
8D - General Single-Stage Small-Signal Amplifier Design

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1.0 General Single-Stage Small-Signal Amplifier Design Procedures

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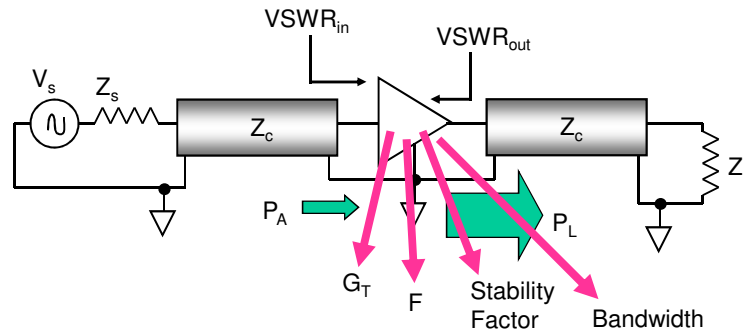
Practical Single-Stage Small-Signal Amplifier Design (1)

- Thus far we have considered different aspects of small-signal amplifier design.
- We have look at stability analysis and simultaneous conjugate match for maximum power gain under unconditionally stable case.
- Using Constant G_p Circle to determine Γ_L for conditionally stable amplifier, or when we do not require maximum power gain.
- Plotting Constant Noise Figure Circle to optimize Γ_s for optimum noise performance.
- Plotting Input Mismatch Circle to optimize for $VSWR_{in}$ and to set the actual transducer power gain (in collaboration of Constant G_p Circle).
- A general single-stage amplifier can be designed to meet multiple parameters, e.g. power gain, bandwidth, noise figure, input and output mismatch.

Practical Single-Stage Small-Signal Amplifier Design (2)

- Unfortunately these parameters compete with each other in determining the required load and source impedance value.
- For instance, when we want to maximize power gain, we usually have to sacrifice stability and noise performance.
- When we desire low noise figure, we have to trade off with moderate input mismatch and lower power gain.
- In designing an amplifier, we use various circles learnt in the previous sections to help us to balance the trade-off carefully.
- After finding the optimum load and source reflection coefficients, impedance transformation is usually employed to map the actual load/source impedance to the desired value.
- Computer-aided design is often compulsory for optimum design.

Practical Single-Stage Small-Signal Amplifier Design (3)

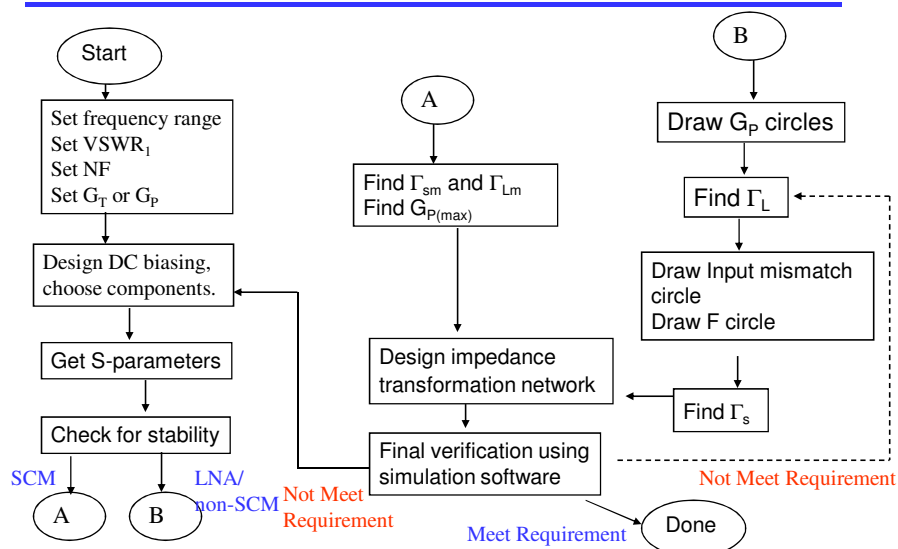


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Single-Stage Small-Signal Amplifier Design Flow



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Summary for Chapter 7 & 8

- Stability Factor check for unconditionally stable amplifier:

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

- Simultaneous Conjugate Match: Sets both Γ_L and Γ_S
- Only when amplifier is unconditionally stable, $K > 1$.

$$G_{P(\max)} = \frac{|S_{21}|}{|S_{12}|} (K - \sqrt{K^2 - 1})$$

$$\Gamma_{Sm} = \frac{1}{2B_1} \left(A_1 - \left(A_1^2 - 4|B_1|^2 \right)^{\frac{1}{2}} \right) \quad \Gamma_{Lm} = \frac{1}{2B_2} \left(A_2 - \left(A_2^2 - 4|B_2|^2 \right)^{\frac{1}{2}} \right)$$

$$A_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |D|^2$$

$$A_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |D|^2$$

$$B_1 = S_{11} - DS_{22}^*$$

$$B_2 = S_{22} - DS_{11}^*$$

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Summary for Chapter 7 & 8

- Constant Power Gain: Sets Γ_L
- Can be applied for both unconditionally stable and conditionally stable amplifier.

$$g_2 = \frac{G_P}{|S_{21}|^2} \quad C_2 = S_{22} - DS_{11}^* \quad G_{P(MSG)} = \frac{|S_{21}|}{|S_{12}|}$$

$$T_{G_P} = \frac{-g_2 \operatorname{Re}(C_2)}{-1 - |S_{22}|^2 g_2 + |D|^2 g_2} + j \frac{g_2 \operatorname{Im}(C_2)}{-1 - |S_{22}|^2 g_2 + |D|^2 g_2}$$

$$R_{G_P} = \frac{\sqrt{1 - 2K|S_{12}S_{21}|g_2 + |S_{12}S_{21}|^2 g_2^2}}{|-1 - |S_{22}|^2 g_2 + |D|^2 g_2|}$$

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Summary for Chapter 7 & 8

- Constant Noise Figure: Sets Γ_s

$$F = F_m + \frac{G_i}{R_s} |Z_S - Z_m|^2 = F_m + \frac{R_i}{G_s} |Y_S - Y_m|^2$$

$$N_i = \frac{Z_o(F - F_m)|1 + \Gamma_m|^2}{4R_e} = \frac{(F - F_m)|1 + \Gamma_m|^2}{4Z_o G_i}$$

$$\Gamma_{Fcenter} = \frac{\Gamma_m}{1 + N_i}$$

$$R_{Frad} = \frac{\sqrt{N_i^2 + N_i(1 - |\Gamma_m|^2)}}{1 + N_i}$$

Summary for Chapter 7 & 8

- Constant Input Mismatch: Sets Γ_s

$$G_T = M_1 G_P \quad M_1 = \frac{(1 - |\Gamma_s|^2)(1 - |\Gamma_1|^2)}{|1 - \Gamma_1 \Gamma_s|^2}$$

$$1 - \rho^2 = M_1 \quad VSWR_1 = \frac{1 + \sqrt{1 - M_1}}{1 - \sqrt{1 - M_1}} \quad M_1 = 1 - \left(\frac{VSWR_1 - 1}{VSWR_1 + 1} \right)^2$$

$$\Gamma_{Scenter} = \frac{M_1 \Gamma_1^*}{1 - (1 - M_1) |\Gamma_1|^2} \quad R_{Srad} = \frac{\sqrt{1 - M_1} (1 - |\Gamma_1|^2)}{1 - (1 - M_1) |\Gamma_1|^2}$$

Example 1 (Textbook)- General Amplifier Design Example

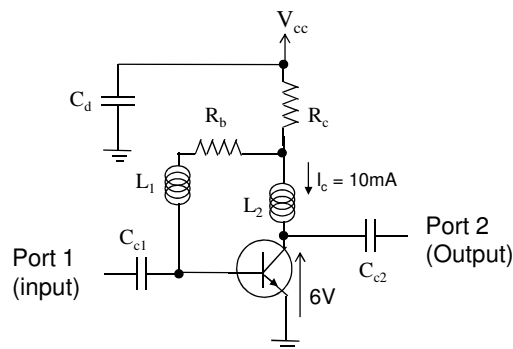
- A BJT, biased at $I_C = 10\text{mA}$, $V_{CE} = 6\text{V}$ is operated at $f = 2.4\text{GHz}$. The biasing network is shown in the next slide. The corresponding S-parameters are $s_{11} = 0.3\angle 30^\circ$, $s_{12} = 0.2\angle -60^\circ$, $s_{21} = 2.5\angle -80^\circ$, $s_{22} = 0.2\angle -15^\circ$. The noise parameters of the BJT are $F_{m(\text{dB})} = 1.7\text{dB}$, $R_e = 4\Omega$ and $\Gamma_m = 0.5\angle 45^\circ$. Assume $Z_o = 50\Omega$.
- Design a Low-Noise Amplifier using the BJT circuit, with:
 - A power gain G_p of at least 8dB.
 - Noise figure F less than 2.0dB.
 - VSWR_1 less than 2.0.
 - The Amplifier has a source of 50Ω and load of 50Ω .

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D.C. Biasing Network



Simulated S-parameters @ 2.4GHz

$S_{11} = 0.3\angle 30^\circ = 0.260 + j0.150$	
$S_{12} = 0.2\angle -60^\circ = 0.100 - j0.173$	
$S_{21} = 2.5\angle -80^\circ = 0.434 - j2.462$	
$S_{22} = 0.2\angle -15^\circ = 0.193 - j0.052$	

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General Amplifier Design Example

- Stability Analysis : $K=1.178 > 1$ and $|D|=0.555 < 1$. So the amplifier is unconditionally stable and the maximum power gain is:

$$G_{P(\max)} = \frac{|S_{21}|}{|S_{12}|} (K - \sqrt{K^2 - 1}) = 6.942 \text{ or } 8.42\text{dB}$$

- So the power gain fulfills the requirement. This is the value that can be obtained if we apply Simultaneous Conjugate Match (SCM). In this case $G_p = G_T = G_A$.
- Computing the source and load impedance for maximum power gain:

$$\Gamma_{sm} = 0.2815 - j0.091$$

$$\Gamma_{Lm} = 0.0444 + j0.1157$$

- For the next step, we will plot the constant input mismatch circles and constant noise figure (F) circles on the Smith chart for Γ_s plane, with $\Gamma_L = \Gamma_{Lm}$.
- Then we make sure that the location of Γ_{sm} fulfill the requirements of $F < 2.0\text{dB}$ and $VSWR_1 < 2.0$.

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General Amplifier Design Cont...

- For $\Gamma_L = \Gamma_{Lm}$:

$$\Gamma_1 = 0.2815 + j0.091 = \Gamma_{sm}^*$$

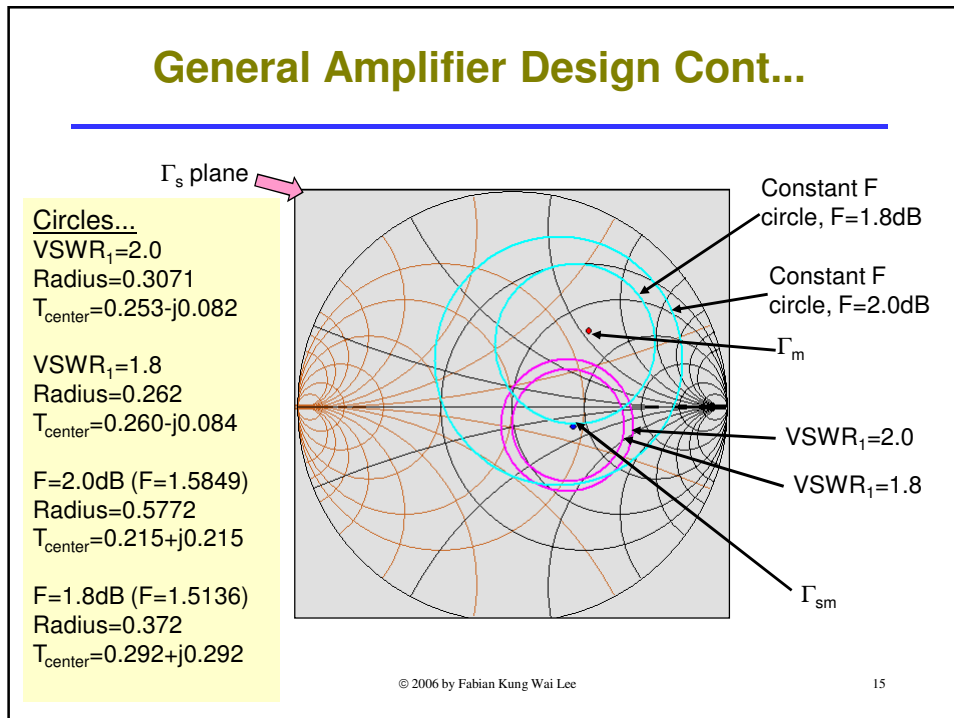
- Now with this information we could calculate the radius and center of the constant input mismatch or $VSWR_1$ circles.

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General Amplifier Design Cont...



General Amplifier Design Cont...

- From the previous slide, we see that all the requirements are fulfilled. So the required source and load reflection coefficients are:

$$\Gamma_{sm} = 0.2815 - j0.091$$

$$\Gamma_{Lm} = 0.0444 + j0.1157$$

- Noting that Γ_{sm} is near the F=1.8dB Circle, the performance parameters of the amplifier are:

$$G_p = 6.942 \text{ or } 8.42\text{dB.}$$

$$VSWR_1 = 1 \text{ or } M = 1.$$

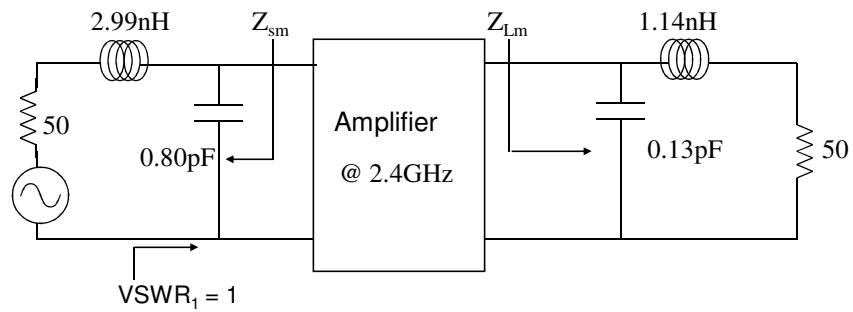
$$F \cong 1.568 \text{ or } 1.5136\text{dB} < 2.0\text{dB.}$$

- Finding the source and load impedance: $Z_s = Z_o \frac{1 + \Gamma_{sm}}{1 - \Gamma_{sm}} = 86.982 - j17.349$

$$Z_L = Z_o \frac{1 + \Gamma_{Lm}}{1 - \Gamma_{Lm}} = 53.134 + j12.487$$

General Amplifier Design Cont...

- Since the original source and load impedance do not correspond to these values, impedance transformation networks are used at the input and output port of the amplifier.
- The final block diagram:

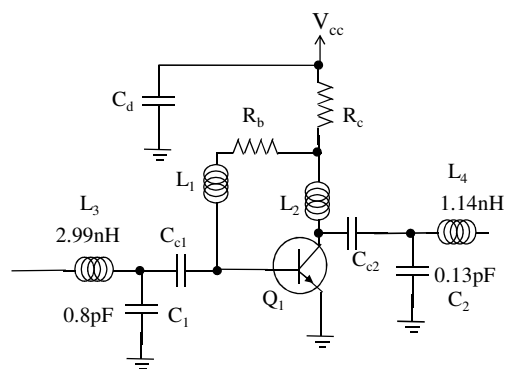


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Complete Schematic of the Example



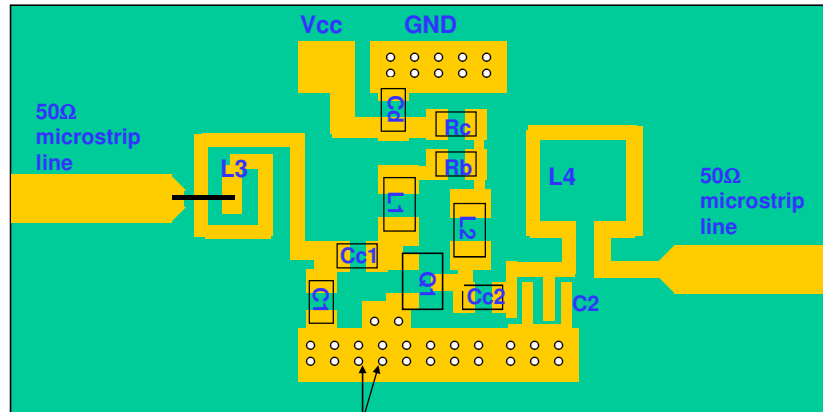
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Suggested Layout for the Example

- Proposed layout, on 0.8mm thick FR4 substrate. Bottom is ground plane.



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Plated through holes
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Further Readings

- For more examples of practical microwave amplifiers design, please see the book by:
- [1] C. W. Sayre, "Complete wireless design", 2001, McGraw-Hill.
- [2] Gilmore R., Besser L., "Practical RF circuit design for modern wireless systems", Vol. 1 & 2, 2003, Artech House.

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2.0 Practical Amplifier Design Example - Low-Noise Amplifier with Fixed G_T and Input Mismatch

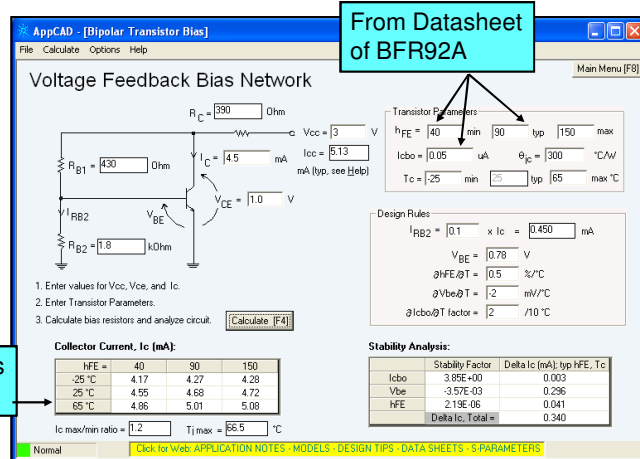
Introduction

- In this exercise we are going to design and built a low-noise amplifier, optimized for operation at 850 to 920 MHz.
- The RF transistor BFR92A is used for this exercise. This is a wideband NPN transistor with $f_T = 5$ GHz (at $I_C = 30$ mA and $V_{CE} = 10$ V). **Using a transistor with $f_T > 5 \times f_o$ allows us to reduce the dc collector current (I_C), thereby reducing idle power dissipation.**
- The circuit is intended for operation at a supply voltage of 3.0 to 3.3 V.
- The software Advanced Design System, ADS2003C from Agilent Technologies is used for the computer analysis.

D.C. Biasing Design (1)

- Voltage feedback bias is chosen.
- AppCAD is used to estimate the initial biasing resistor values and to perform the necessary d.c. stability analysis

D.c. stability analysis results



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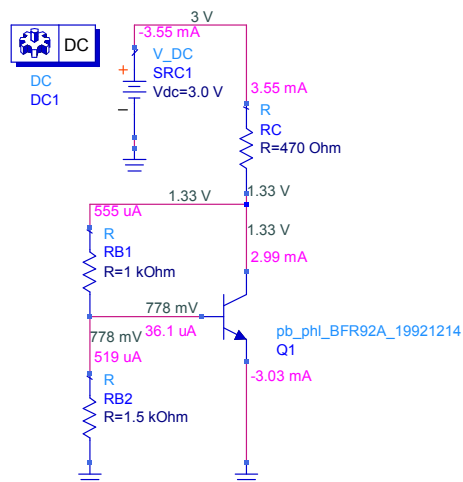
D.C. Biasing Design (2)

Simulated result using nonlinear d.c. solver, with SPICE model of BFR92A

$$I_C = 3.0 \text{ mA}$$

$$V_{CE} = 1.33 \text{ V}$$

Theoretical max voltage swing at collector of $Q_1 = 2 \times 1.33 = 2.66 \text{ V}$



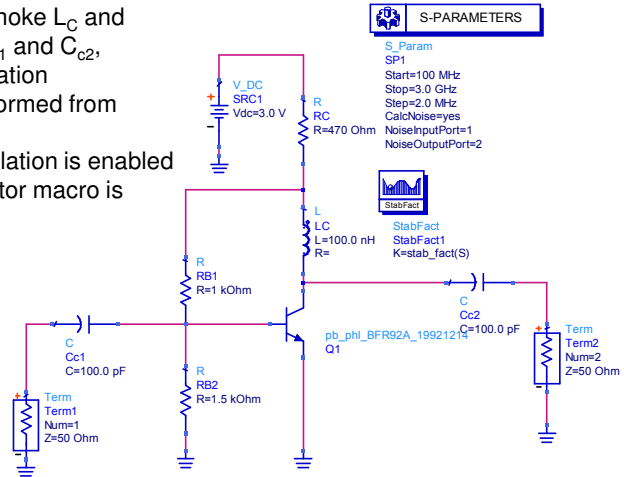
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A.C. Analysis (1)

- Upon adding in RF choke L_C and coupling capacitors C_{c1} and C_{c2} , small-signal a.c. simulation (S-parameters) is performed from 100MHz to 3000MHz.
- Note that noise calculation is enabled and the Roulette K factor macro is also inserted.



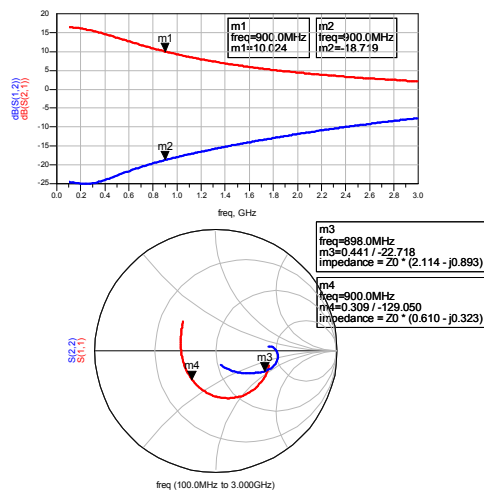
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A.C. Analysis (2)

S_{21} of the a.c. analysis indicates power gain G_p of greater than 9dB between 800 to 900 MHz.



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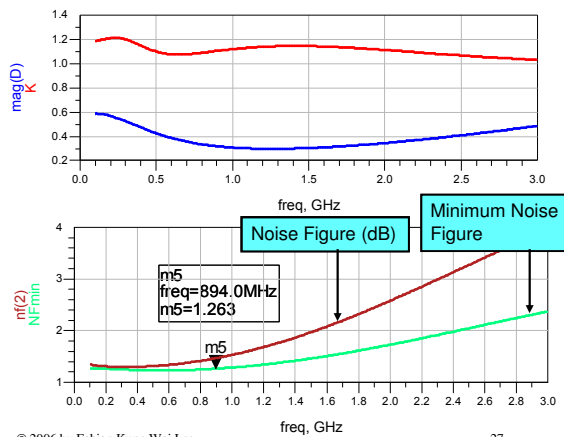
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A.C. Analysis (3)

- Furthermore the basic amplifier circuit is unconditionally stable. As indicated by $K > 1$ and $|D| < 1$ within the analysis frequency range.
- We do not have to worry about stability greater than 3GHz as for the d.c. biasing used, transistor Q_1 f_T is expected to be less than 3GHz.
- Also noise calculation shows that theoretically a noise figure of less than 1.26 can be achieved.

$$\text{Eqn } D = S_{11}^* S_{22} - S_{12}^* S_{21}$$



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A.C. Analysis at 900MHz (1)

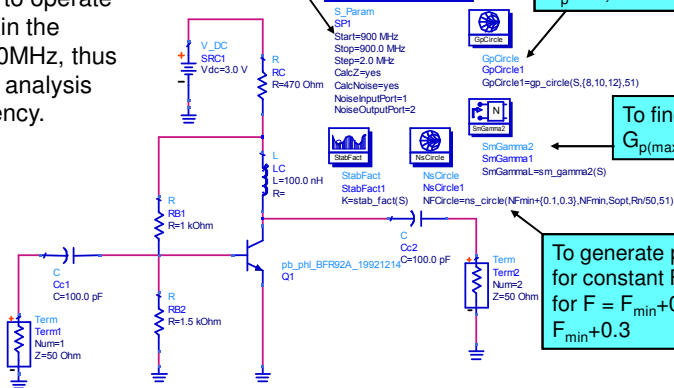
The target is to operate the amplifier in the vicinity of 900MHz, thus we focus the analysis at this frequency.

Start and stop at 900MHz, also enable computation of Z parameters

To generate points for constant G_p circles for $G_p = 8, 10$ and 12dB

To find Γ_L at $G_p(\text{max})$

To generate points for constant F circles for $F = F_{\text{min}} + 0.1$ and $F_{\text{min}} + 0.3$



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A.C. Analysis at 900MHz (2)

• We write our own macro to generate points for constant Input Mismatch circle on Smith Chart for Γ_s . Here m1 and m2 are markers in the Smith Charts.

• Mininput is the user specified Input Mismatch Factor.

Macro to generate Constant Input Mismatch Circle

```
Eqn TL = m1 Eqn Ts = m2 Eqn D=S11*S22-S12*S21
Eqn T1 = (S11-D*TL)/(1-S22*TL) Eqn Zo=50
Eqn Rminput = (sqrt(1-Minput)*(1-mag(T1)*mag(T1)))/(1-(1-Minput)*mag(T1)*mag(T1))
Eqn Tmcenter=(Minput*conj(T1))/(1-(1-Minput)*mag(T1)*mag(T1))
Eqn Theta= generate(0,2*Pi,51)
Eqn Minput_Circle = Tmcenter+Rminput*exp(j*Theta)
```

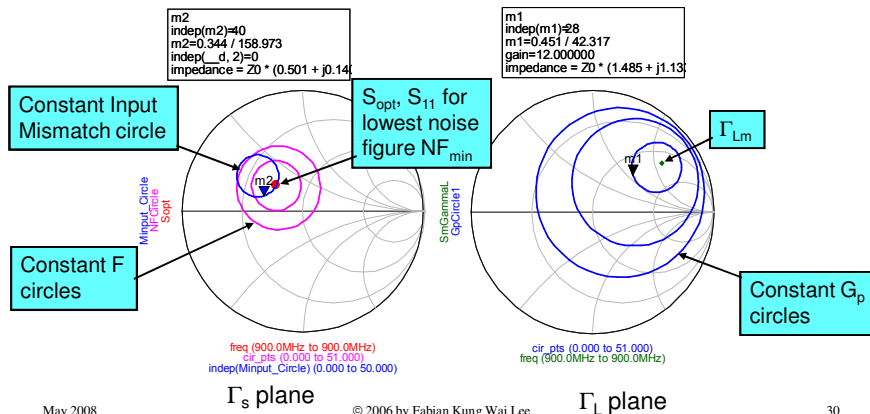
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A.C. Analysis at 900MHz (3)

Two Smith Charts are plotted. Markers m1 and m2 are chosen such that power gain $G_p=12.0\text{dB}$ and noise figure F is the minimum. As marker m1 changes, the constant Input Mismatch Circle size and position on Γ_s plane change accordingly.



A.C. Analysis at 900MHz (4)

- From the Smith Charts, after some tuning, the chosen load and source impedance are as shown.
- Observe that transducer power gain $G_T = \text{Minput} \times G_p$. Or in dB
 $G_{TdB} = 10\log(\text{Minput}) + 10\log(G_p) = -0.458 + 12 = 11.542$
- Noise figure of better than $1.264 + 0.1$ dB can be achieved.

Eqn $Z_L = Z_o \cdot (1+TL)/(1-TL)$

Eqn $Z_s = Z_o \cdot (1+m2)/(1-m2)$

Eqn $GT = ((1-\text{pow}(\text{mag}(TL),2)) \cdot \text{pow}(\text{mag}(S21),2) \cdot (1-\text{pow}(\text{mag}(Ts),2))) / (\text{pow}(\text{mag}(1-S22*TL),2) \cdot \text{pow}(\text{mag}(1-T1*Ts),2))$

Eqn $GT_dB = 10 \cdot \log(GT)$

Small-signal requirement of Amplifier:

Input Mismatch Factor		Eqn Minput = 0.95
ZL	Zs	
74.248 + j56.640	27.924 + j9.515	
GT_dB	K	freq
11.777	1.105	900.0MHz

NOTE:

1. Set a reasonable input mismatch factor "Minput" (between 0 to 1).
2. Move marker m1 along constant Gp circles to obtain suitable load impedance and m2 along the constant input mismatch circle to obtain suitable source impedance.

Noise parameters:

freq	Sopt	Rn	nf(2)	NFmin
900.0MHz	-0.231 + j0.218	5.117	1.468	1.264

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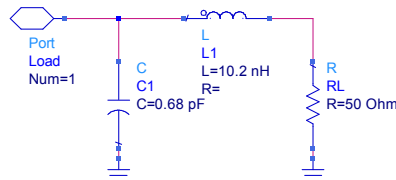
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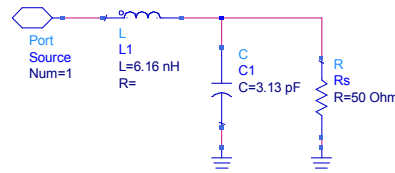
Input and Output Impedance Transformation Network

The following LC networks are used:

1. Load Network: to transform $Z_L = 50$ to $74+j57$ (approximate) at 900MHz.
2. Source Network: to transform $Z_s = 50$ to $28+j10$ (approximate) at 900MHz.



Load network



Source network

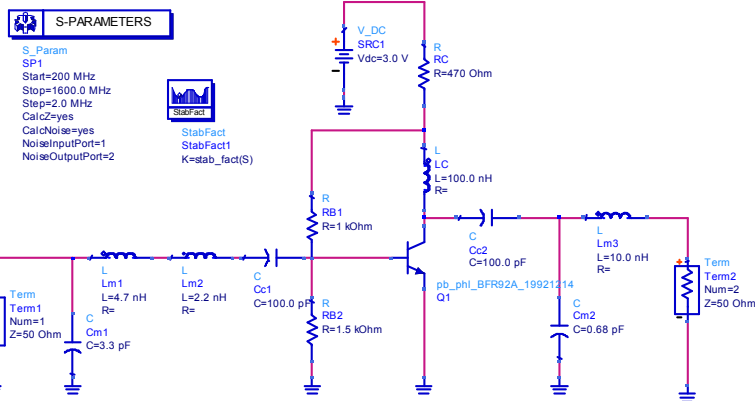
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The Complete Schematic

Practical L and C values are used to approximate the source and load transformation networks



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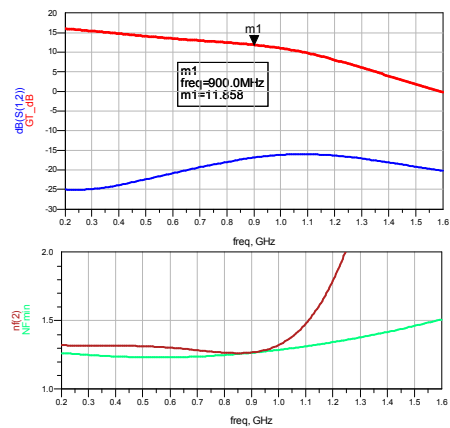
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A.C. Analysis of the Complete Schematic

The small-signal performance of the matched circuit, from 200 to 1600MHz

Important parameters at 900MHz:

freq	ntf(2)	GT_dB	dB(S(1,1))	dB(S(2,2))	K
900.0MHz	1.267	11.858	-15.857	-15.714	1.108



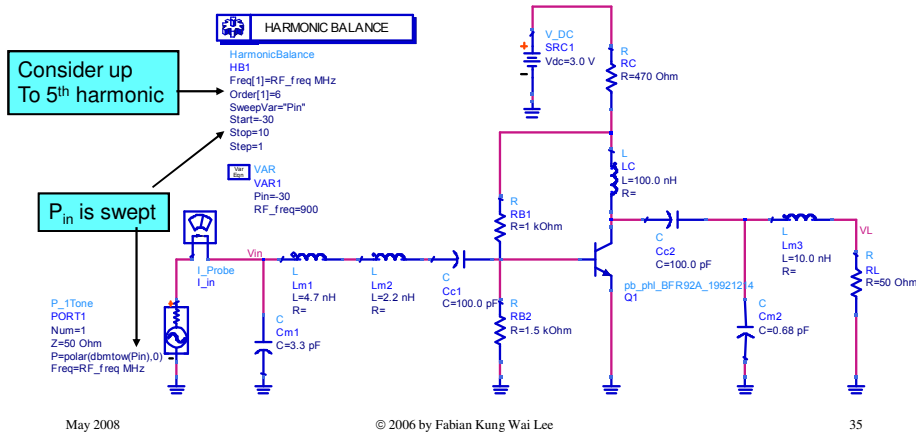
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Large Signal A.C. Analysis – Gain Compression (1)

- Finally a large-signal frequency domain analysis is carried out using Harmonic Balance method.
- Input available power P_{in} is swept from -30dBm to 10dBm.



Large Signal A.C. Analysis – Gain Compression (2)

- Node voltages VL, Vin and current I_in are arrays.
- The following equations are used to compute the load power P_{L1} and input power Pin1 at fundamental frequency (RF_freq).

$$\text{Eqn } Z_0 = 50$$

$$\text{Eqn } R_L = Z_0$$

$$\text{Eqn } P_{L1} = 0.5 * (\text{pow}(\text{mag}(V_L[1]), 2) / R_L)$$

$$\text{Eqn } P_{L1_dBm} = 10 * \log(P_{L1}) + 30 \quad \leftarrow \text{Power in dBm!}$$

$$\text{Eqn } P_{in1} = 0.5 * (\text{real}(V_{in}[1] * \text{conj}(I_{in.i}[1])))$$

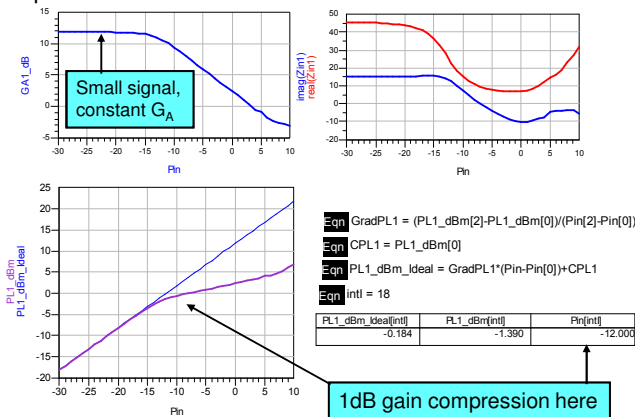
$$\text{Eqn } Z_{in1} = V_{in}[1] / I_{in.i}[1]$$

$$\text{Eqn } GA1_dB = 10 * \log(P_{L1}) - (P_{in1} - 30)$$

Index = 0: d.c.
Index = 1: Fundamental
Index = 2: 1st Harmonic
Index = 3: 2nd Harmonic
etc...

Large Signal A.C. Analysis – Gain Compression (3)

- The large-signal frequency domain analysis result.
- G_{A1_dB} is the Transducer Power Gain in dB at fundamental frequency.
- As seen 1dB gain compression occurs around $P_{in} = -12dBm$



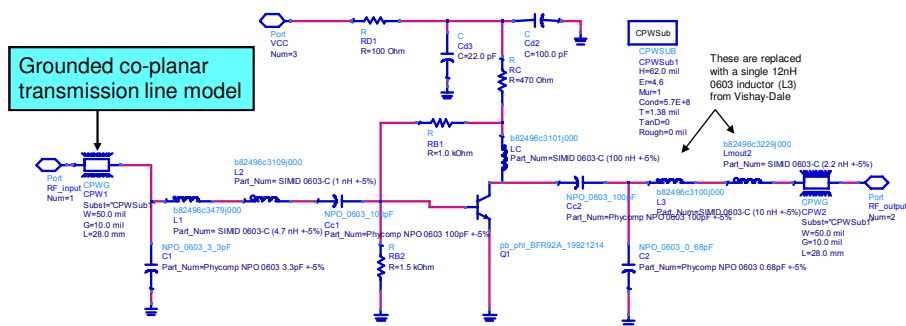
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Using Real Inductors and Capacitors

- After the actual circuit is built, some tuning is performed on the passive component values.
- It is discovered the following values give the optimum performance.



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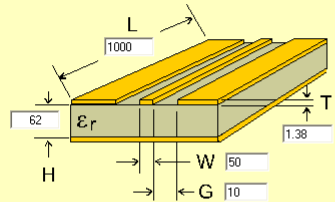
Designing the Co-Planar Transmission Line on Both Ends

AppCAD - [CPW]

File Calculate Select Parameters Options Help

Coplanar Waveguide With Groundplane No Groundplane

Calculate Z0 [F4]



$Z_0 = 49.8 \Omega$
 Elect Length = 0.140 λ
 Elect Length = 50.4 Degrees
 1.0 Wavelength = 7143.679 mil
 $V_p = 0.605$ fraction of c
 $\epsilon_{eff} = 2.73$
 Shape factor = 0.714

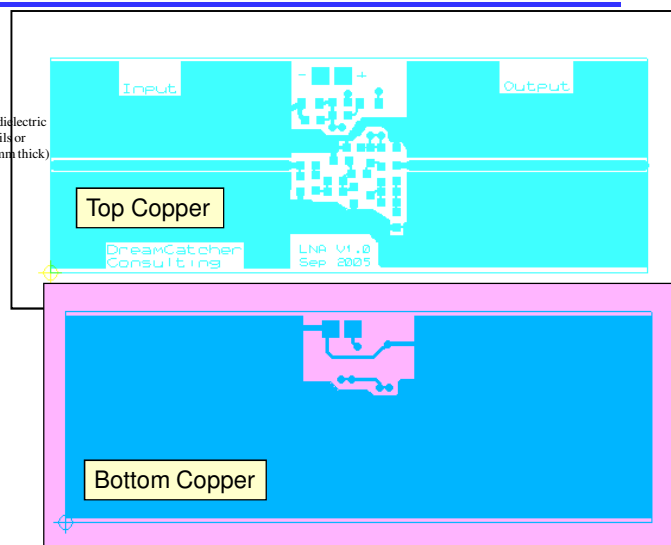
Dielectric: $\epsilon_r = 4.6$
 FR-4
 Frequency: 1 GHz
 Length Units: mils

Normal

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PCB Layout

A 2-layer PCB used.

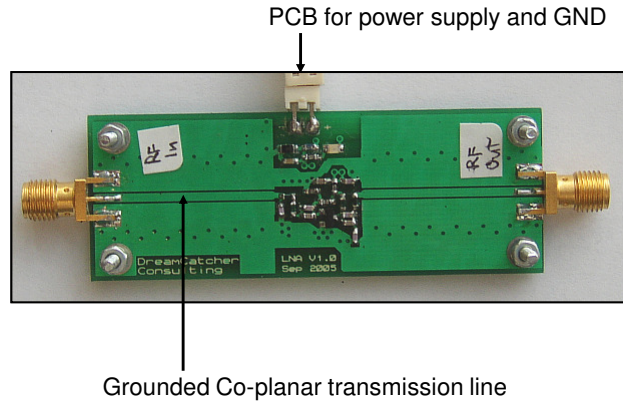


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The Actual Hardware



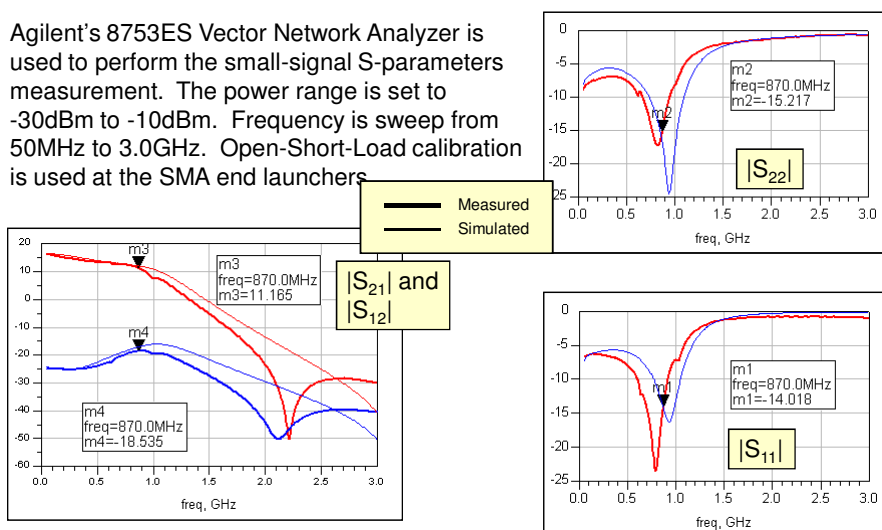
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Measurement Results

Agilent's 8753ES Vector Network Analyzer is used to perform the small-signal S-parameters measurement. The power range is set to -30dBm to -10dBm. Frequency is sweep from 50MHz to 3.0GHz. Open-Short-Load calibration is used at the SMA end launchers.



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Appendix 1 – Monolithic Microwave Integrated Circuit (MMIC) Amplifier

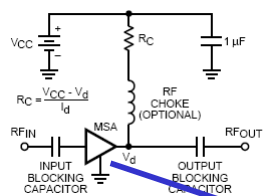
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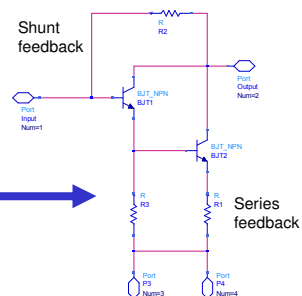
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Monolithic Microwave Integrated Circuit (MMIC)

- Nowadays you can easily built an RF amplifier using MMIC amplifier module.
- These usually contain a Darlington transistor pair with series and shunt feedbacks. The feedback serve to increase the bandwidth of the amplifier and internally match the input and output impedance to 50Ω.
- For example see Avago Technologies' MSA series devices datasheet.



Example of MMIC amplifier schematic



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