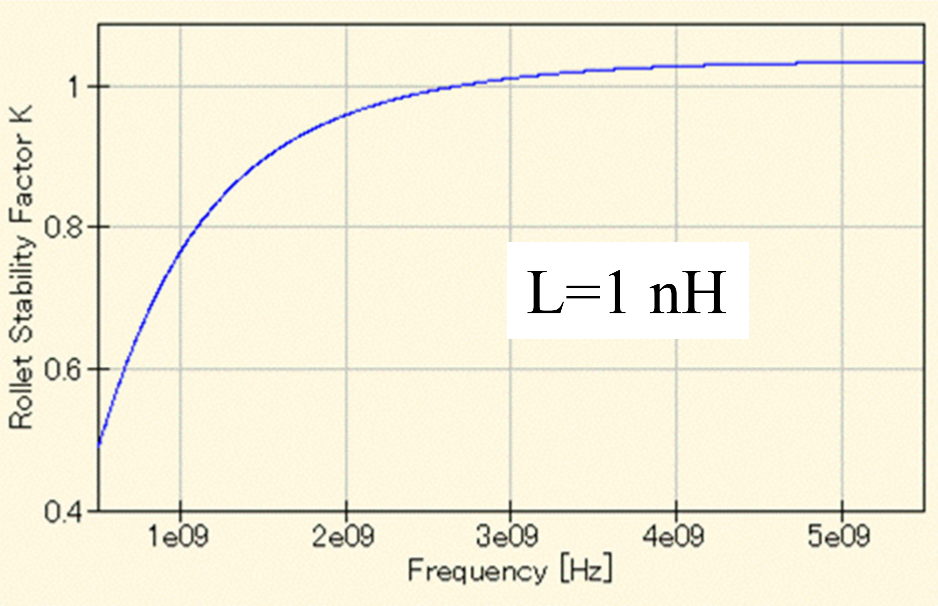

L=1 nH

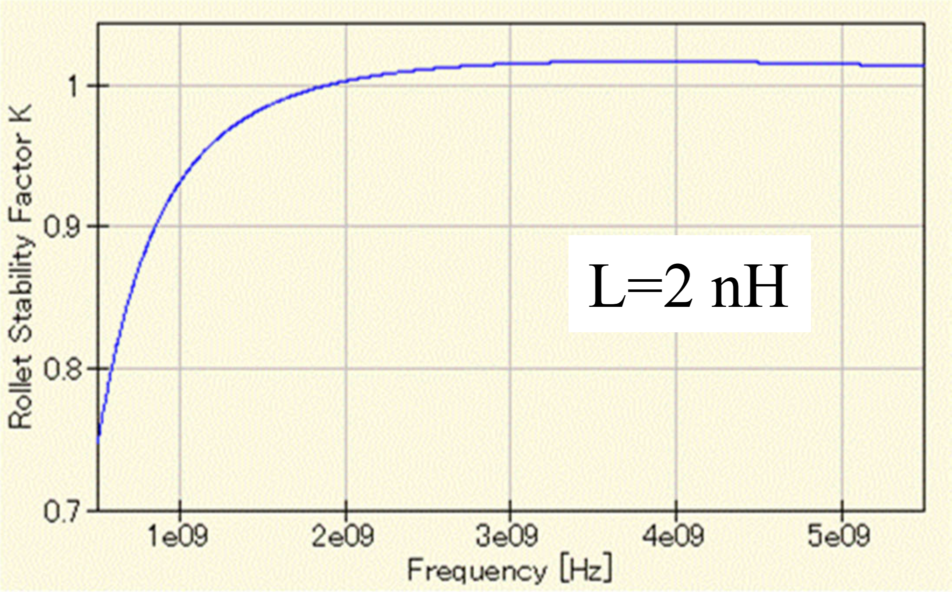

L=2 nH

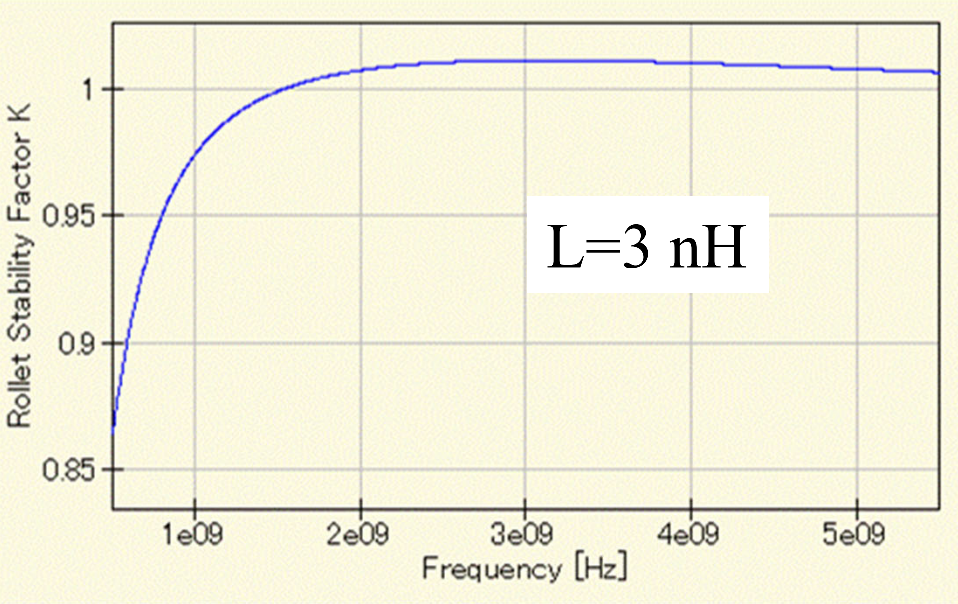

L=3 nH

Simulation Results

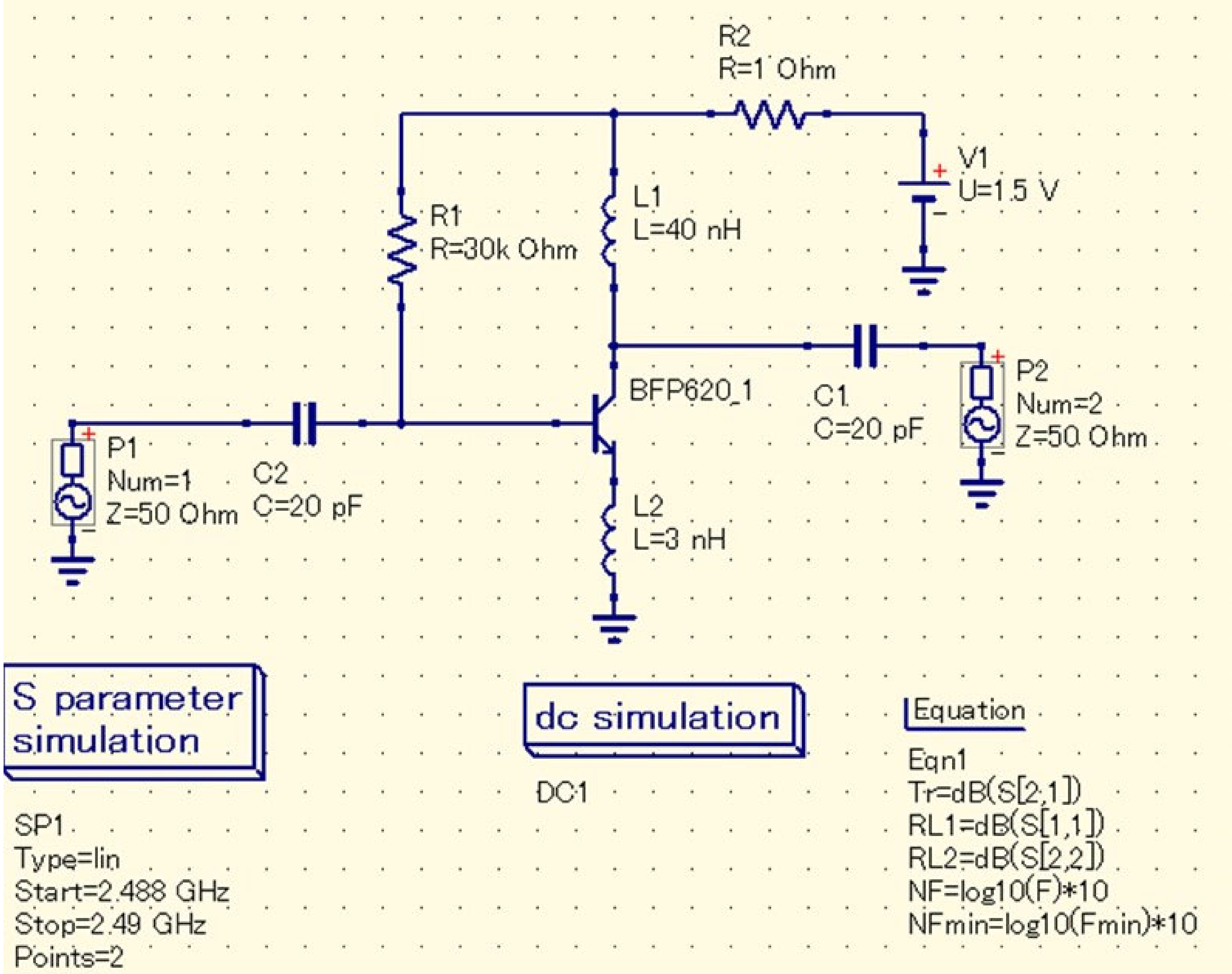

L=0 nH


L=1 nH


L=2 nH


L=3 nH

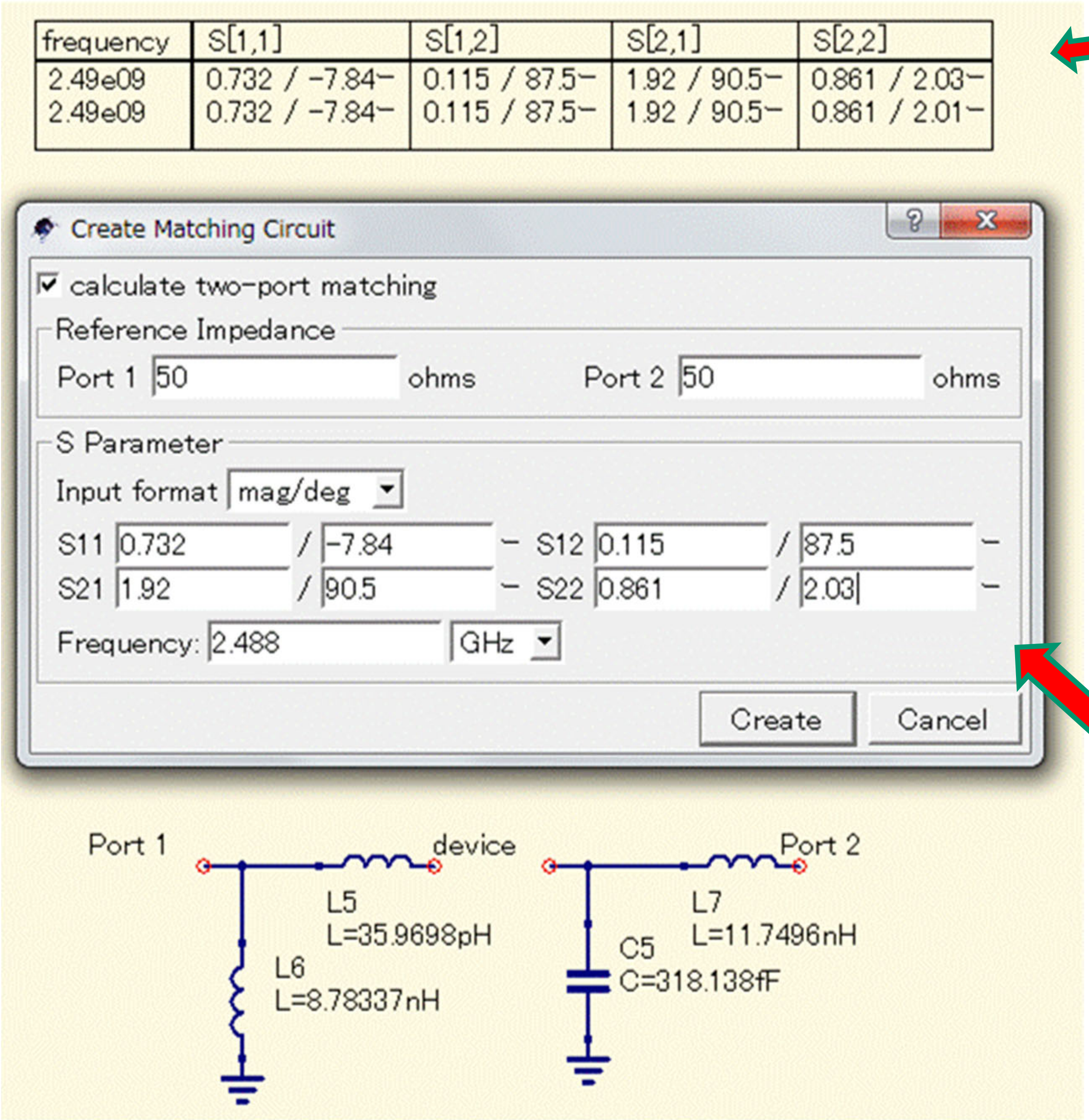
Step 3 Design Matching Circuits



SP1
Type=lin
Start=2.488 GHz
Stop=2.49 GHz
Points=2

Eqn1
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10

Procedure



frequency	S[1,1]	S[1,2]	S[2,1]	S[2,2]
2.49e09	0.732 / -7.84-	0.115 / 87.5-	1.92 / 90.5-	0.861 / 2.03-
2.49e09	0.732 / -7.84-	0.115 / 87.5-	1.92 / 90.5-	0.861 / 2.01-

Create Matching Circuit

☑ calculate two-port matching

Reference Impedance

Port 1 50 ohms Port 2 50 ohms

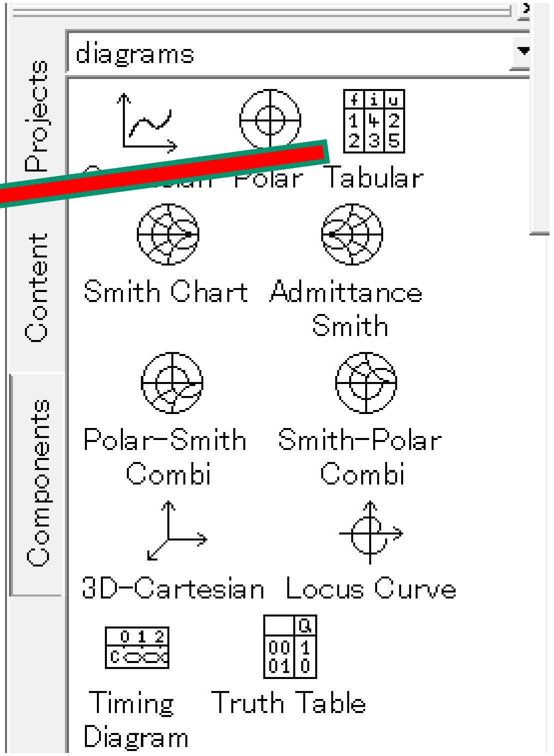
S Parameter

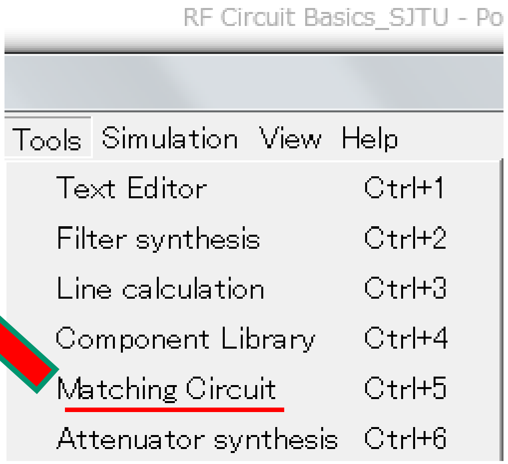
Input format mag/deg

S11 0.732 / -7.84 - S12 0.115 / 87.5 -

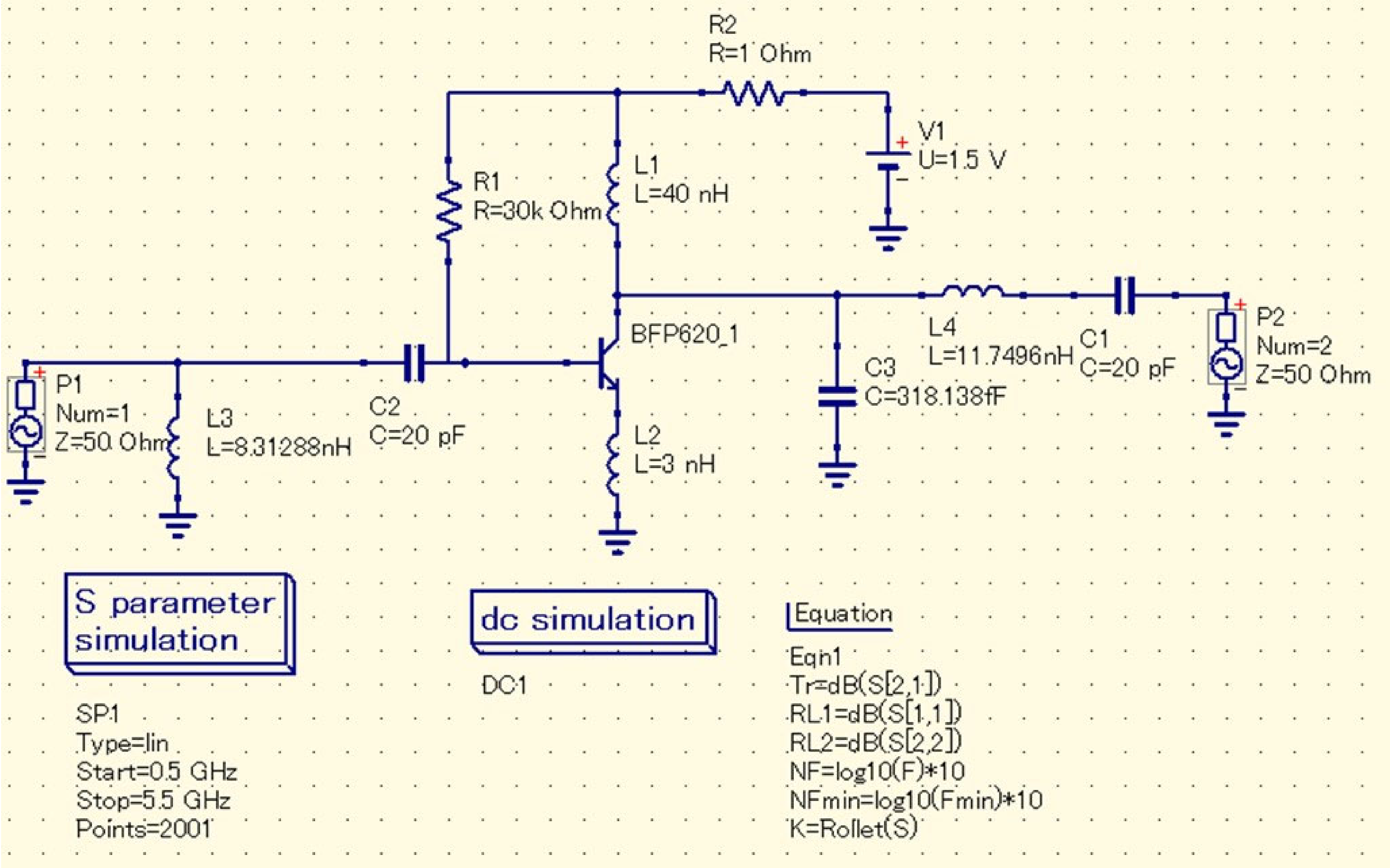
S21 1.92 / 90.5 - S22 0.861 / 2.03 -

Frequency: 2.488 GHz





After Adding Designed Matching Circuit

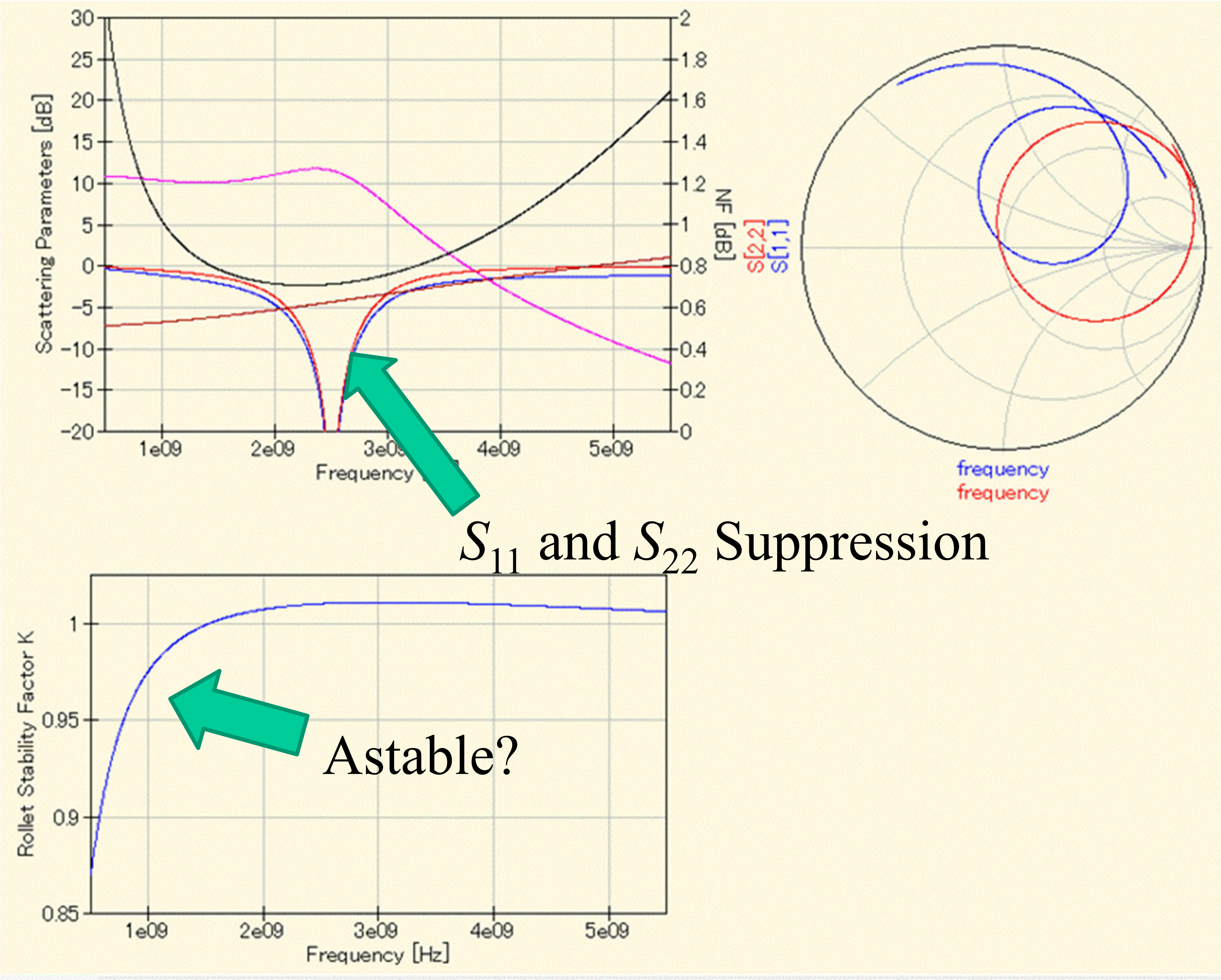


SP1
Type=lin
Start=0.5 GHz
Stop=5.5 GHz
Points=2001

DC1

Eqn1
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10
K=Rollet(S)

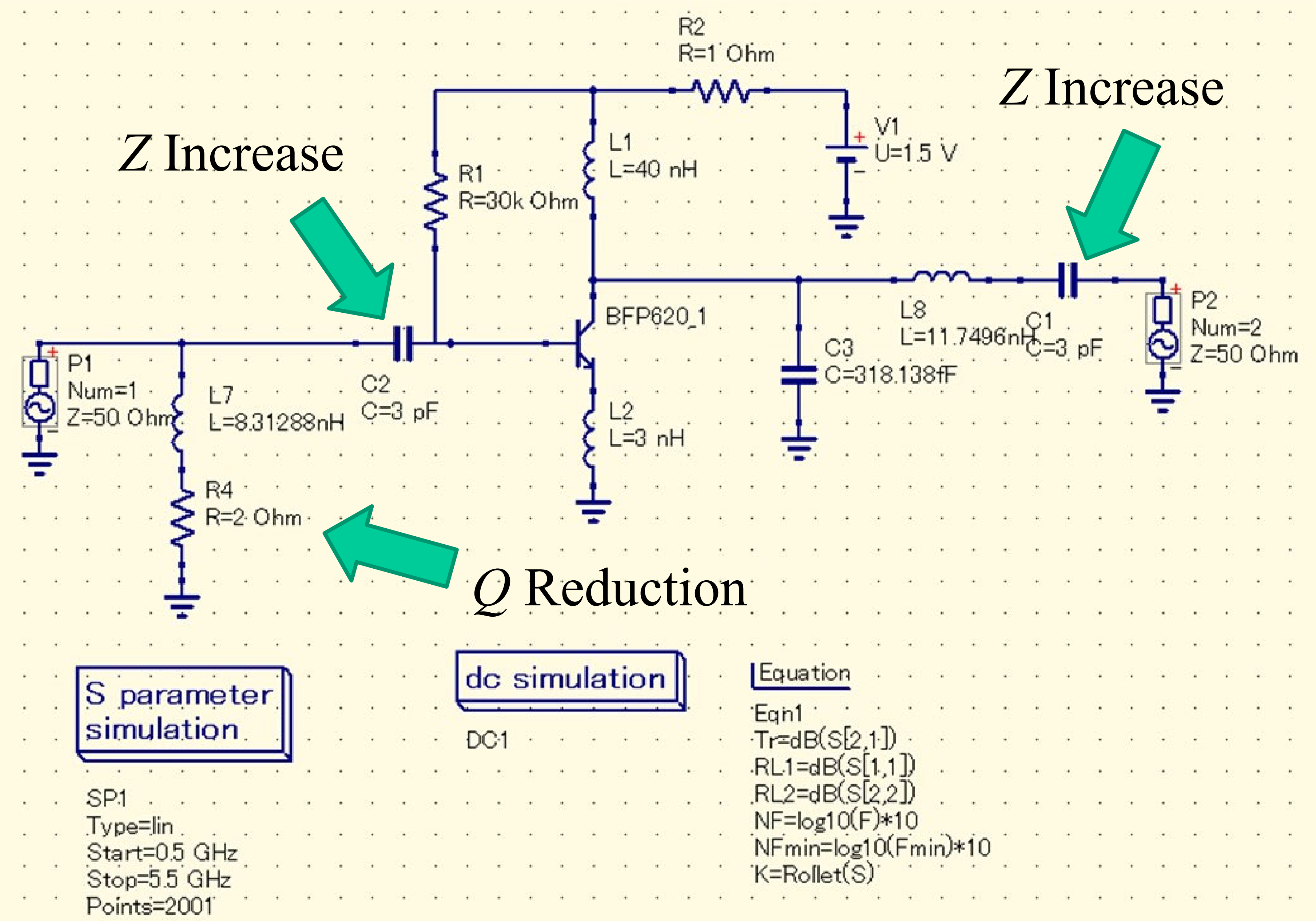
Simulated Results



S_{11} and S_{22} Suppression

Astable?

Step 4 Stabilization



Z Increase

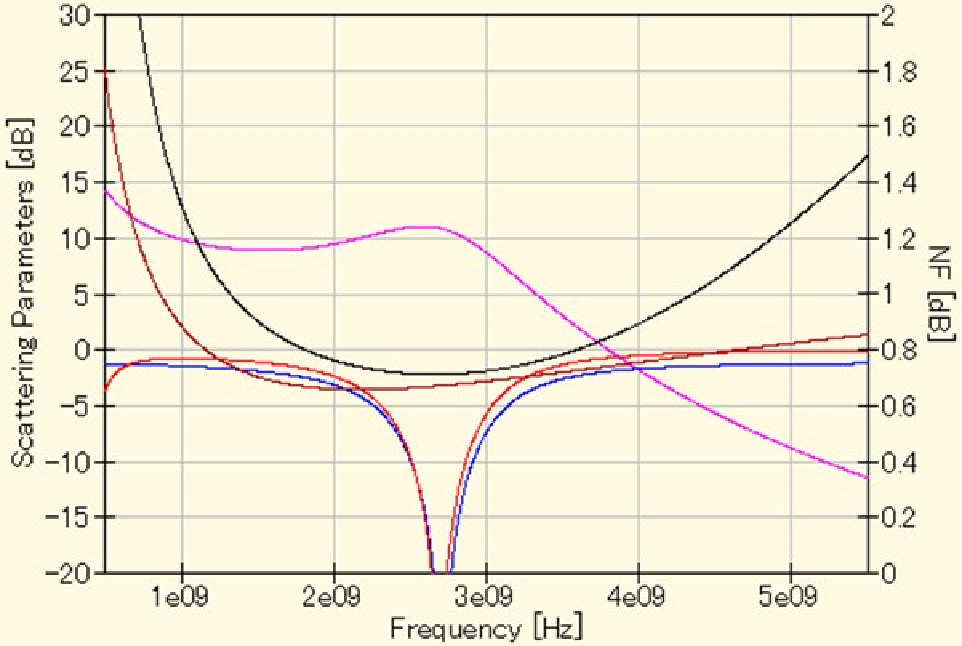
Z Increase

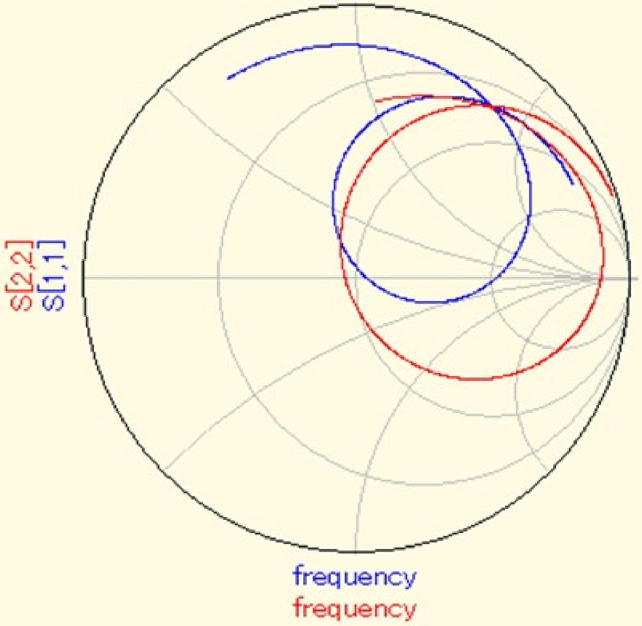
Q Reduction

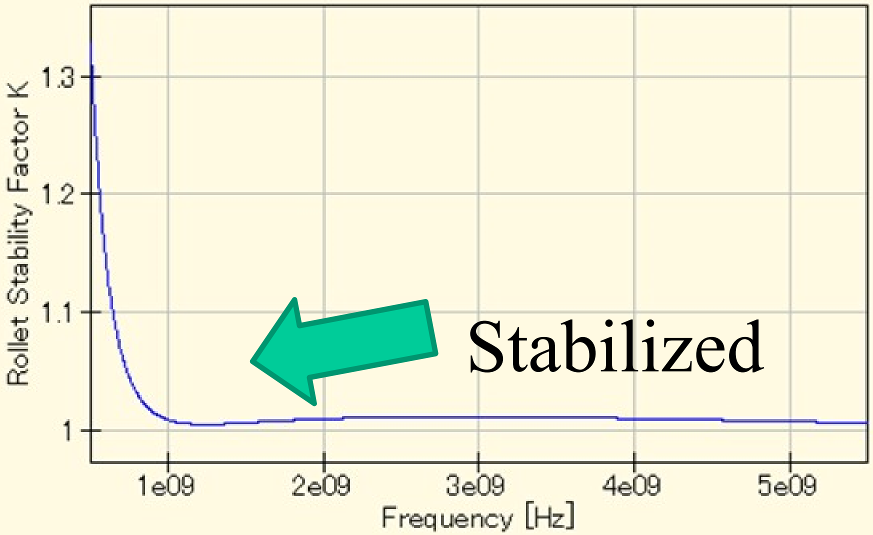
SP1
Type=lin
Start=0.5 GHz
Stop=5.5 GHz
Points=2001

Eqn1
Tr=dB(S[2,1])
RL1=dB(S[1,1])
RL2=dB(S[2,2])
NF=log10(F)*10
NFmin=log10(Fmin)*10
K=Rollet(S)

Simulation Results

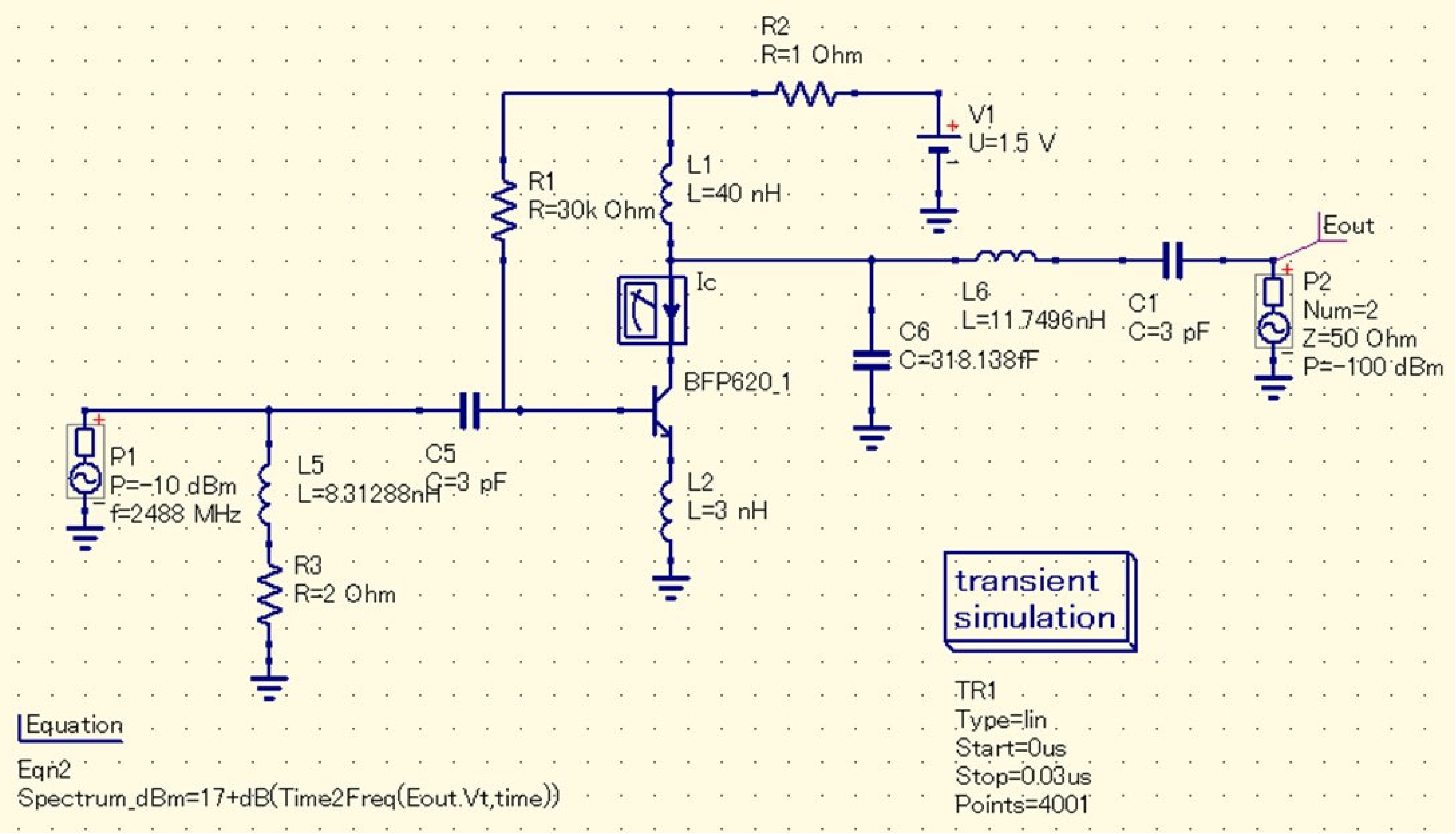






Stabilized

Step 5 Transient Analysis

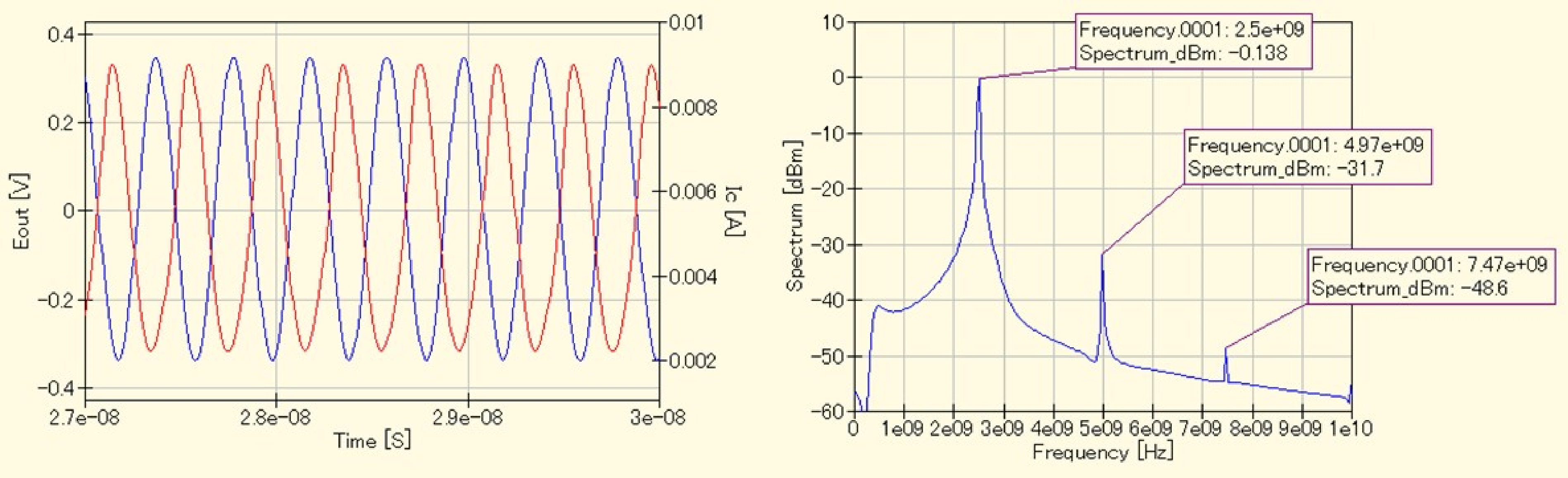


Eqn2
Spectrum_dBm=17+dB(Time2Freq(Eout.Vt,time))

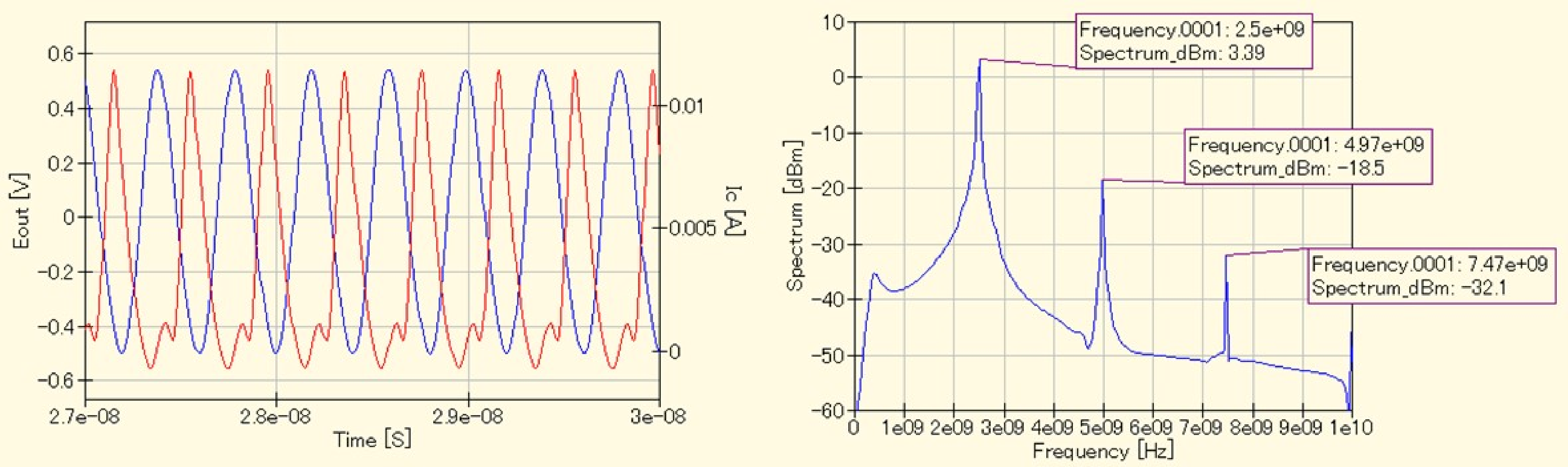
TR1
Type=lin
Start=0us
Stop=0.03us
Points=4001

Simulation Results

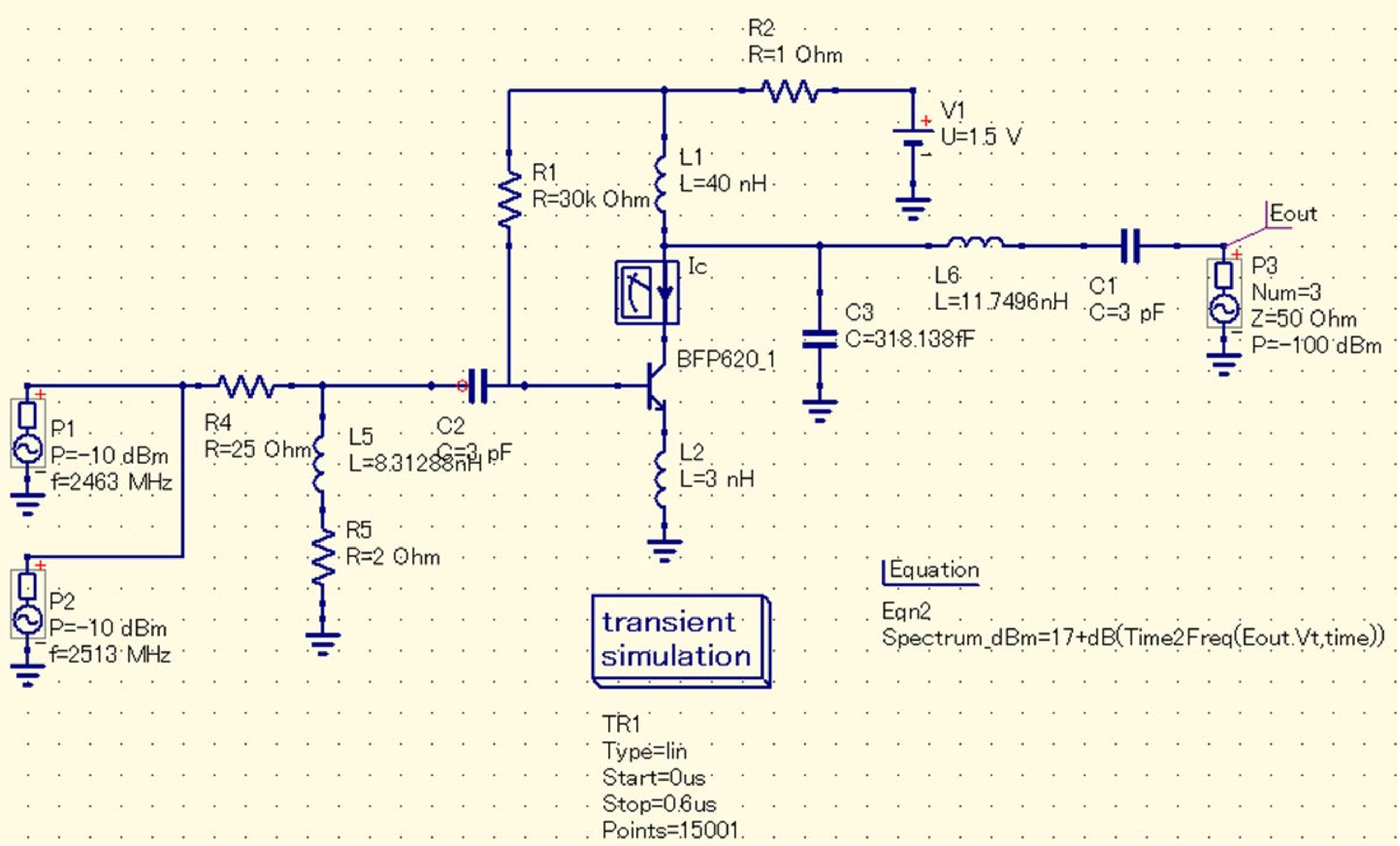
Pin=-10 dBm



Pin=-5 dBm



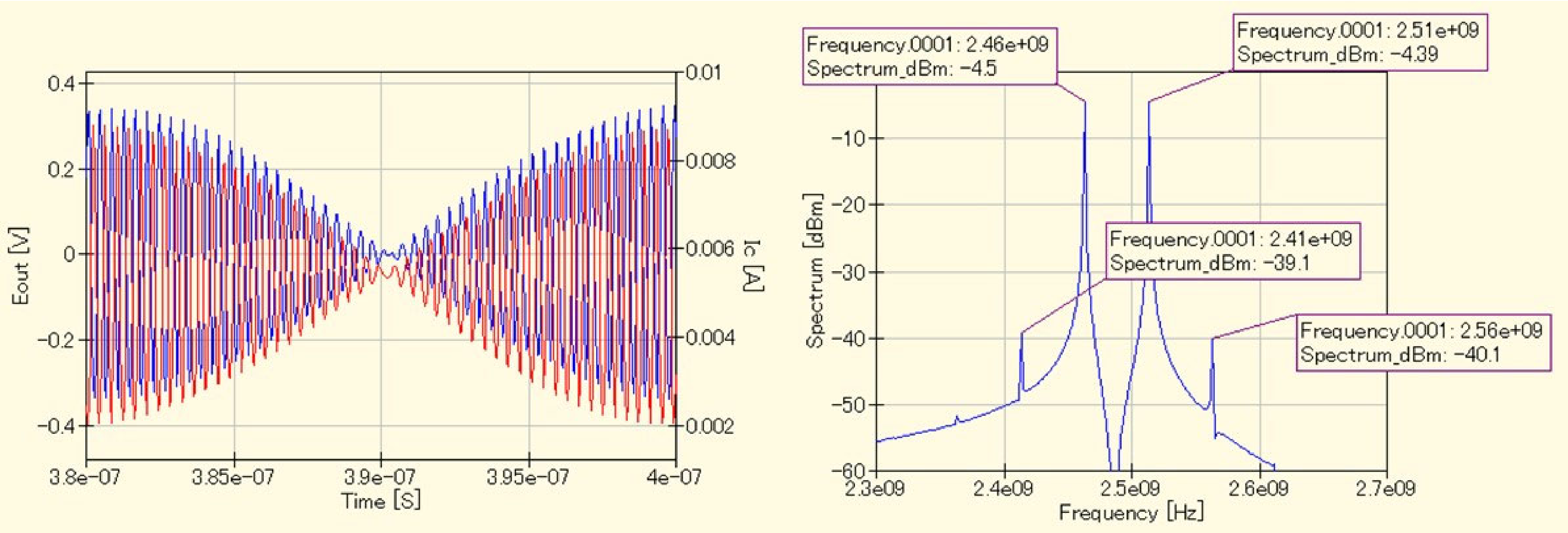
Step 6 Two Tone Analysis



TR1
Type=lin
Start=0us
Stop=0.6us
Points=15001

Eqn2
Spectrum_dBm=17+dB(Time2Freq(Eout.Vt,time))

Two Tone Test Result



$P_{2a\pm b}$ [dBm]=2×P_a [dBm] + P_b [dBm] - 2×OIP3 [dBm]

-40.1=2×(-4.39) + (-4.5) - 2×OIP3

OIP3 =13.4 [dBm]