Lecture #11: LNA (Low Noise Amplifier) Design

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     - **Optimum Width *Wopt* of Device**
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8. **Why AGC?**
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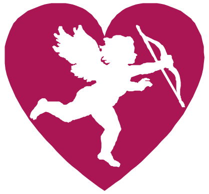
1. Introduction

- **Importance of LNA in a communication system**
  - **Sensitivity of a receiver is mainly determined by the noise figure of LNA**
  - **Linearity**
  - **Isolation**
  - **AGC (AtomaticGain Conrol)**

- **Topics**
  - **Typical design procedure**
  - **Improve of linearity**
  - **CascodeLNA**
  - **AGC**

- **A great challenge : Simultaneously to get G_{max} and NF_{min}**



1. Single-ended single device LNA

- **Specification**

- **Size of Device**

  Restriction of *W/L* due to the consideration of *Vgs*
  Optimum Width, *Wopt,* of Device due to consideration of NF_{min}

- **Raw device setup and testing**

  “Zero” capacitors and “infinitive “ inductors
  Tested parameters :S_{11}, Γ_{opt}, S_{21}, S_{22}, μ, NF and G circles

- **A great challenge : Simultaneously to get G_{max} and NF_{min}**

  Tradictionalstatus : Trade-off between G_{max} and NF_{min}

  Key Issue : $\boxed{S_{11}^{*} = \Gamma_{opt}}$

- **Three way to get *Gmax* and *NFmin* Simultaneously**

  Degeneration inductor
  Variation of current drain
  Variation of device size

- **Example**

oSpecification

The main goals for the design example are

Vcc **=3.0** ***V*****,**
Icc **<3.0** ***mA*****,**
Frequency range = 850 to 940 ***MHz*****,**
NF **< 2.5** ***dB*****,**
Gain > 10 ***dB*****,**
IP**3 > 0** ***dBm*****,**
IP**2 > 40** ***dBm*****.**

o Size of Device

* Restriction of *W/L* due to the consideration of *Vgs*

$$I_d = \frac{m_n C_{ox}}{2} \frac{W}{L} \left(V_{gs} - V_{th}\right)^2$$

$$g_m = m_n C_{ox} \frac{W}{L} \left(V_{gs} - V_{th}\right)$$

$$I_d = \frac{1}{2} g_m \left(V_{gs} - V_{th}\right)$$

$$C_{ox} = \frac{e_{ox}}{t_{ox}}$$

$$g_m = \sqrt{2 m_n C_{ox} \frac{W}{L} I_d}$$

$$V_{gs} = 2 \frac{I_d}{g_m} + V_{th}$$

Example:

ε_{ox} =3.45x10-13*F/cm*,

t_{ox} = 23.3 A^o=23.3x10^{-8} *cm*,

μ_n = 170 *cm2/V-sec*,

C_{ox} = 14.81 *fF/ μ*^{2},

V_{tn} =0.49 *V*,

μ_n C_{ox}= 251.72 *μA/V*^{2}.

Table 11.1 Restriction of *W/L* due to the consideration of *Vgs*

ε_{ox} (F/cm)	t_{ox} (A°)	t_{ox} (cm)	C_{ox} (fF/μ²)	μ_n cm²/(V.s)	$\mu_n C_{ox}$ (μA/V²)	I_d (mA)	W (μm)	L (μm)	W/L	g_m (mA/V)	R_d (kΩ)	V_{tn} (V)	V_{gs} (V)
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	0.9	0.09	10.00	2.24	1.00	0.49	1.38
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	9	0.09	100.00	7.10	1.00	0.49	0.77
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	90	0.09	1000.00	22.44	1.00	0.49	0.58
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	204	0.09	2268.33	33.79	1.00	0.49	0.55
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	450	0.09	5000.00	50.17	1.00	0.49	0.53
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	900	0.09	10000.00	70.95	1.00	0.49	0.52
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	1.00	1800	0.09	20000.00	100.34	1.00	0.49	0.51
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	0.9	0.09	10.00	3.17	1.00	0.49	1.75
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	9	0.09	100.00	10.03	1.00	0.49	0.89
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	90	0.09	1000.00	31.73	1.00	0.49	0.62
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	204	0.09	2268.33	47.79	1.00	0.49	0.57
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	450	0.09	5000.00	70.95	1.00	0.49	0.55
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	900	0.09	10000.00	100.34	1.00	0.49	0.53
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	2.00	1800	0.09	20000.00	141.91	1.00	0.49	0.52
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	0.9	0.09	10.00	5.02	1.00	0.49	2.48
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	9	0.09	100.00	15.87	1.00	0.49	1.12
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	90	0.09	1000.00	50.17	1.00	0.49	0.69
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	204	0.09	2268.33	75.56	1.00	0.49	0.62
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	450	0.09	5000.00	112.19	1.00	0.49	0.58
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	900	0.09	10000.00	158.66	1.00	0.49	0.55
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	5.00	1800	0.09	20000.00	224.37	1.00	0.49	0.53

ε_{ox} (F/cm)	t_{ox} (A^o)	t_{ox} (cm)	C_{ox} (fF/μ^2)	μ_n $cm^2/(V.s)$	$\mu_n C_{ox}$ ($\mu A/V^2$)	I_d (mA)	W (μm)	L (μm)	W/L	g_m (mA/V)	R_d ($k\Omega$)	V_{tn} (V)	V_{gs} (V)
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	0.9	0.09	**10.00**	**7.10**	1.00	**0.49**	**3.31**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	9	0.09	**100.00**	**22.44**	1.00	**0.49**	**1.38**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	90	0.09	**1000.00**	**70.95**	1.00	**0.49**	**0.77**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	204	0.09	**2268.33**	**106.86**	1.00	**0.49**	**0.68**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	450	0.09	**5000.00**	**158.66**	1.00	**0.49**	**0.62**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	900	0.09	**10000.00**	**224.37**	1.00	**0.49**	**0.58**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**10.00**	1800	0.09	**20000.00**	**317.31**	1.00	**0.49**	**0.55**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	0.9	0.09	**10.00**	**10.03**	1.00	**0.49**	**4.48**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	9	0.09	**100.00**	**31.73**	1.00	**0.49**	**1.75**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	90	0.09	**1000.00**	**100.34**	1.00	**0.49**	**0.89**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	204	0.09	**2268.33**	**151.13**	1.00	**0.49**	**0.75**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	450	0.09	**5000.00**	**224.37**	1.00	**0.49**	**0.67**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	900	0.09	**10000.00**	**317.31**	1.00	**0.49**	**0.62**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**20.00**	1800	0.09	**20000.00**	**448.75**	1.00	**0.49**	**0.58**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	0.9	0.09	**10.00**	**15.87**	1.00	**0.49**	**6.79**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	9	0.09	**100.00**	**50.17**	1.00	**0.49**	**2.48**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	90	0.09	**1000.00**	**158.66**	1.00	**0.49**	**1.12**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	204	0.09	**2268.33**	**238.95**	1.00	**0.49**	**0.91**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	450	0.09	**5000.00**	**354.77**	1.00	**0.49**	**0.77**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	900	0.09	**10000.00**	**501.71**	1.00	**0.49**	**0.69**
3.45E-13	23.3	2.33E-07	14.81	170.0	251.72	**50.00**	1800	0.09	**20000.00**	**709.53**	1.00	**0.49**	**0.63**

* Restriction of *W/L* due to the consideration of *Vgs*

- The underlined values of V_{gs} in the most right column in Table 4.1 are unacceptable because they are higher than 0.7*V*, which is considered as a highest value of V_{gs} when the DC power supply is low, say, 1.0 to 1.8 *V*.
- Therefore, the rows with the underlined values of V_{gs} in Table 4.1 must be abandoned in the selection of the ratio *W/L*. It implies that the ratio of *W/L* is restricted for the given values of I_d and g_m due to the limitation on V_{gs}.
- The rest rows in Table 4.1 are acceptable and are the candidates. They will be furthermore selected with the consideration ofso-called "power-constrained noise optimization."

* Optimum Width W_{opt} of Device

$$W_{opt} = \frac{1}{3wLC_{ox}R_S}$$

Example:

ε_{ox} =3.45x10-13*F/cm*,

t_{ox} = 23.3 *A°*=23.3x10^{-8} *cm*,

μ_n = 170 *cm2/V-sec*,

C_{ox} = 14.81 *fF/* μ^2,

V_{tn} =0.49 *V*,

μ_n C_{ox}= 251.72 $\mu A/V^2$.

where
W_{opt}= Optimum width of device (MOSFET transistor);
ω = Operation angular frequency;
L = Length of device (MOSFET transistor);
C_{ox} = Capacitance per unit area of the gate oxide;
R_S = Source resistance.

,

* **Optimum of Length L_{opt} and Optimum of Width W_{opt} of Device**

$$W_{opt} = \frac{1}{3wLC_{ox}R_S}$$

$$I_d = \frac{m_n C_{ox}}{2}\frac{W_{opt}}{L}\left(V_{gs} - V_{th}\right)^2$$

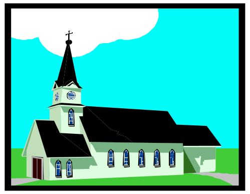
$$\boxed{\begin{aligned} L = L_{opt} &= \sqrt{\frac{m_n}{6wI_d R_S}}\left(V_{gs} - V_{th}\right) \\ W = W_{opt} &= \frac{1}{3wL_{opt}C_{ox}R_S} \end{aligned}}$$

o Raw Device Set-up and Testing

* The purpose of raw device testing is twofold:

- **To see if this raw device can approach a good LNA design or not.**
  A good LNA design is that
  The minimum of Noise figure and the maximum of gain
  can be obtained simultaneously.

- **To create a starting point for impedance matching so as to continue the next design step.**



* Set-up for raw device testing

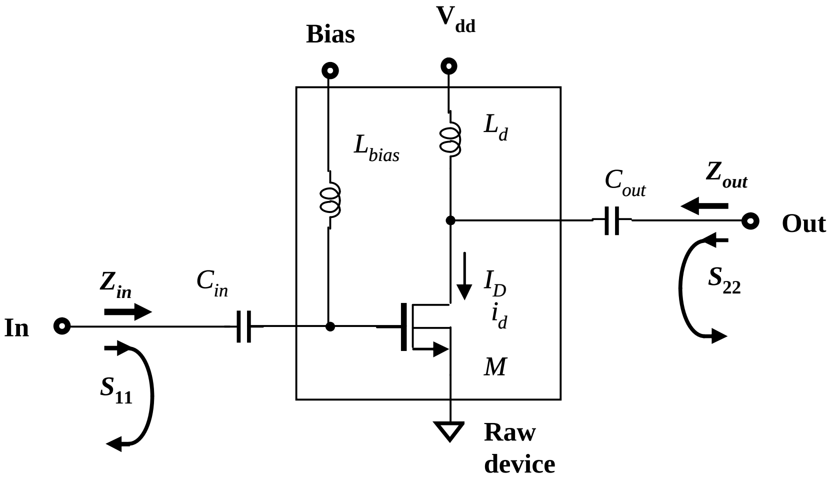
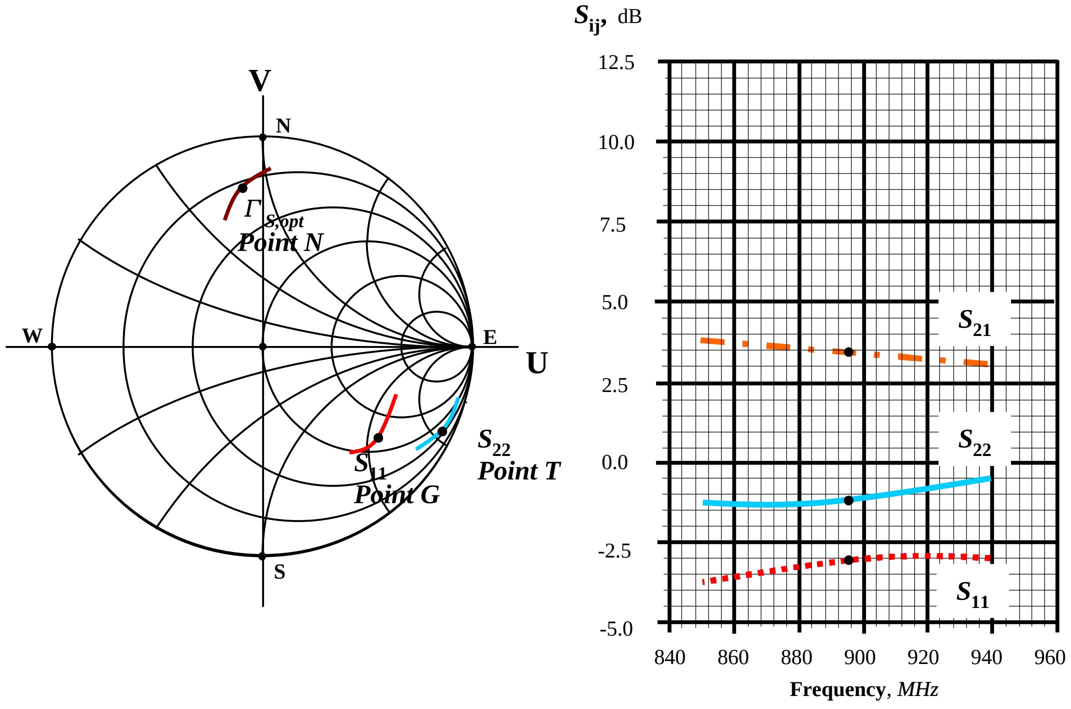


Figure 11.1 Setup for raw device testing, f =850 to 940 *MHz*, I_D=2.6 *mA*
C_{in}, C_{out} : "Zero" capacitor;
L_{bias}, L_c, L_d : "Infinitive" inductor.

$$\frac{\Delta f}{f_o} = \frac{940 - 850}{895} = 10.05\%$$

* Raw device testing

Main tested parameters: S11, Γopt



(a) S_{11}, S_{22} and $\Gamma_{S,opt}$ on Smith Chat

(b) Magnitude of S_{ij}, dB

Figure 11.2 ***S*** **parameters from raw device testing , f =850 to 940 *MHz*, I_D =2.6 *mA***
(The intermediate frequency 895*MHz* is marked with dot on each trace.)

* Haus' Theory

(H. A. Hauset. al., "Representation of Noise in Linear Twoports," Proceedings of the IRE, Vol. 48, pp. 69-74, January, 1960.)

$$NF = NF_{\min} + \frac{R_n}{G_s}\left[\left(G_S - G_{S,opt}\right)^2 + \left(B_S - B_{S,opt}\right)^2\right]$$

Where NF = Noise figure of the noisy block;
NF_{min} = Minimum of noise figure of the noisy block;
R_n = Equivalent noise resistance;
Y_S = Admittance of input source;
G_S = Conductance of input source;
B_S = Subceptanceof input source.
$Y_{S,opt}$ = Optimum admitttanceof input source;
$G_{S,opt}$ = Optimum conductance of input source;
$B_{S,opt}$ = Optimum subceptanceof input source.

$$Y_S = G_S + jB_S$$

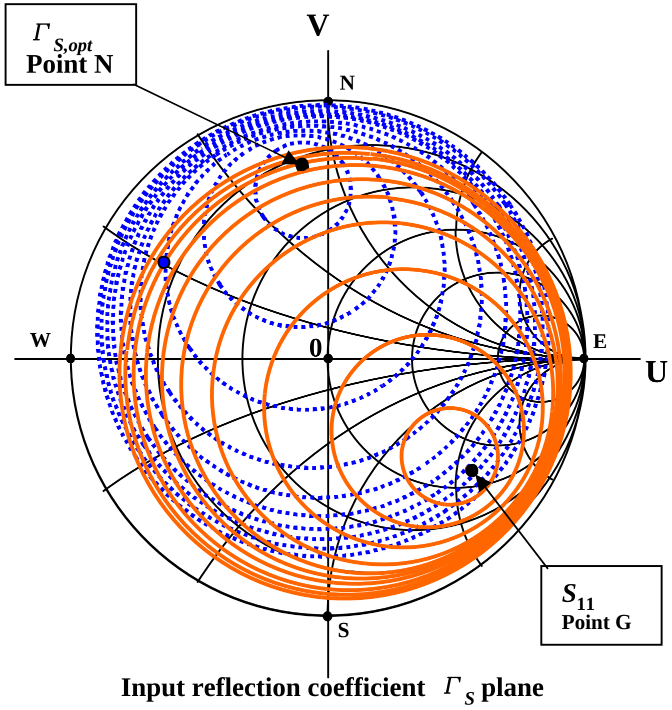
$$Y_{S,opt} = G_{S,opt} + jB_{S,opt}$$

$$\Gamma_S = \Gamma_{S,opt}$$

* Raw device testing

NF, Gain and NF circles

At point G, *G* = *Gmax* = 3.0 *dB*, and *NF* = 8.7*dB*,
At point N, *G* = -4.8 *dB*, and *NF* = *NFmin* = 5 *dB*.



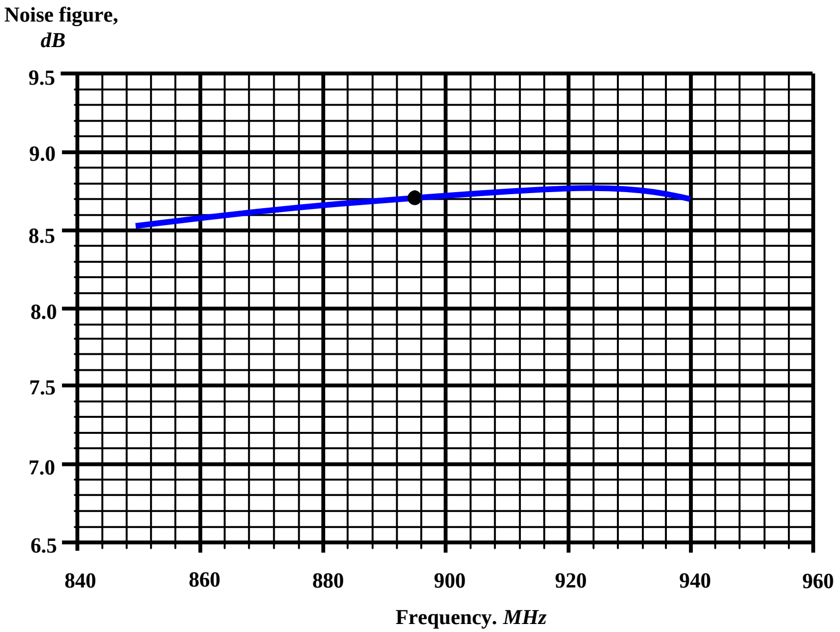


Figure 11.3 Noise Figure from 850 to 940 *MHz*, I_D =2.6 *mA* *NF* = 8.7 *dB* when f = 895 *MHz*

Figure 11.3 Constant gain circles and constant noise figure circles when *f* =895 *MHz*

- * Gain circles: G_{max} = 3.0 *dB* at point G, step = -1.0 *dB*,
- * Noise figure circles: NF_{min} = 5 dB at point N, step = 0.5 *dB*.

* Impedance matching

Is it possible to pull the point G and N together after input impedance matching network is build?

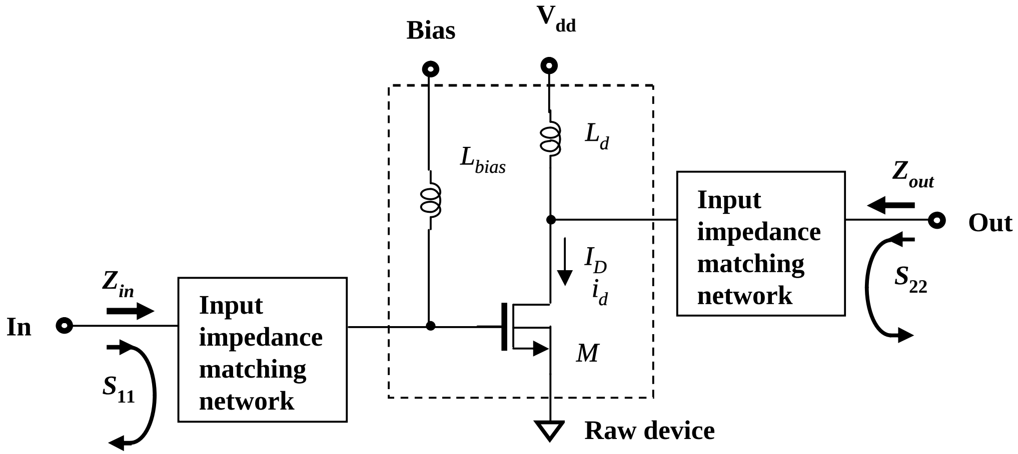
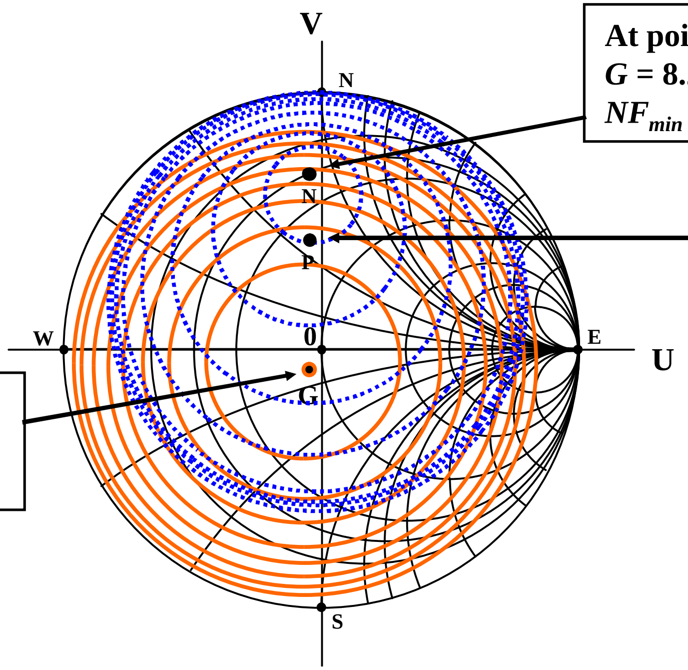


Figure 11.4 Input and output impedance matched networks are added to the raw device.

f =850 to 940 MHz, I_D=2.6 mA
C_{in}, C_{out} : “Zero” capacitor;
L_{bias}, L_c, L_d : “Infinitive” inductor.

- **The answer is**

Impedance matching is not a good assistant to the NF_{min}!
Trade-off must be taken!



At point N,
$G = 8.2\ dB$,
$NF_{min} = 1.8\ dB$,

At point P,
$G = 11.3\ dB$,
$NF = 2.3\ dB$,

At point G,
$G = G_{max} = 13\ dB$,
$NF = 3.0\ dB$,

Input reflection coefficient Γ_S plane

Figure 11.5 Constant gain circles and constant noise figure circles when f =895 MHz
- **Gain circles: G_{max} = 13 dB at point G, step = 1.0 dB,**
- **Noise figure circles: NF_{min} = 1.8 dB at point N, step = 0.5 dB,**

o Challenge for a good LNA design

* Optimum of Source Reflection coefficient, Γopt

- **In order to enable the raw device approaching to the minimumof noise figure, $\Gamma S,opt$ is a required optimum of source reflection coefficient, ΓS, looked from the raw device toward the source.**

- **On the other hand, in order to enable the raw device approaching to the maximum of gain, *Gmax*, *S*11* is a required value of source reflection coefficient, ΓS, looked from the raw device toward the source since the actual reflection coefficient looked from the source toward the raw device is *S*11.**

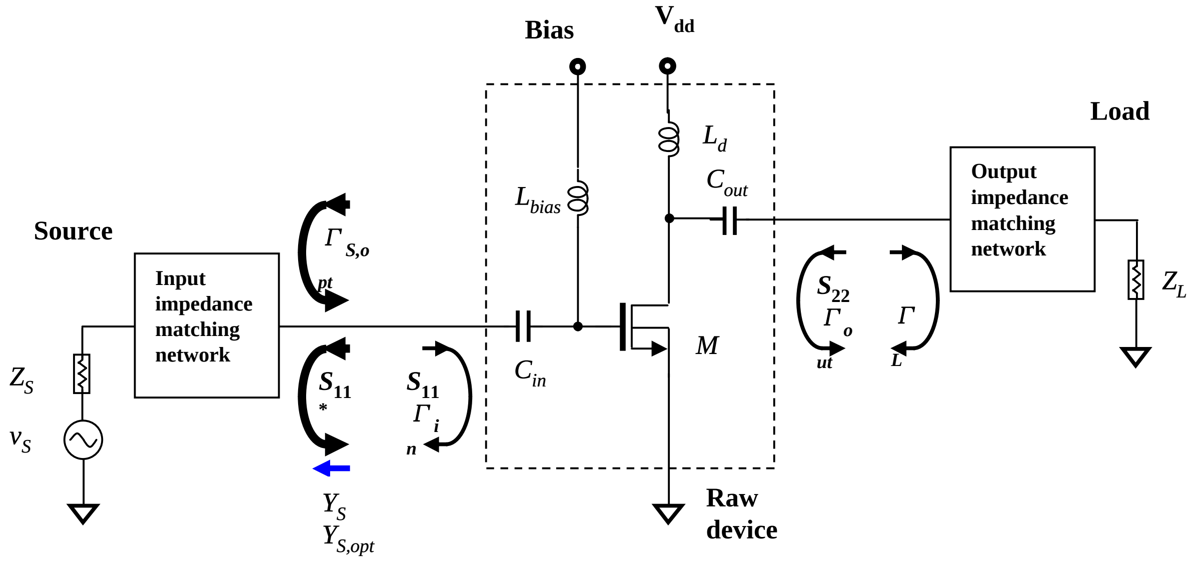


Figure 11.6 Directions of $\Gamma_{S,opt}$, Γ_{in} and Γ_{out}, S_{11} and S_{11}^* in the schematic for the raw device testing

- **Key Issue**

$$\boxed{\Gamma_{S,opt} = S_{11}^{*}}$$

* Schemes to satisfy the condition: $\Gamma_{S,opt} = S_{11}^{*}$

1) **Increase or decrease of current drain, I_D,**

The S parameters as well as the values of $\Gamma S,opt$ will be changed as the current drain is varied.
The condition, $\Gamma S,opt = S11^*$, could be reached at an appropriate amount of current drain.

2) **Change of device size,**

The S parameters as well as the values of $\Gamma S,opt$ will be changed as the device size is varied.
The condition, $\Gamma_{S,opt} = S_{11}^{*}$, could be reached at an appropriate device size.
Of course, this scheme is only possible to the IC designerbut not to the designer who implements the circuits by discrete parts.

3) **Addition of degeneration part,**

Up to the design experience in the practical design, this is an easy way to get success.

4) **And so on.**

* Addition of degeneration inductor

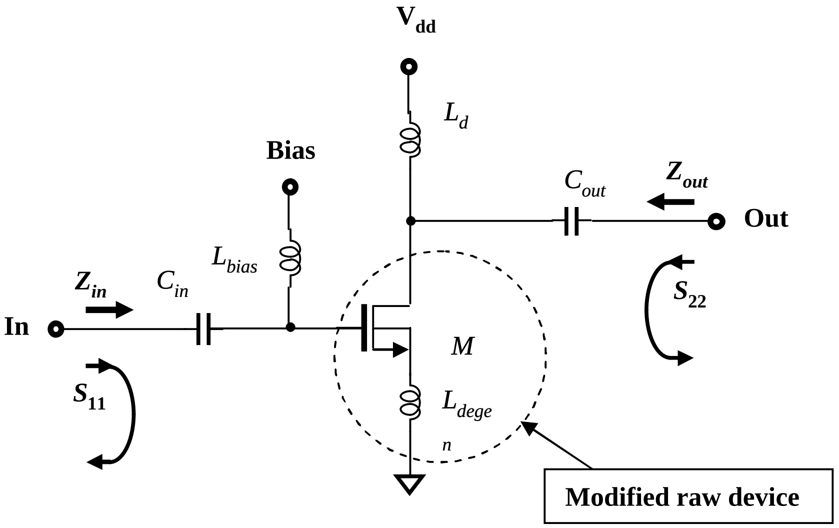
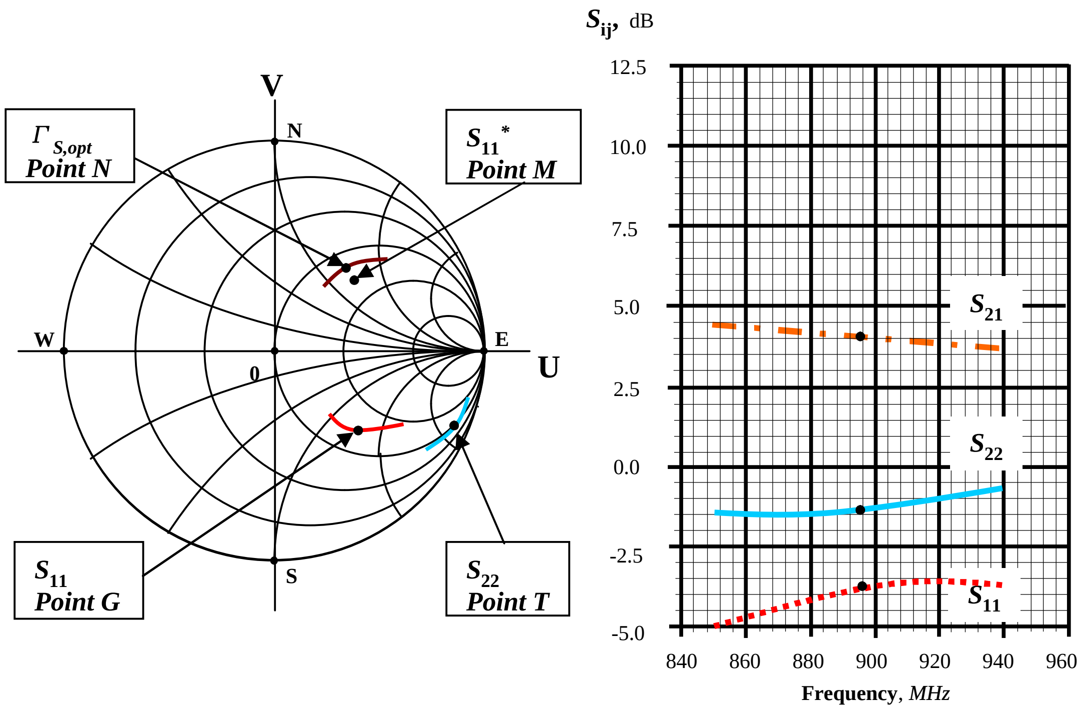


Figure 11.7 Setup for modified raw device testing by adding of degeneration inductor

L_{degen} : Degeneration inductor.
C_{in}, C_{out} : "Zero" capacitor;
L_{bias}, L_c, L_d : "Infinitive" inductor.

* S_{11} and Γ_{opt} adjusted by degeneration inductor



(a) S_{11}, S_{22} and $\Gamma_{S,opt}$ on Smith Chat

(b) Magnitude of S_{ij}, dB

Figure 11.8 ***S* parameters from modified raw device testing , *f* =850 -940 *MHz*, I_D =2.6 *mA***
(The intermediate frequency 895*MHz* is marked with dot on each trace.)

* Variation of Input Impedance due to Degeneration Inductor

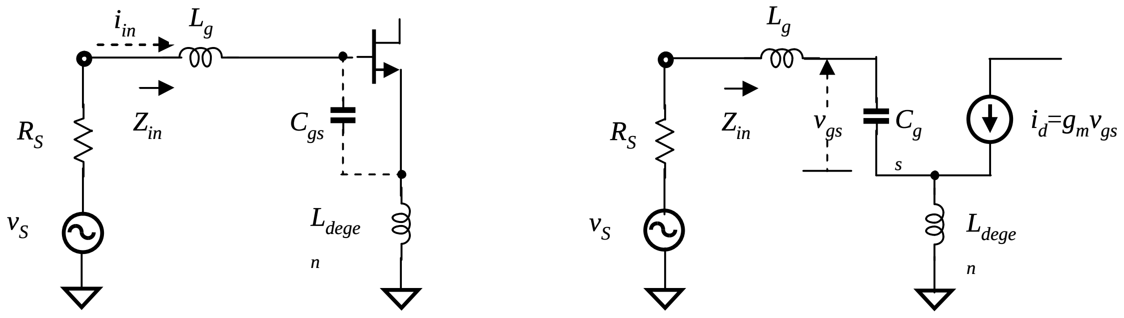
1) MOSFET

$$v_{in} = i_{in}\left(jL_g w + \frac{1}{jC_{gs} w} \right) + (i_{in} + i_d) jL_{\deg en} w = i_{in} j\left(L_g w - \frac{1}{C_{gs} w} \right) + (i_{in} + g_m V_{gs}) jL_{\deg en} w$$

$$v_{in} == i_{in} j\left(L_g w - \frac{1}{C_{gs} w} \right) + \left(i_{in} + g_m i_{in} \frac{1}{jC_{gs} w} \right) jL_{\deg\ en} w$$

$$Z_{in} = \frac{v_{in}}{i_{in}} = R_{in} + jX_{in}$$

$$Z_{in} = j(L_g + L_{\deg en})w + \frac{1}{jC_{gs} w} + \frac{g_m}{C_{gs}} L_{\deg en} = j\left[(L_g + L_{\deg en})w - \frac{1}{C_{gs} w} \right] + L_{\deg en} w_T$$



(a) Input stage **(b) Equivalent of input stage**

Figure 11.9 The input stage of MOSFET transistor with common source configuration

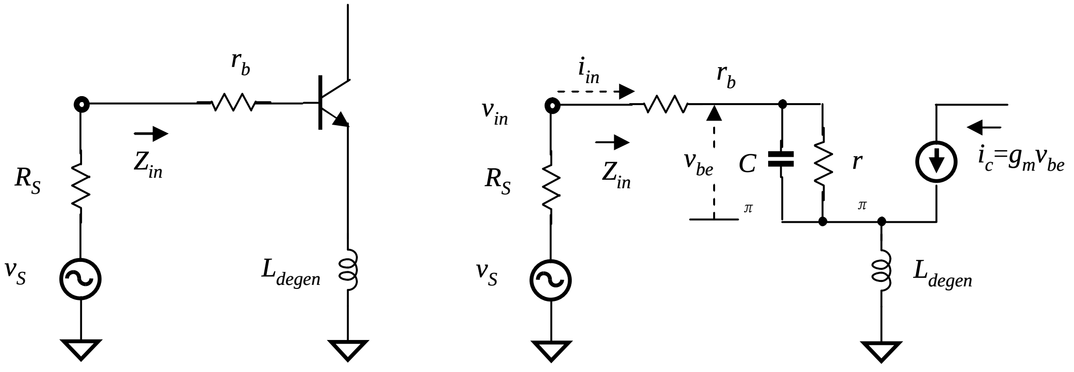
2) Bipolar

$$r_p // C_p = \frac{r_p}{1+jC_p w r_p} = \frac{r_p}{1+\left(C_p w r_p\right)^2} - j\frac{C_p w r_p{}^2}{1+\left(C_p w r_p\right)^2}$$

$$v_{in} = i_{in}\left(r_b + r_p // C_p\right) + \left(i_{in} + i_c\right)L_{degen}w \qquad i_c = g_m v_{be} = g_m i_{in}\left(r_p // C_p\right)$$

$$Z_{in} = \frac{v_{in}}{i_{in}} = r_b + r_p // C_p + j\left[1 + \left(r_p // C_p\right)g_m\right]L_{deg\,en}w$$

$$Z_{in} = r_b + r_p + \frac{L_{degen}C_p w^2 g_m r_p{}^2}{1+\left(C_p w r_p\right)^2} + j\left[1 + \frac{\left(g_m - \frac{C_p}{L_{degen}} r_p\right) r_p}{1+\left(C_p w r_p\right)^2}\right]L_{degen}w$$



(a) Schematic of input stage **(b) Equivalent of input stage**

Figure 11.10 The input stage of a bipolar transistor with a degeneration inductor

* Input and output impedance matching

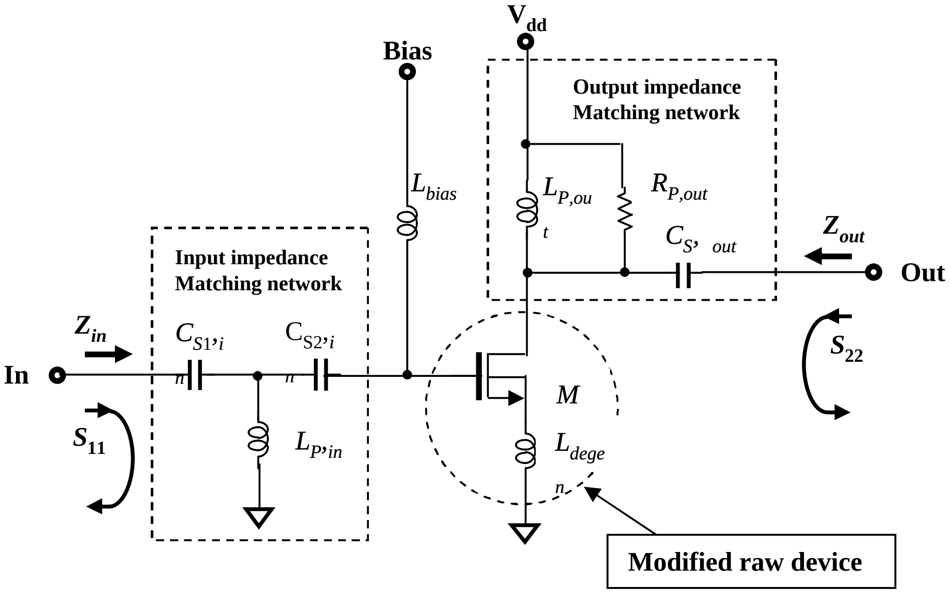
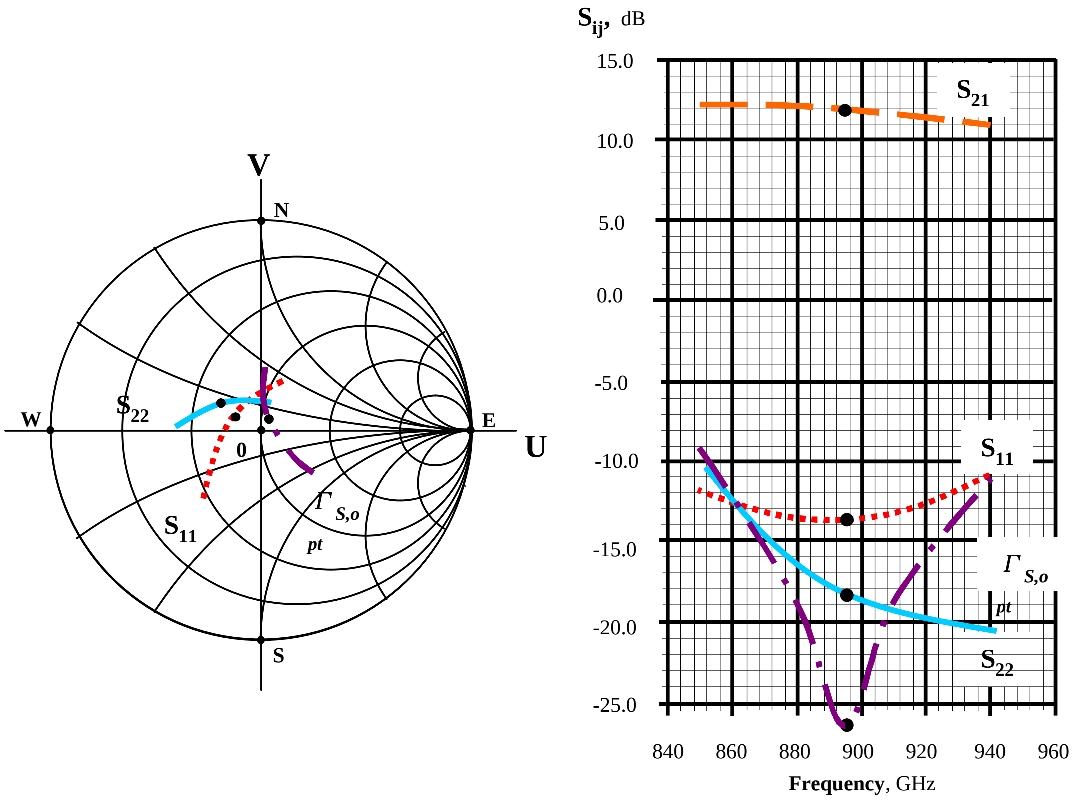


Figure 11.11 Impedance matching of modified raw device by parts:
At input : $C_{S1,in} = 1\ pF$, $L_{P,in} = 20\ nH$, $C_{S2,in} = 39\ pF$.
At output : $L_{P,out} = 15\ nH$, $R_{P,out} = 1500\ \Omega$, and $C_{S,out} = 1.6\ pF$



(a) S_{11}, S_{22} and $\Gamma_{S,opt}$ on Smith Chat

(b) Magnitude of S_{ij}, dB

Figure 11.12 ***S* parameters of the design example, f =850 -940 *MHz*, I_D =2.6 *mA***
(The intermediate frequency 895*MHz* is marked with dot on each trace.)
Theinput and output impedances are matched by parts:
At input: $C_{S1,in}$ = 1 *pF*. $L_{P,in}$ = 20 *nH*, $C_{S2,in}$ = 39 *pF*.
At output: $L_{P,out}$ = 15 *nH* $R_{P,out}$ =1500 Ω, $C_{S,out}$ = 1.6 *pF*

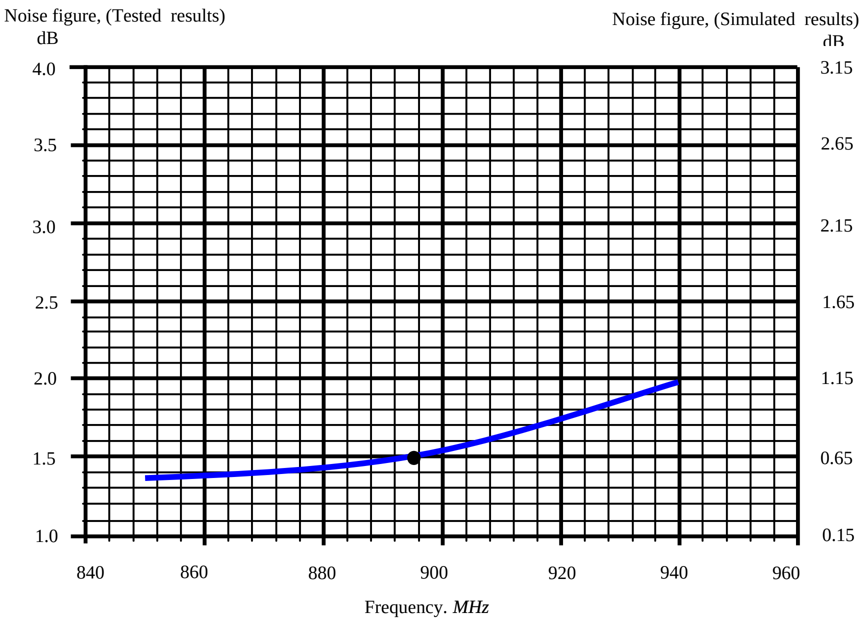


Figure 11.13 **Noise Figure of the design example,** **f =850 to 940 MHz, I_D =2.6 mA**

NF = 1.5 dB when f = 895 GHz

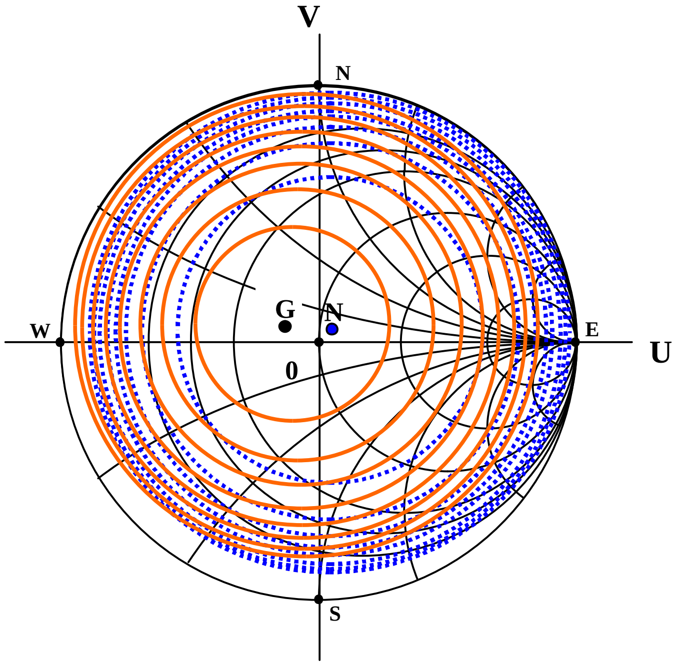


Figure 11.14 **Constant gain circles and constant noise figure circles**
when f =895 MHz
Gain circles: G_{max} = 12 dB at point G, step = 1.0 dB,
NF circles: NF_{min} = 1.5 dB at point N, step = 0.5 dB.

$\mu = 1.1 > 1$

$G = 12$ dB

$NF = 1.5$ dB

o Stability

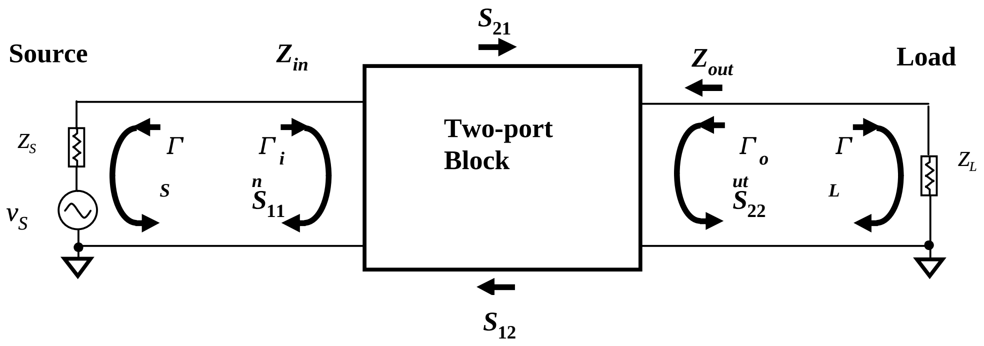


Figure 11.15 Different reflection coefficients and S parameters in a two-port block

$$|\Gamma_S| < 1$$

$$|\Gamma_L| < 1$$

$$|\Gamma_{in}| < 1$$

$$|\Gamma_{out}| < 1$$

$$K = 1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2$$

$$K > 1$$

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}|$$

$$|\Delta| < 1$$

$$m = \frac{1 - [mag(S_{11})]^2}{mag[S_{22} - \Delta conj(S_{11})] + mag(S_{21}S_{12})}$$

$$m > 1$$

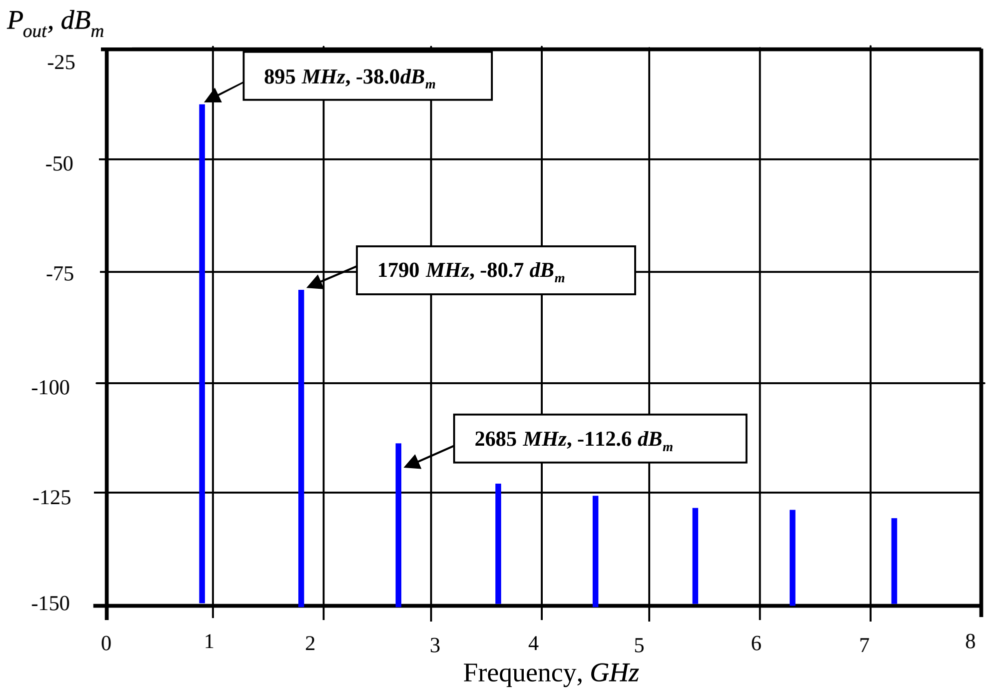


Figure 11.16 Spectrum at LNA output , f_o = 895 *MHz*, P_{in} = -50 *dB$_m$*

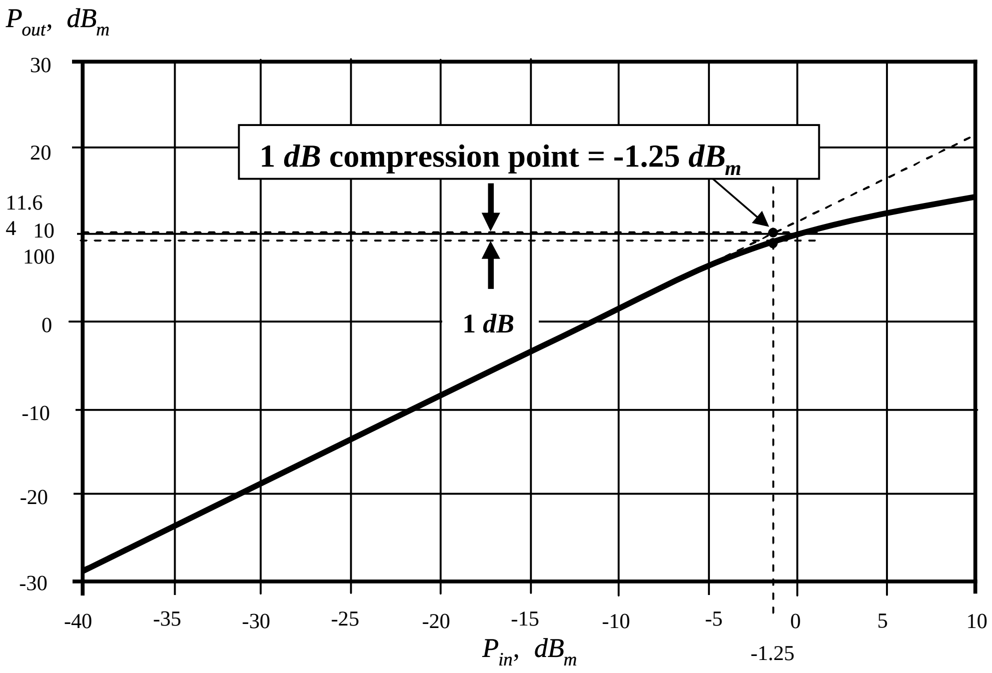


Figure 11.17 1*dB* compression point when f_o = 895 *MHz*

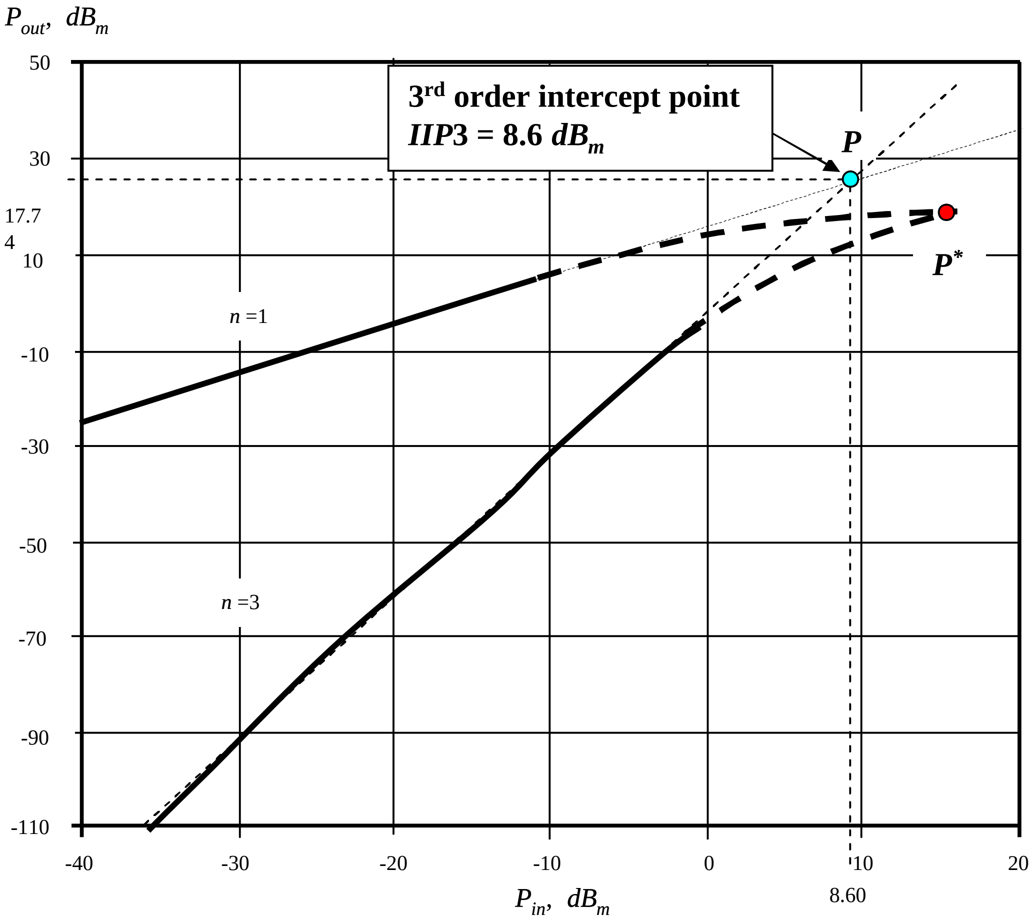


Figure 11.18 **3^{rd} order input intercept point when $f_o = 895\ MHz$**

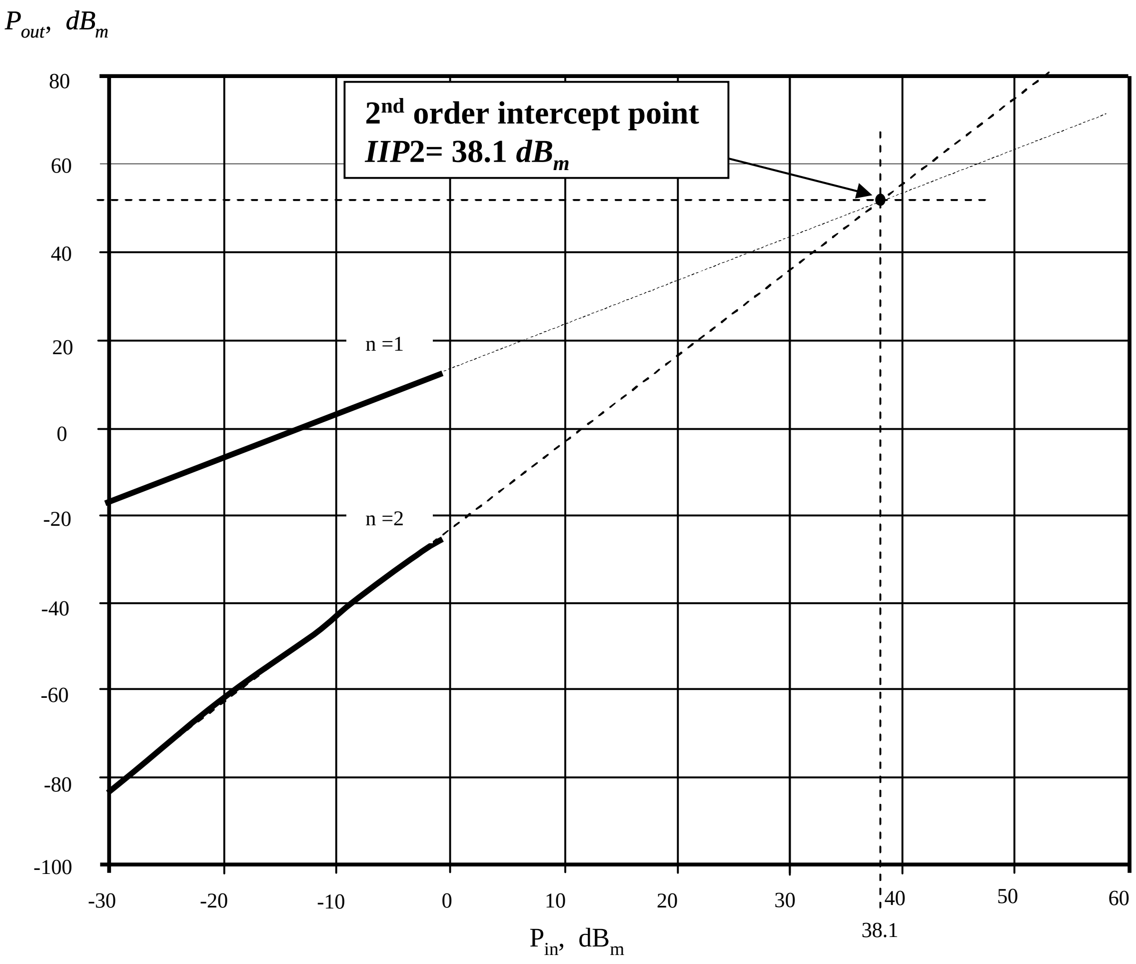
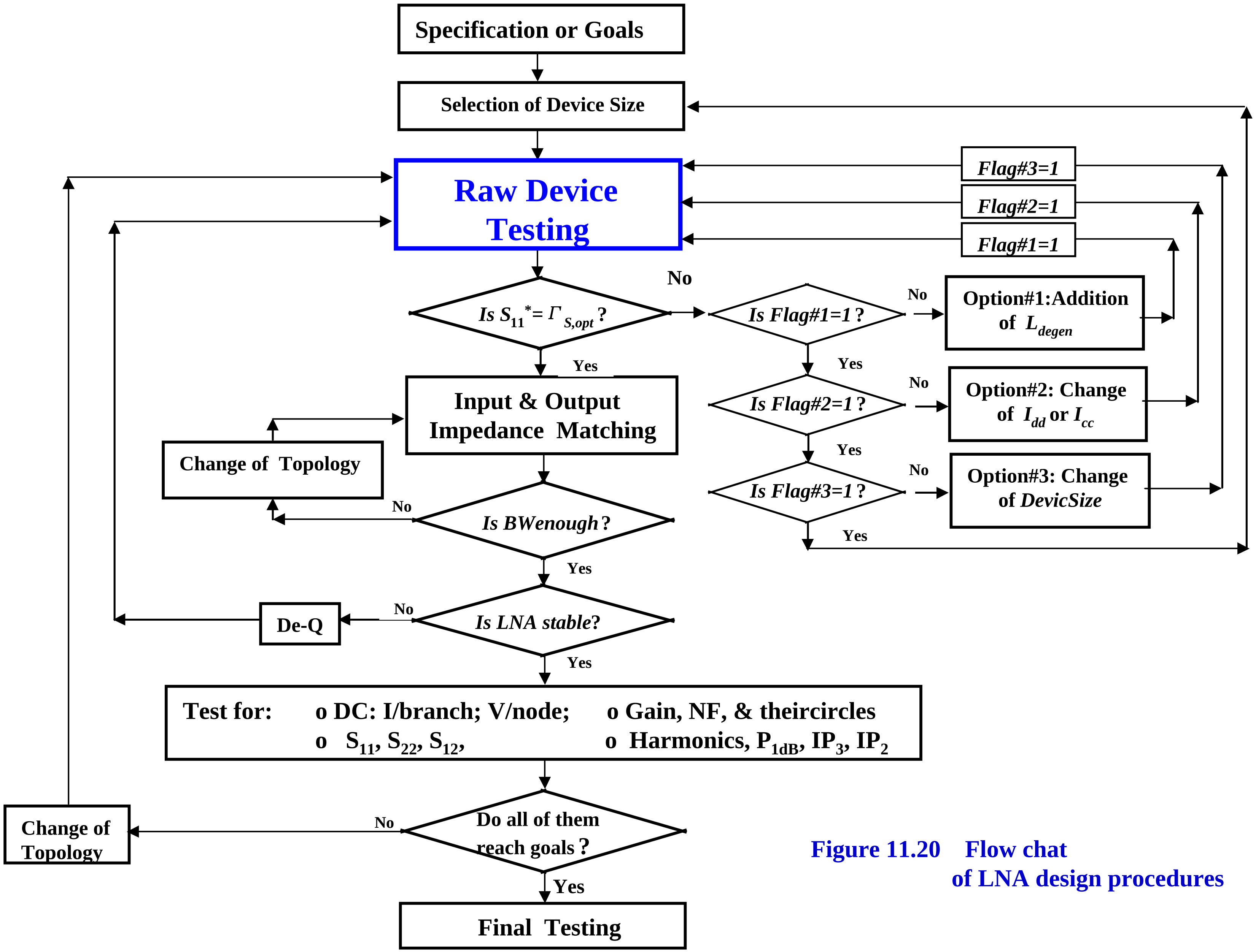


Figure 11.19 **2nd order input intercept point when f_o = 895 MHz**



Specification or Goals

Selection of Device Size

Raw Device Testing

Is $S_{11}^{*} = \Gamma_{S,opt}$?

No

Is *Flag#1=1* ?

No

Option#1:Addition of L_{degen}

Flag#1=1

Yes

Is *Flag#2=1* ?

No

Option#2: Change of I_{dd} or I_{cc}

Flag#2=1

Yes

Is *Flag#3=1* ?

No

Option#3: Change of *DevicSize*

Flag#3=1

Yes

Yes

Input & Output Impedance Matching

Is *BWenough* ?

No

Change of Topology

Yes

Is *LNA stable*?

No

De-Q

Yes

Test for:
o DC: I/branch; V/node;
o S_{11}, S_{22}, S_{12},
o Gain, NF, & theircircles
o Harmonics, P_{1dB}, IP_3, IP_2

Do all of them reach goals ?

No

Change of Topology

Yes

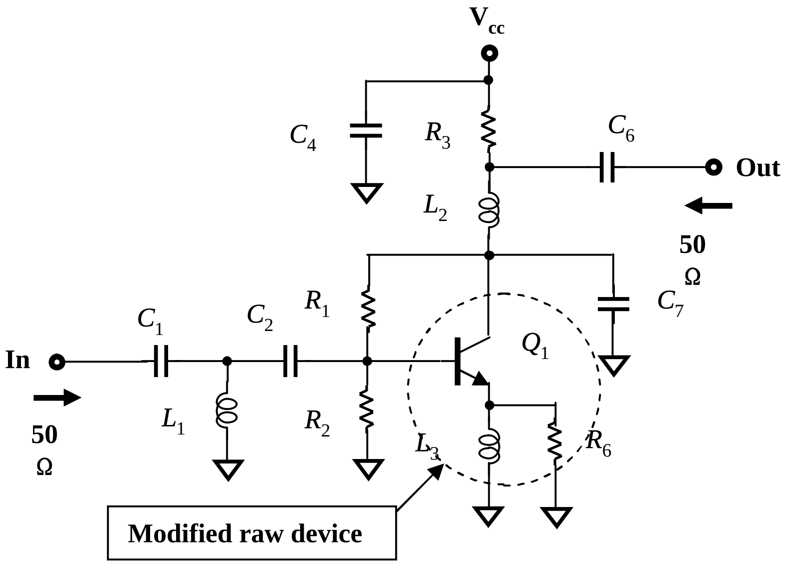
Final Testing

Figure 11.20 Flow chat of LNA design procedures

o Other examples

* LNA Design for VHF radio

	Specification		Final tested result	
Frequency range	**130 *MHz* to 180 *MHz***			
Device	**BFQ67 (Manufactured by Siemens)**			
DC power supply	**3**	***V***		
Current drain	**< 4**	***mA***	**3.47**	***mA***
Gain	**> 10**	***dB***	**15.0**	***dB***
Noise Figure	**< 2**	***dB***	**1.75**	***dB***
***IIP*3**	**> 0**	***dBm***	**2.5**	**dBm**
Input return	**< -10**	***dB***	**-40.0**	***dB***
Output return	**< -10**	***dB***	**-12.2**	***dB***



Part list
(Purchased from MuRata)

C_1	13 *pF*
C_2	1500 *pF*
C_4	1500 *pF*
C_6	1500 *pF*
C_7	6.2 *pF*
L_1	92 *nH*
L_2	92 *nH*
L_3	33 *nH*
R_1	3.3 *k Ω*
R_2	3.3 *k Ω*
R_3	390 *Ω*
R_6	100 *Ω*
Q_1	BFQ67

Figure 11.21 LNA designed for VHF radio

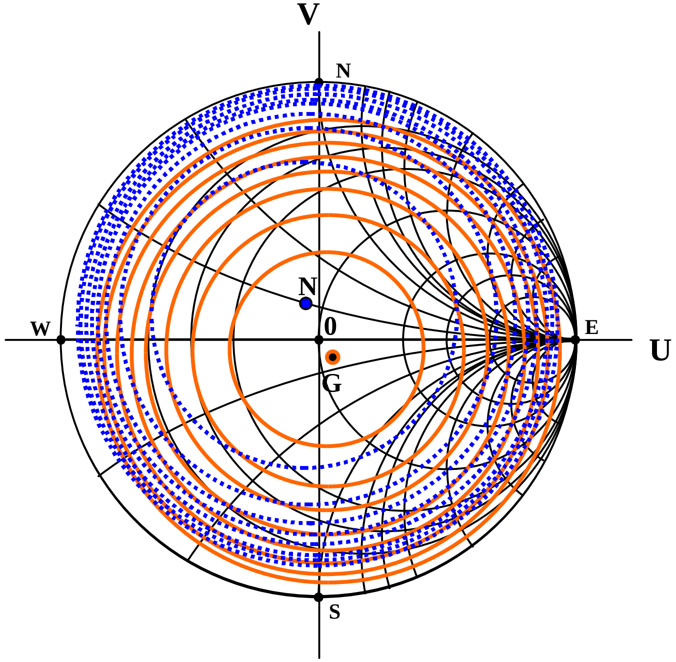


Figure 11.22 Constant gain circles and constant noise figure circles when f =150 MHz

- o Gain circles: G_{max} = 15 dB at point G, step = 1.0 dB,
- o Noise figure circles: NF_{min} = 1.75 dB at point N, step = 0.25 dB,

o Other examples

* LNA Design for UHF radio

	Specification		Final tested result	
Frequency range	**400 *MHz* to 470 *MHz***			
Device	**BFQ67 (Manufactured by Siemens)**			
DC power supply	**3**	***V***		
Current drain	**< 4**	***mA***	**3.43**	***mA***
Gain	**> 10**	***dB***	**12.0**	***dB***
Noise Figure	**< 2**	***dB***	**1.5**	***dB***
***IIP*3**	**> 0**	***dBm***	**5.0**	**dBm**
Input return	**< -10**	***dB***	**-17.8**	***dB***
Output return	**< -10**	***dB***	**-16.0**	***dB***

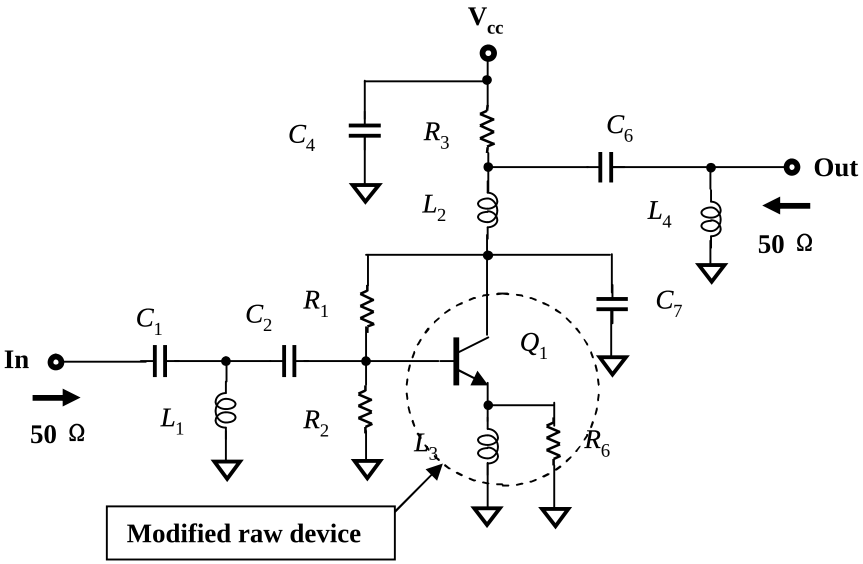


Figure 11.23 LNA designed for UHF radio

Part list
(Purchased from MuRata)

C_1	10 pF
C_2	150 pF
C_4	150 pF
C_6	150 pF
C_7	1.5 pF
L_1	33 nH
L_2	33 nH
L_3	5.6 nH
L_4	33 nH
R_1	3.3 $k\Omega$
R_2	3.3 $k\Omega$
R_3	390 Ω
R_6	390 Ω
Q_1	BFQ67

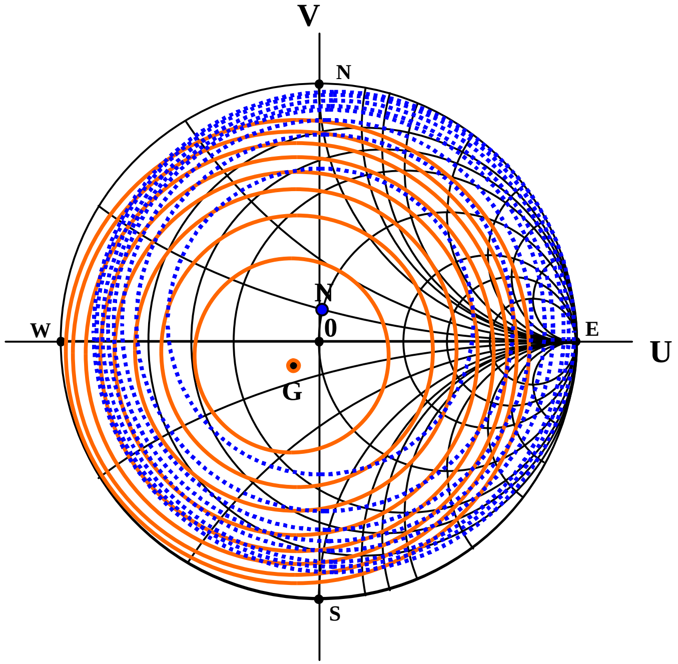


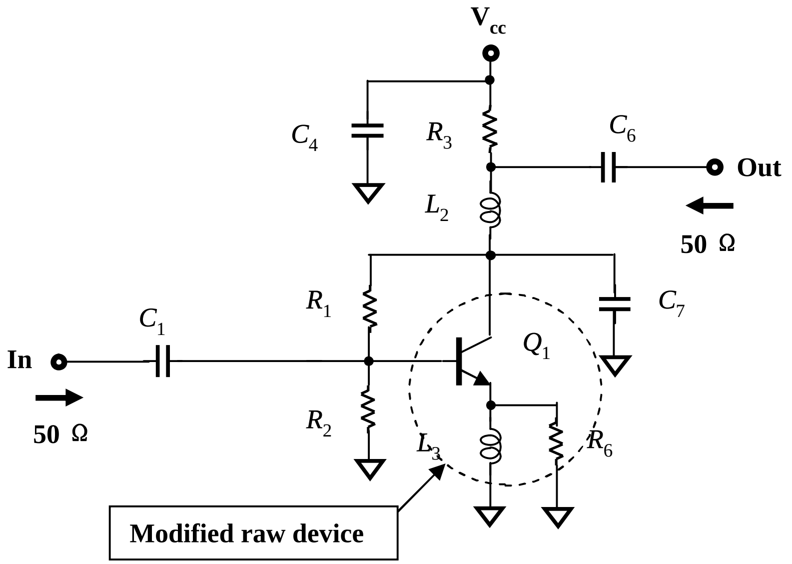
Figure 11.24 Constant gain circles and constant noise figure circles when f =450 MHz

- **Gain circles: G_{max} = 12 dB at point G, step = 1.0 dB,**
- **Noise figure circles: NF_{min} = 1.5 dB at point N, step = 0.25 dB,**

o Other examples

* LNA Design for 800/900 MHzradio

	Specification		Final tested result	
Frequency range	**850 *MHz* to 940 *MHz***			
Device	**BFQ67 (Manufactured by Siemens)**			
DC power supply	**3**	***V***		
Current drain	**< 4**	***mA***	**3.48**	***mA***
Gain	**> 10**	***dB***	**11.0**	***dB***
Noise Figure	**< 2**	***dB***	**1.8**	***dB***
***IIP*3**	**> 0**	***dBm***	**8.6**	***dBm***
Input return	**< -10**	***dB***	**-11.7**	***dB***
Output return	**< -10**	***dB***	**-17.0**	***dB***



Part list
(Purchased from MuRata)

C_1	**150 *pF***
C_4	**39 *pF***
C_6	**39 *pF***
L_2	**33 *nH***
L_3	**4.7 *nH***
R_1	**3.3 *k* Ω**
R_2	**3.3 *k* Ω**
R_3	**390 Ω**
R_6	**390 Ω**
Q_1	**BFQ67**

Figure 11.25 LNA designed for 800/900 MHz radio

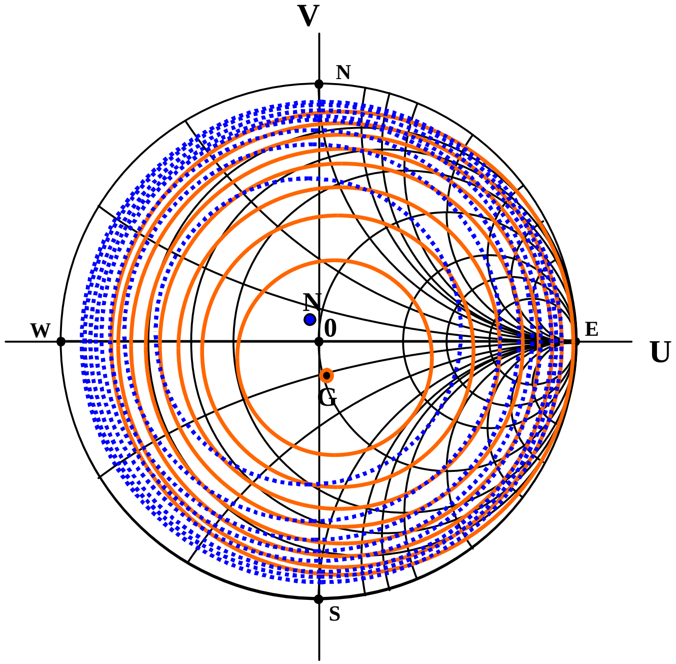


Figure 11.26 **Constant gain circles and constant noise figure circles when f =850 MHz**

- **Gain circles: G_{max} = 11 dB at point G, step = 1.0 dB,**
- **Noise figure circles: NF_{min} = 1.8 dB at point N, step = 0.25 dB.**

o Single-ended CascodeLNA

* Bipolar CE-CB cascodedevices

$$R_i = R_{i1} = r_{p1}$$

$$R_{o1} = r_{o1}$$

$$R_{i2} = r_{e2} = \frac{1}{g_{m2} + \frac{1}{r_{p2}}} = \frac{1}{1+b_2} r_{p2} \approx \frac{r_{p2}}{b_2}$$

$$R_o = r_{o2}\left(1 + \frac{g_{m2} r_{o1}}{1 + \frac{g_{m2} r_{o1}}{b_2}}\right) \qquad R_o \approx b_2 r_{o2}$$

if $g_{m2} r_{o1} >> b_2 >> 1$

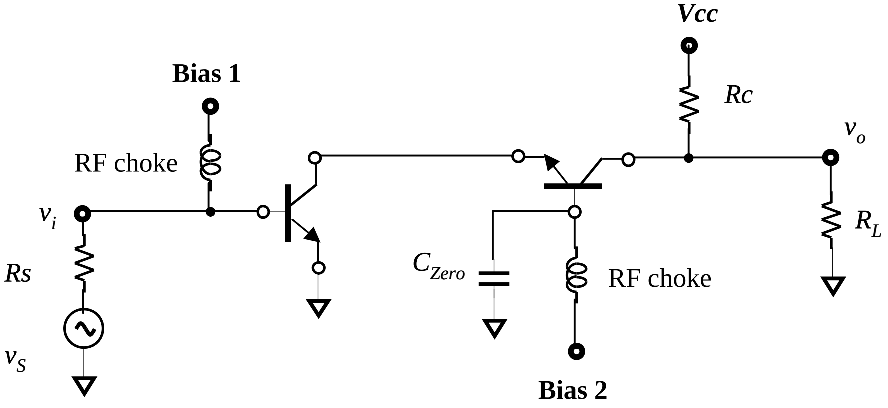


Figure 11.27 A bipolar cascodeamplifier

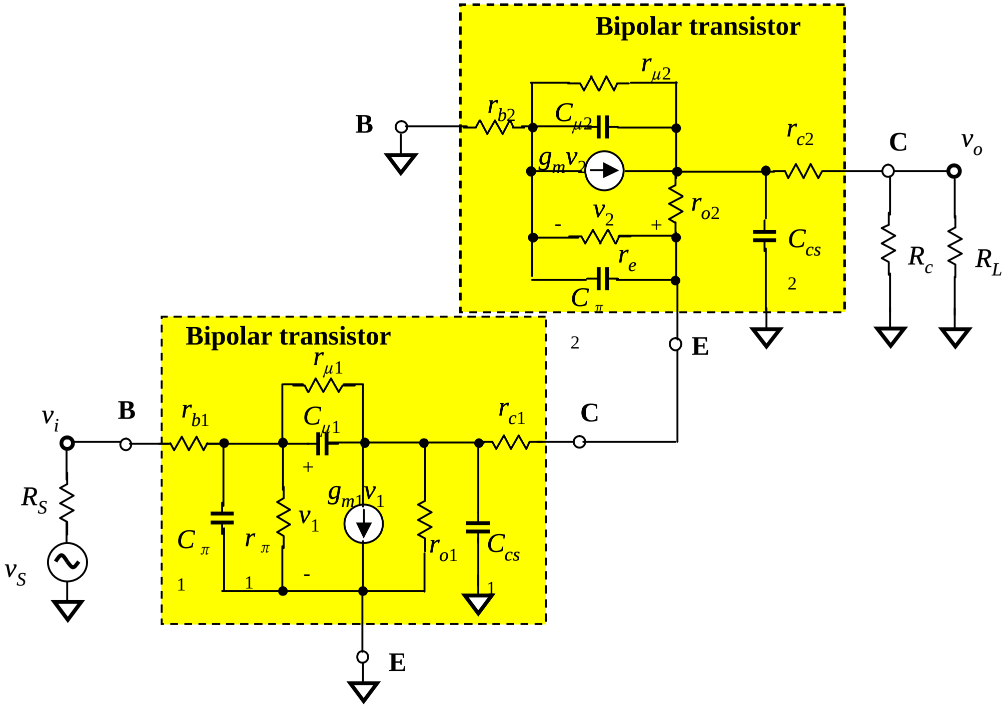


Figure 11.28 Equivalent circuit of bipolar cascodeamplifier with CE-CB configuration

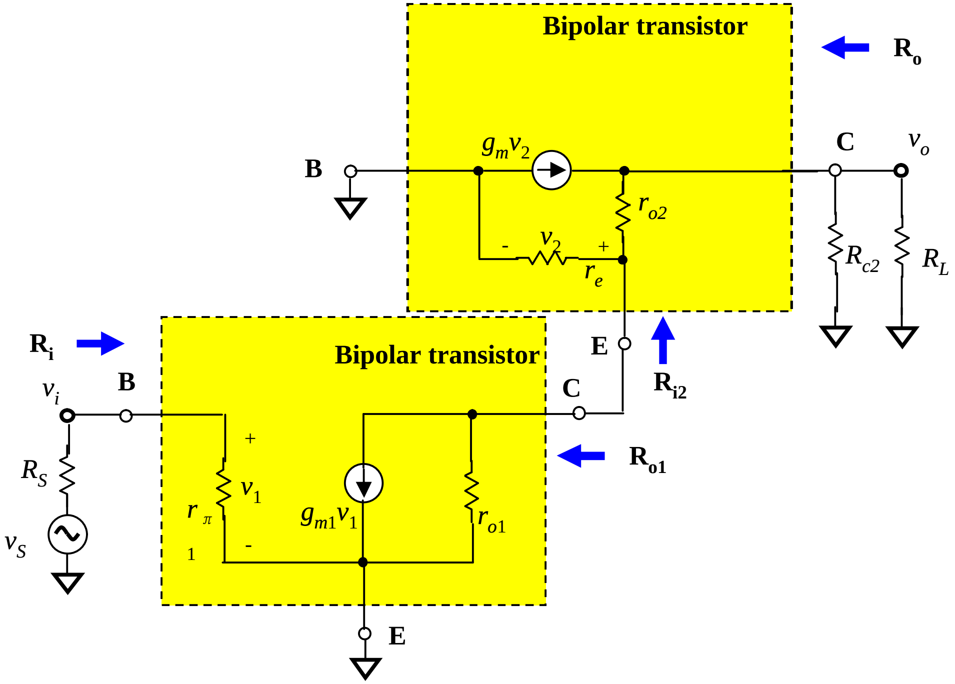


Figure 11.29 Equivalent circuit of bipolar cascodeamplifier with CE-CB configuration at low frequencies and the resistors, r_b, r_μ, and r_c, are neglected

$$A_{v1} = -g_{m1} r_{o1} // R_{i2} \approx -g_{m1} \frac{r_{p2}}{b_2}$$

Assume that

$$g_{m1} = g_{m2}$$

$$r_{p1} = r_{p2}$$

$$b_1 = b_2$$

Then,

$$A_{v1} = -1$$

$$G_m = g_{m1}$$

$$\boxed{A_v = \frac{v_o}{v_i} \approx -G_m R_o \approx -g_{m1} r_{o2} b_2}$$

$$A_{i1} = b$$

$A_{i2} \approx 1$ **because** $i_{i2} \approx i_{o2}$

$$\boxed{A_i \approx A_{i1} A_{i2} \approx b}$$

* MOSFET CS-CG cascodedevices

$$R_i \to \infty$$

$$R_{i2} = \frac{1}{(g_{m2} + g_{mb2})} + \frac{R_L'}{(g_{m2} + g_{mb2})r_{o2}} \qquad R_L' = R_d \,//\, R_L = \frac{R_d}{R_D + R_L} R_L$$

$$R_{i2} \approx \frac{1}{(g_{m2} + g_{mb2})}$$

$$G_m \approx g_{m1}$$

$$R_o = r_{o1} + r_{o1} + (g_{m2} + g_{mb2})r_{o1}r_{o2} \approx (g_{m2} + g_{mb2})r_{o1}r_{o2}$$

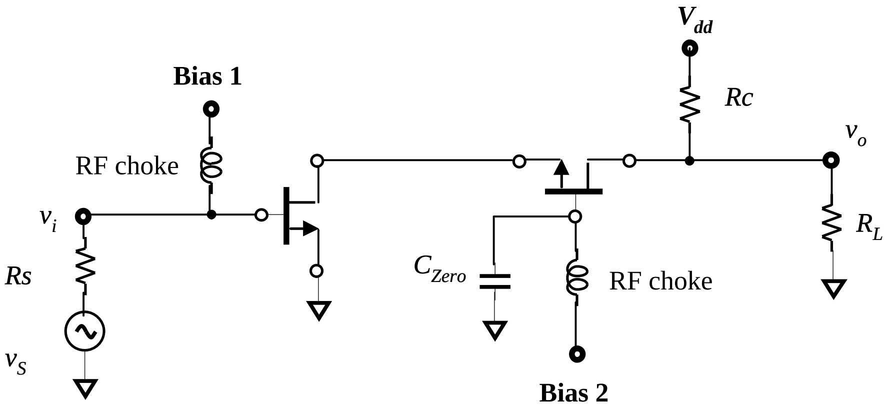


Figure 11.30 A MOSFET cascodeamplifier

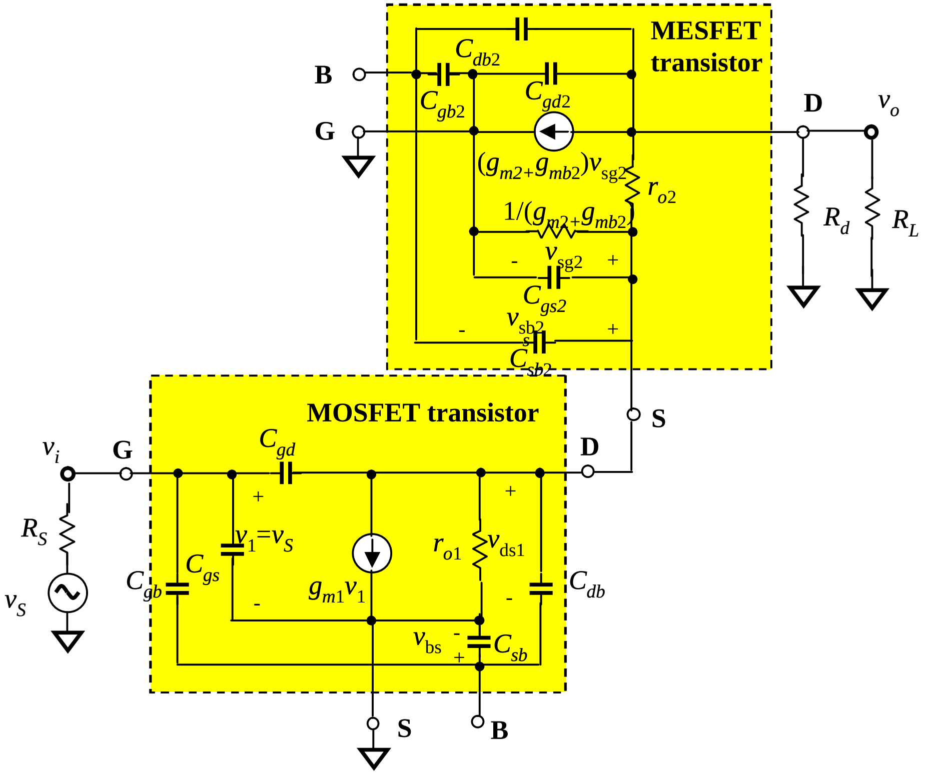


Figure 11.31 Equivalent circuit of MOSFET cascodeamplifier with CS-CG configuration

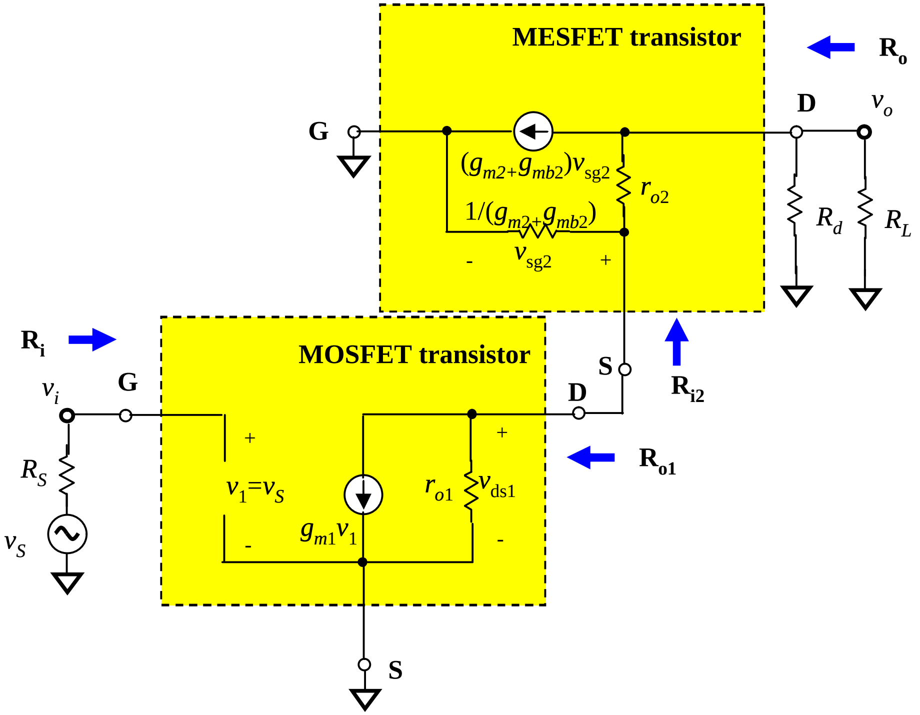


Figure 11.32 Equivalent circuit of MOSFET cascodeamplifier with CS-CG configuration at low frequencies.

$$A_{v1} = -g_{m1} r_{o1} // R_{i2} \approx -g_{m1} R_{i2} \approx -\frac{g_{m1}}{g_{m2} + g_{mb2}}$$

$$g_{m1} = g_{m2}$$

$$A_{v1} \approx -1$$

$$A_{i1} \rightarrow \infty$$

$$A_{i2} \approx 1$$

$$A_v = \frac{v_o}{v_i} \approx -G_m R_o \approx -g_{m1}(g_{m2} + g_{mb2}) r_{o1} r_{o2}$$

- ## Why Cascode

1) It increases the output impedance,

2) It alleviates the Miller effect on a voltage amplifier.

$$A_{v1} = -g_{m1} R_{L1}{}' \, // \, R_{i2} = -g_{m1} R_{L1}{}' \, // \, \frac{r_{p2}}{b_2} \approx -g_{m1} \frac{r_{p2}}{b_2} \approx 1$$

$$g_{m1} = g_{m2}$$

$$C_{i,miller} = C_m \left(1 + g_m R_L{}'\right) \approx C_m$$

$$w_{T1} = \frac{g_{m1}}{C_{p1} + C_{m1}\left(1 + g_{m1} R_{L1}{}'\right)} \Rightarrow w_{T1} = \frac{g_{m1}}{C_{p1} + C_{m1}}$$

$$\boxed{w_{T2} = \frac{g_{m2}}{C_{m2}}}$$

3) Better isolation

4) It could magnify the signal not only voltage but also the power of signal as well.

o Example

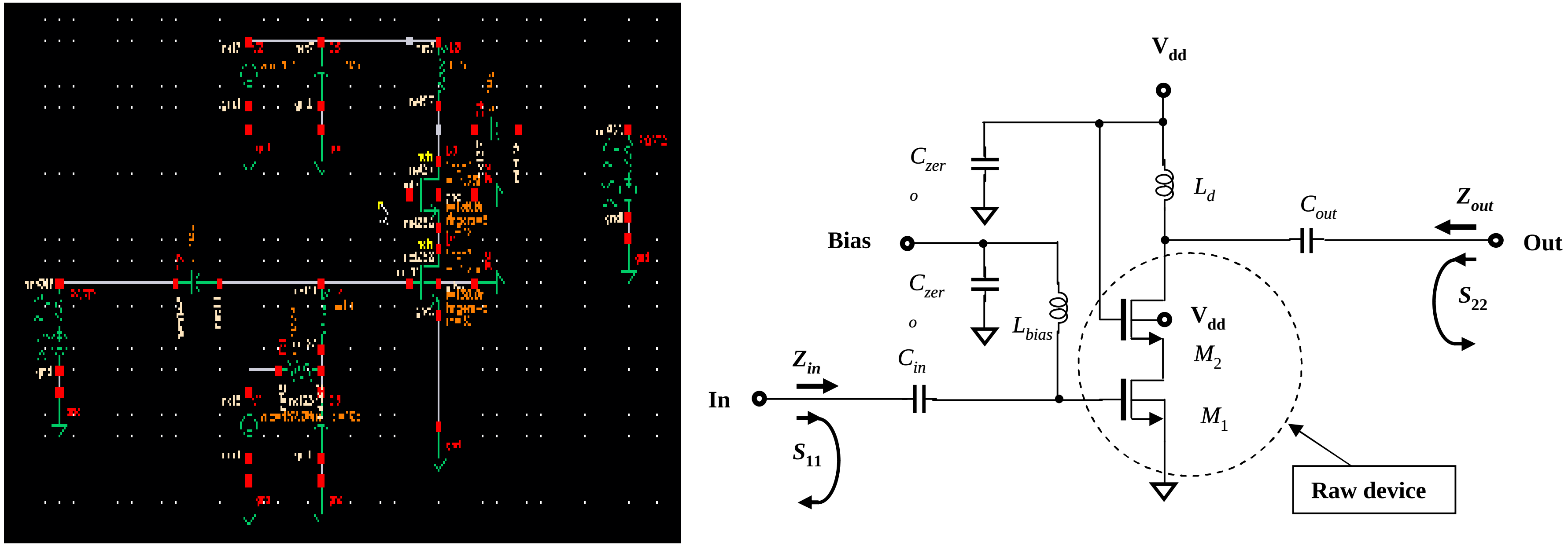
This is an LNA RFIC design example, which is designed for group #1, Band #2 of UWB

DC power supply: *Vdd* = 1.2 *V*,
Current drain: *Itotal* < 5 *mA*,
Operating frequency range: *f* = 3.696 to 4. 4224 *GHz*,
Gain: *G* > 12 dB,
Input return loss: *S*11 <-10 *dB*,
Output return loss: *S*22 <-10 *dB*,
Noise figure: *NF* < 2.5 dB
3rd order input intercept point: *IIP*3 > 5 *dBm*,
2nd order input intercept point: *IIP*2 > 35 *dBm*.

$$BW = \frac{\Delta f}{f} = \frac{4224 - 3696}{(4224 + 3696)/2} = \frac{528}{3960} = 13.3\%$$

L **=130 *nm***
W **= 1.25 *um***
Wtota*l=10 *um
Fingers = 8
Multiplier = 32
Mtotal= 256

* Raw device testing

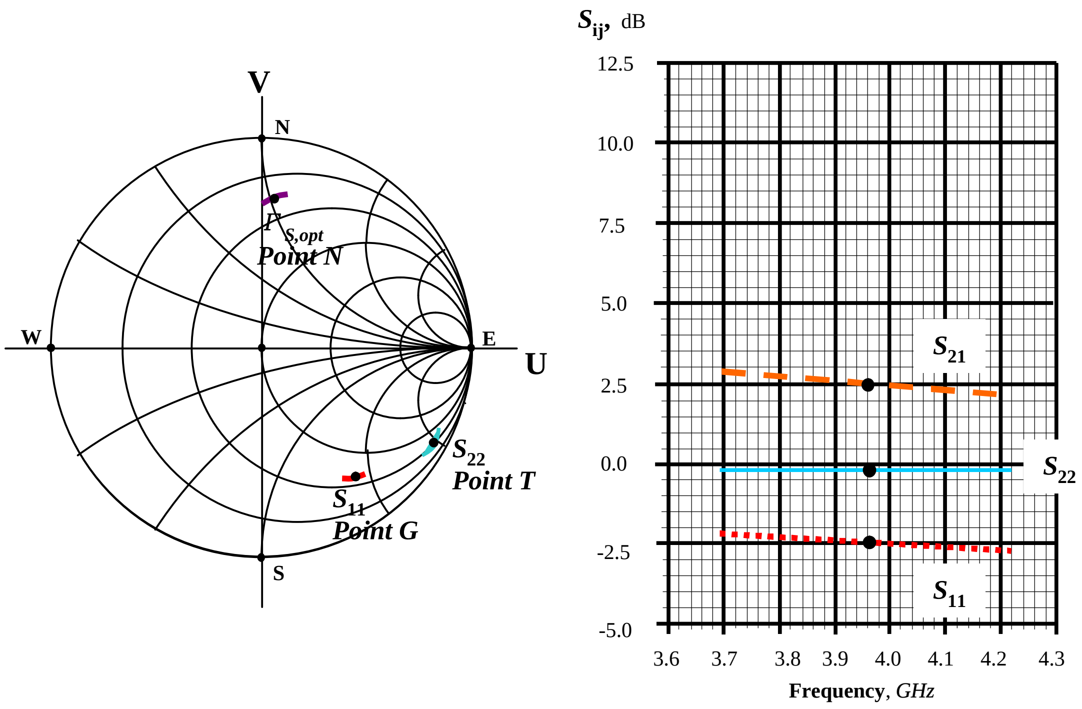


(a) Photo of setup for raw device testing taken from simulation screen

(b) Schematic of set-up for raw device testing re-drawn from the screen photo.

- C_{in}, C_{out}, C_{zero} : “Zero” capacitor;
- L_{bias}, L_d : “Infinitive” inductor.

Figure 11.33 Setup for raw device testing $I_{dd} = 4.54\ mA$ (Bias = 0.482 V)



(a) S_{11} and S_{22} on Smith Chat

(b) Magnitude of S_{ij}, dB

Figure 11.34 *S* parameters from raw device testing
(The intermediate frequency f =3.96 *GHz* is marked by a dot on each trace.)

f, GHz	3.696	3.960	4.224
S_{21}, dB	2.45	2.50	2.58
S_{11}, dB	-2.75	*-2.50*	-2.20
S_{22}, dB	-0.19	-0.18	-0.17

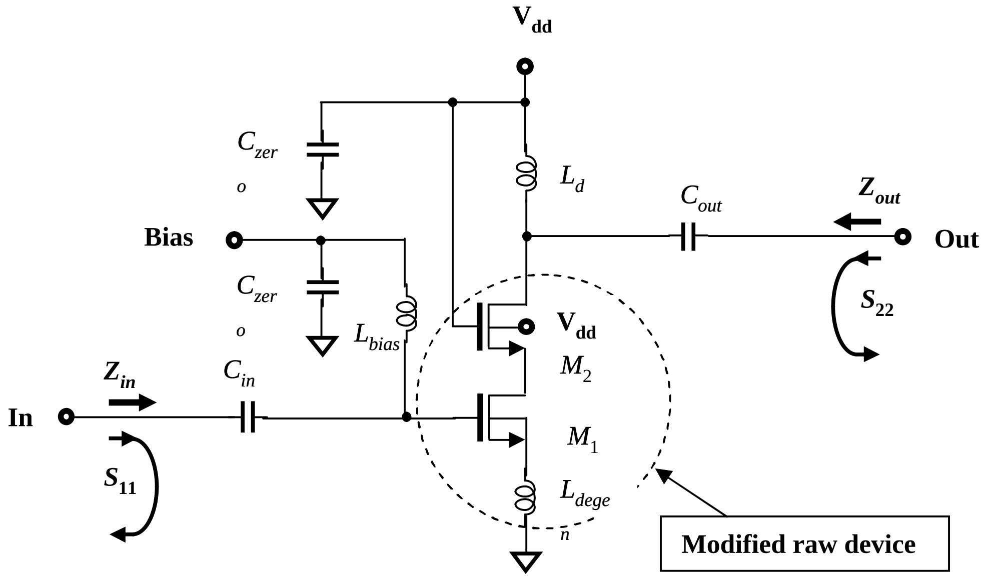
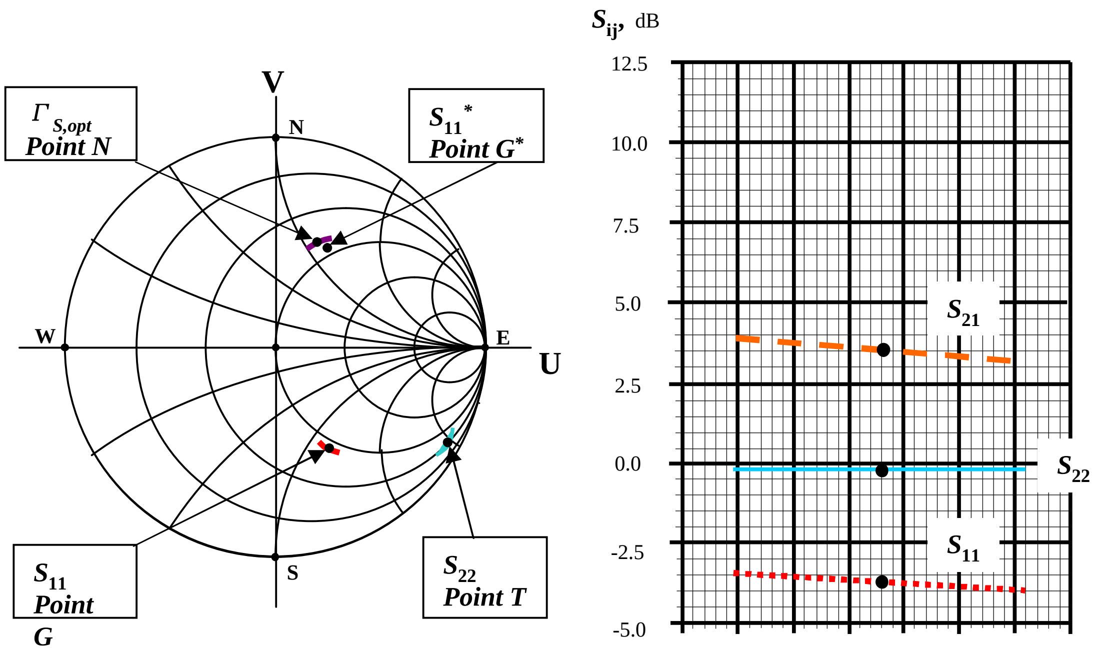


Figure 11.35 Schematic of set-up for modified raw device testing

- **C_{in}, C_{out}, C_{zero} : “Zero” capacitor;**
- **L_{bias}, L_d : “Infinitive” inductor.**

$L_{\deg en} = 0.45$ **nH, which satisfies the condition of** $\Gamma_{S,opt} = S_{11}^{*}$

But $m = 0.95 < 1$



(a) S_{11} **and** S_{22} **on Smith Chat**

(b) Magnitude of S_{ij}**, dB**

Figure 11.36 ***S*** **parameters from modified raw device testing**
(The intermediate frequency f **=3.96** ***GHz*** **is marked by a dot on each trace.)**

- **Gain and Bandwidth**
  - **The 1st try of the impedance matching work**

In input impedance network: $L_{S,\,in} = 4\ nH$, $C_{S,in} = 10\ pF$,

In output impedance network: $L_{P,out} = 10\ nH$, $R_{P,out} = 50\ \Omega$,
$C_{S,out} = 1\ pF$.

- The 1st try to implement impedance matching networks

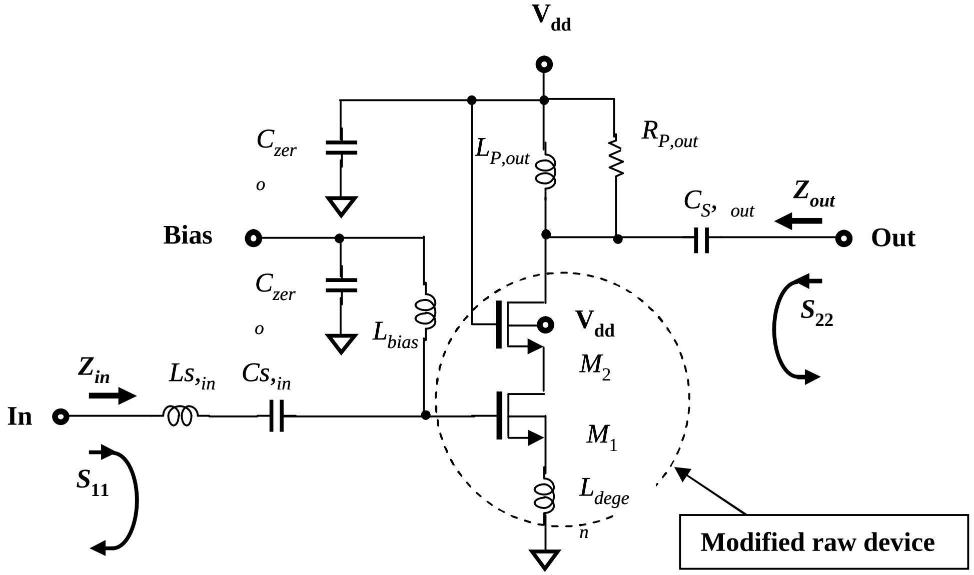


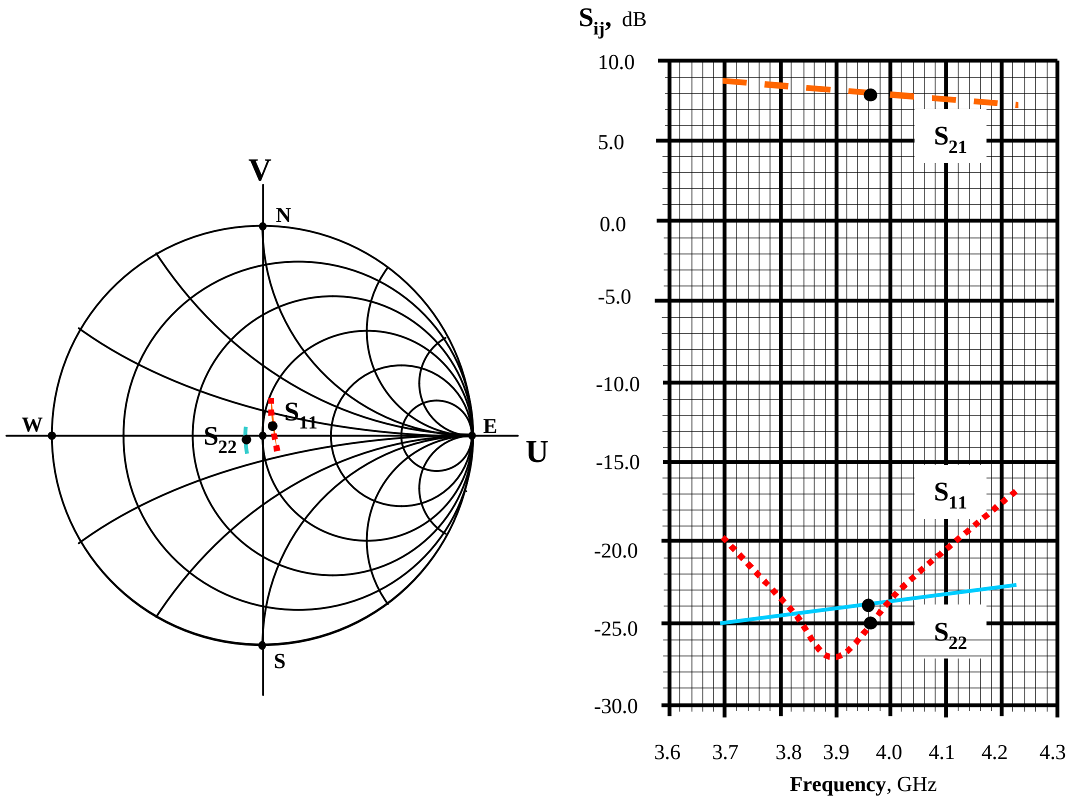
Figure 11. 37 Impedance matching by parts:

At input : $L_{S,\ in}$ = 4 *nH*, $C_{S,in}$ = 10 *pF*.

At output : $L_{P,out}$ = 10 *nH*, $R_{P,out}$ = 500 Ω, and $C_{S,out}$ = 1 *pF*

μ= 1.23 > 1, it is stable!

However, G = 8.0 dB, at f = 3.960 GHz. The gain is too low!



(a)S_{11} and S_{22} on Smith Chat **(b) Magnitude of S_{ij}, dB**

Figure 11.38 S parametersafter input and output impedances are matched by parts:
(The intermediate frequency f =3.96 GHz is marked by a dot on each trace.)
At input: $L_{S,\,in}$ = 4 nH, $C_{S,in}$ = 10 pF.
At output: $L_{P,out}$ = 10 nHand $R_{P,out}$ = 500 Ω, $C_{S,out}$ = 1 pF

- **The 2nd try to re-build impedance matching networks**

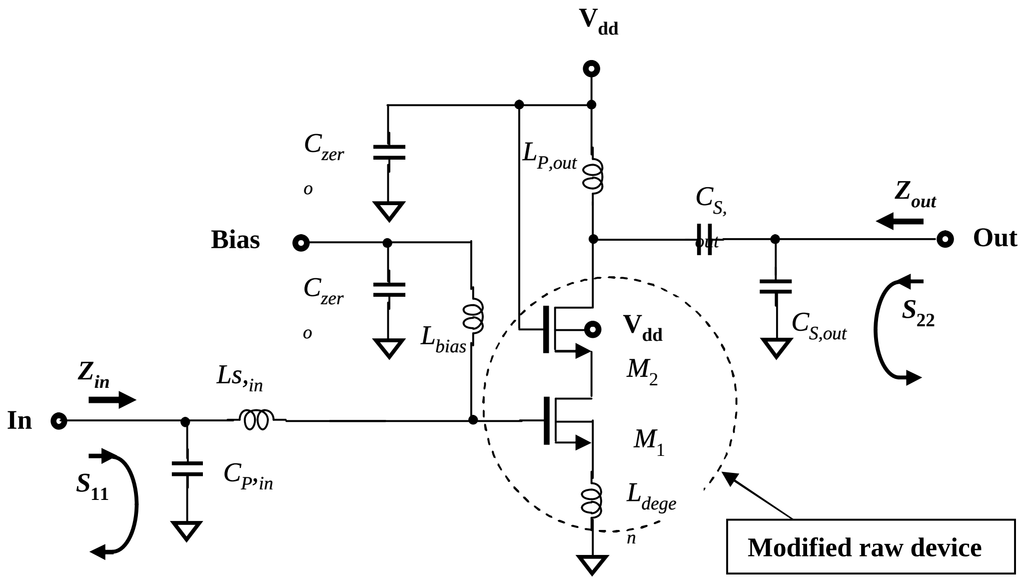
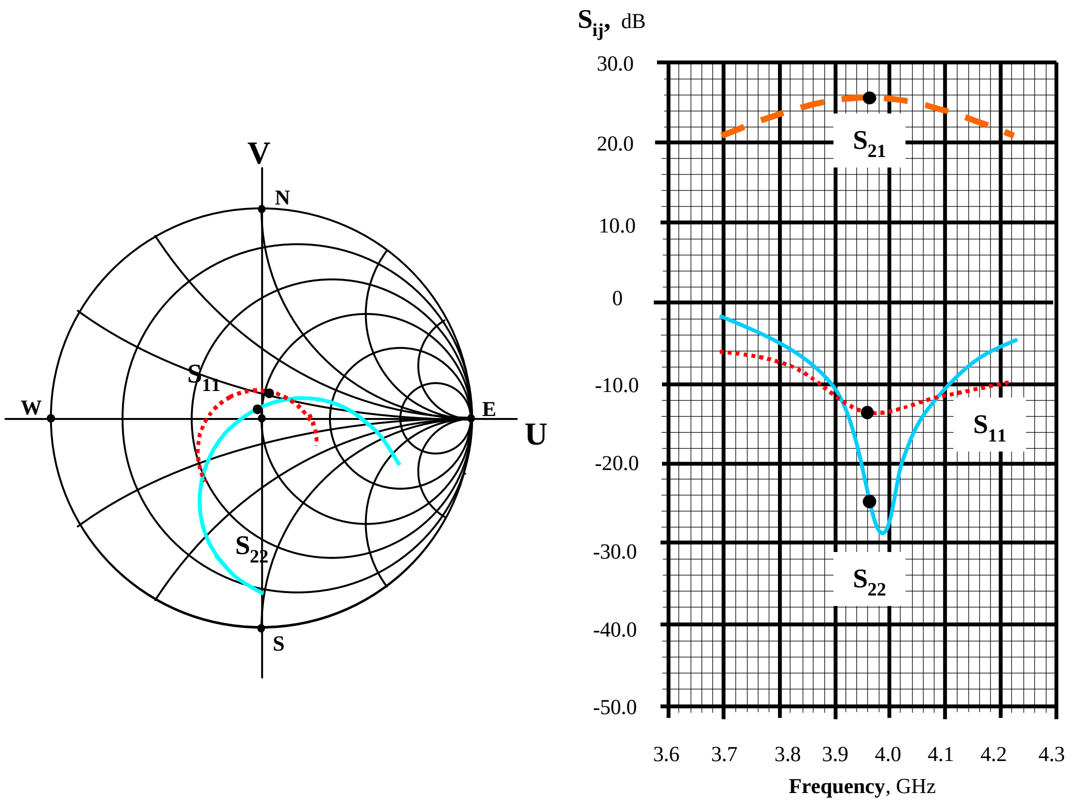


Figure 11.39 Modified impedance matching by parts:

At input : $C_{P,\,in} = 0.3\ pF$, $L_{S,in} = 3.3\ nH$.

At output : $L_{P,out} = 5\ nH$, $C_{S,out} = 0.13\ pF$,

$C_{P,out} = 0.3\ pF$



(a)S_{11} and S_{22} on Smith Chat **(b) Magnitude of S_{ij}, dB**

Figure 11.40 S parametersafter input and output impedances are matched by parts: (The intermediate frequency *f* =3.96 *GHz* is marked by a dot on each trace.)

At input : $C_{P,\,in}$ = 0.3 *pF*, $L_{S,in}$ = 3.3 *nH*.

At output : $L_{P,out}$ = 5 *nH*, $C_{S,out}$ = 0.13 *pF*, and $C_{P,out}$ = 0.3 *pF*

f, GHz	3.696	3.960	4.224
S_{21}, dB	20.8	25.5	25.5
S_{11}, dB	-13.8	*-13.6*	-6.2
S_{22} , dB	-28.8	-25.0	-1.8

In the entire frequency range, the gain, S_{21}> 20.8 dB, is satisfied!

Unfortunately, the bandwidth becomes narrow and is unable to cover the desired frequency range: 3.696 GHz < f < 4.224 GHz!

- **The 3rd try to modify impedance matching networks**

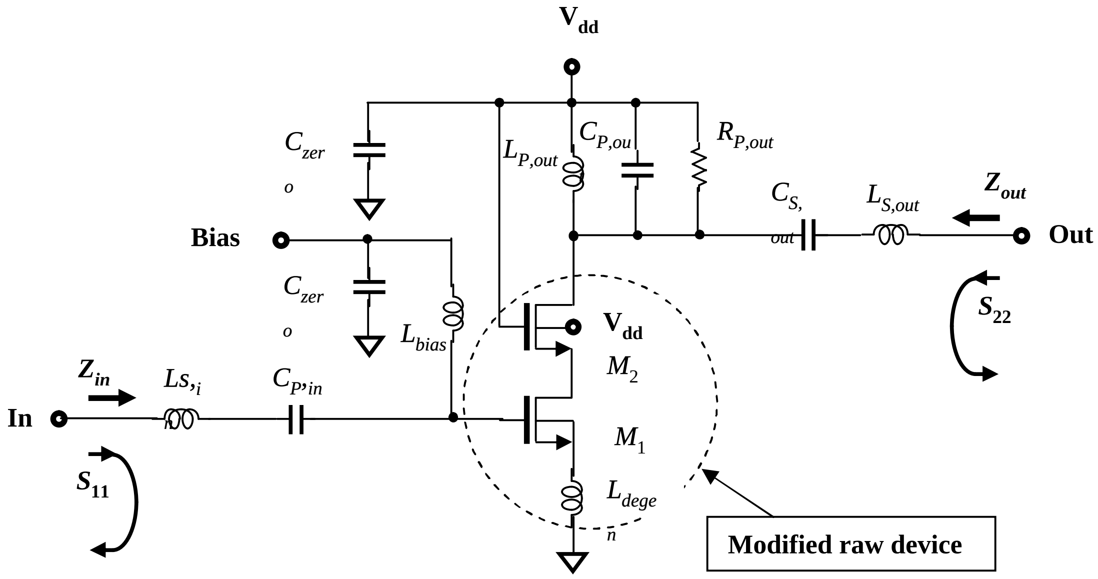
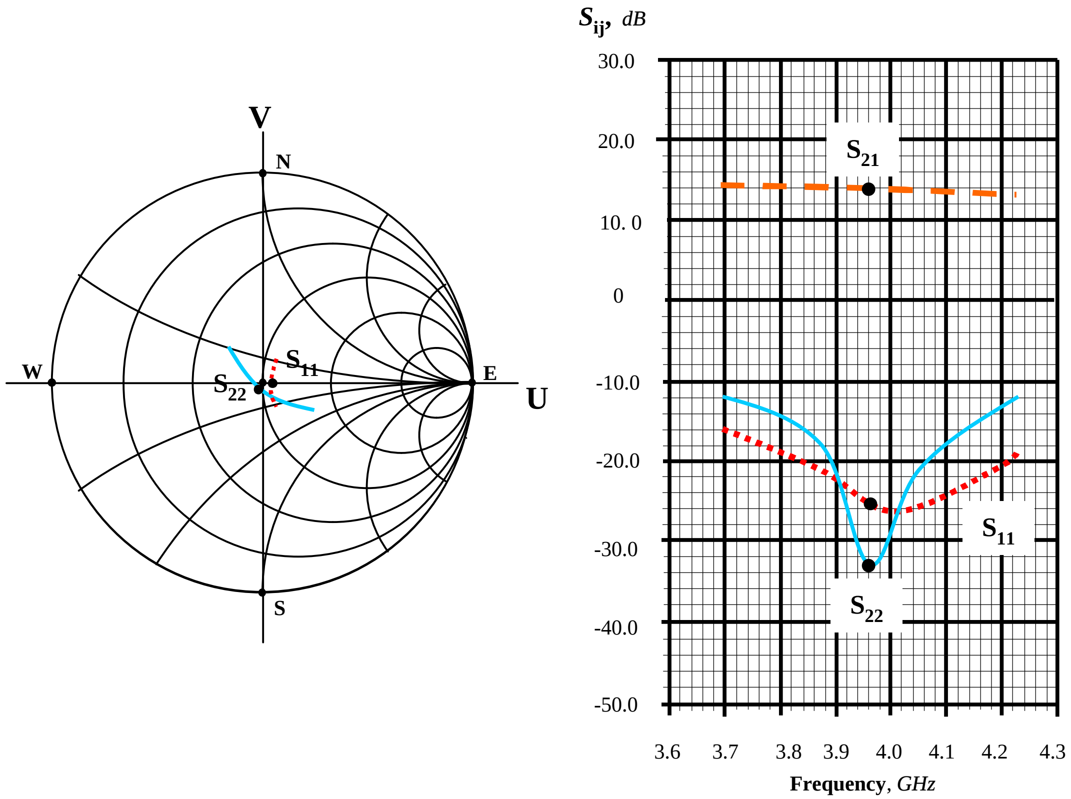


Figure 4.41 **Re-Modified impedance matching by parts:**

At input : $L_{S,\,in}$ = 3.8 nH, $C_{S,in}$ = 5 pF,

At output : $R_{P,out} = 200\ \Omega$, $L_{P,out} = 2\ nH$, $C_{P,out} = 0.97\ pF$,

$C_{S,out} = 10\ pF$, $L_{S,out} = 3.3\ nH$



(a) S_{11} and S_{22} on Smith Chat

(b) Magnitude of S_{ij}, *dB*

Figure 4.42 S parametersafter input and output impedances are matched by parts:
(The intermediate frequency *f* =3.96 *GHz* is marked by a dot on each trace.)

At input : $L_{S,in} = 3.8\ nH$, $C_{S,in} = 5\ pF$,

At output : $R_{P,out} = 200\ \Omega$, $L_{P,out} = 2\ nH$, $C_{P,out} = 0.97\ pF$,

$C_{S,out} = 10\ pF$, $L_{S,out} = 3.3\ nH$.

f, GHz	3.696	3.960	4.224
S_{21}, dB	13.0	14.0	14.3
S_{11}, dB	-26.2	*-25.5*	-15.9
S_{22} , dB	-33.2	-33.1	-11.9

In the entire frequency range, the gain, S_{21}> 13.0 dB, is satisfied!
And the bandwidth becomes wide and is able to cover the desired bandwidth: 3.696 GHz < f < 4.224 GHz!

*   Noise

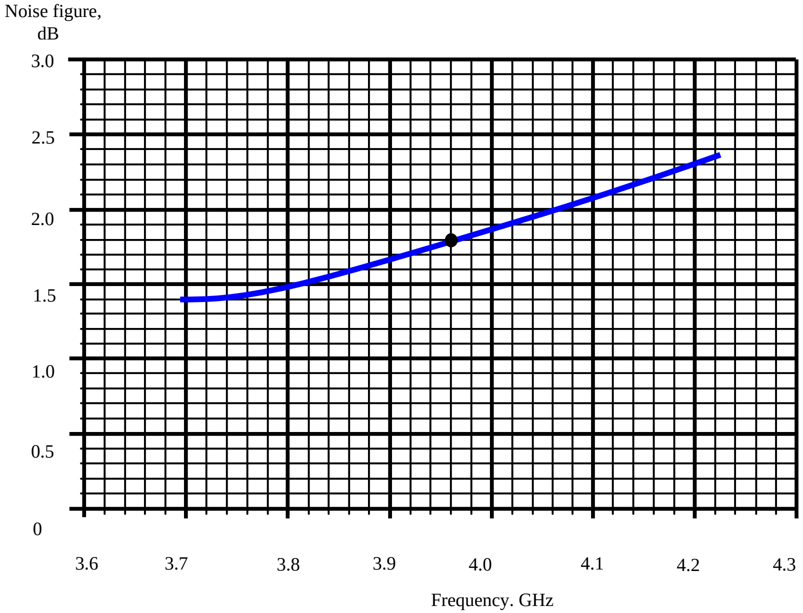


Figure 11.43 **Noise Figure from 3.696 to 4.224 *GHz*.**
NF* = 1.8 *dB* when f = 3.960 *GHz

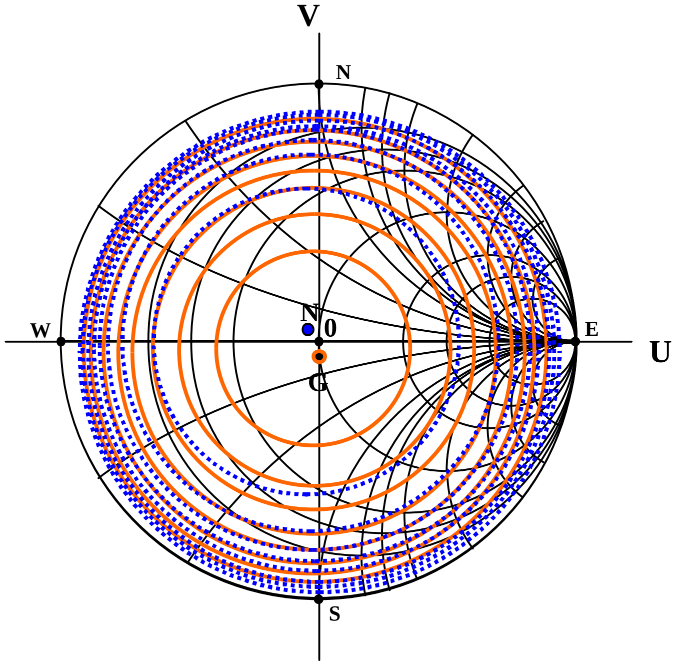


Figure 4.44 **Constant gain circles and constant noise figure circles when f =3.96 GHz**

- **Gain circles: G_{max} = 14 dB at point G, step = 1.0 dB,**
- **Noise figure circles: NF_{min} = 1.8 dB at point N, step = 0.5 dB,**

* Non-Linearity

- **Output Spectrum**

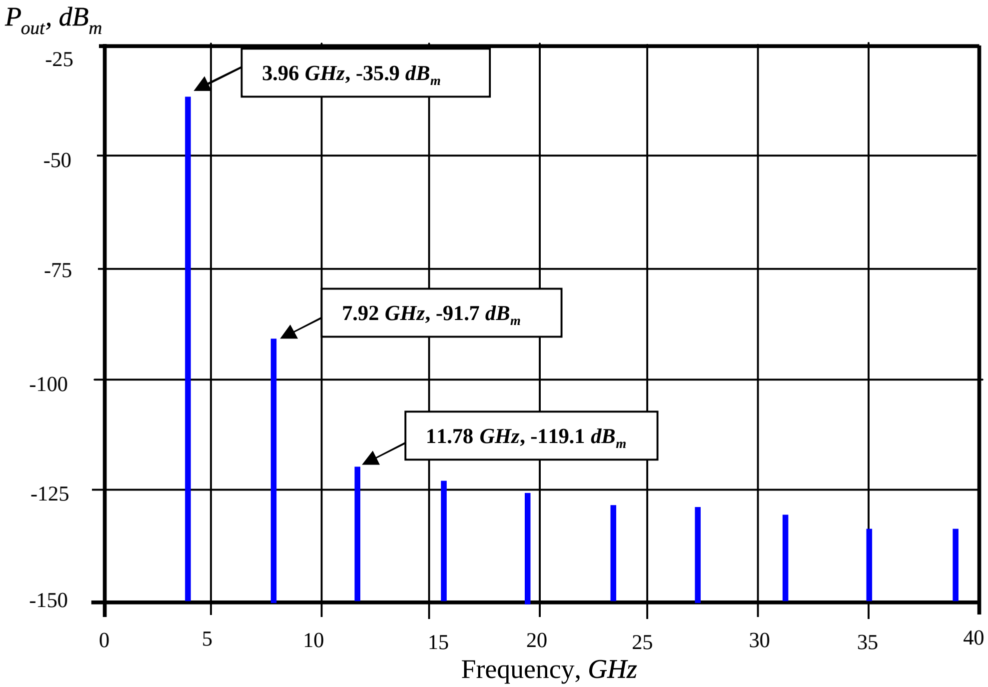


Figure 11.45 Spectrum at LNA output , $f_o = 3.96GHz$, $P_{in} = -50\ dB_m$

- **1 dB Compression Point**

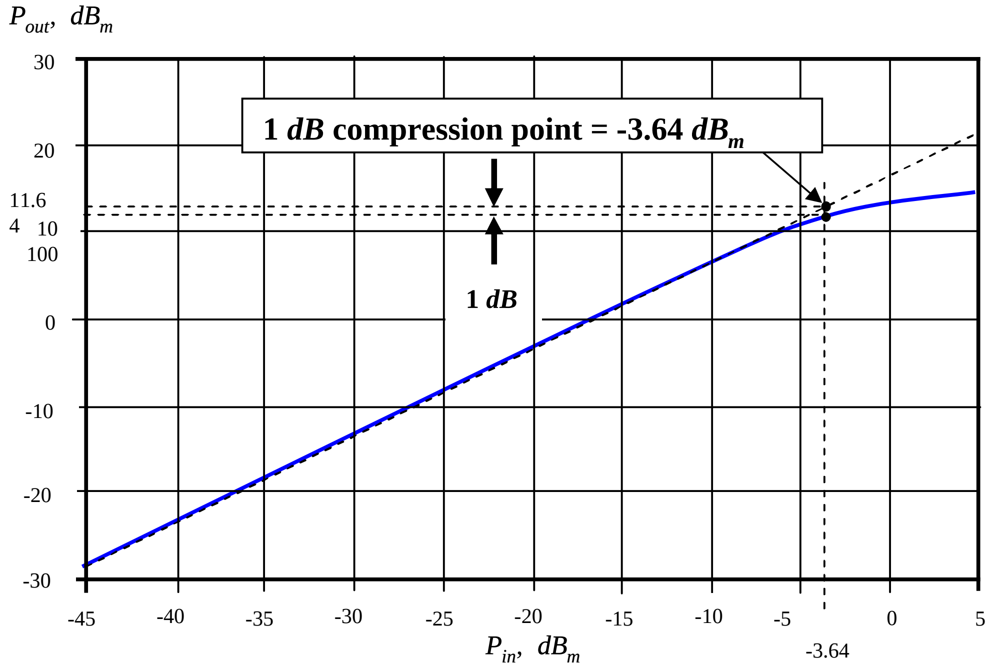


Figure 11.46 1*dB* compression point when $f_o = 3.96\ GHz$

- **3^{rd} order Intercept Point**

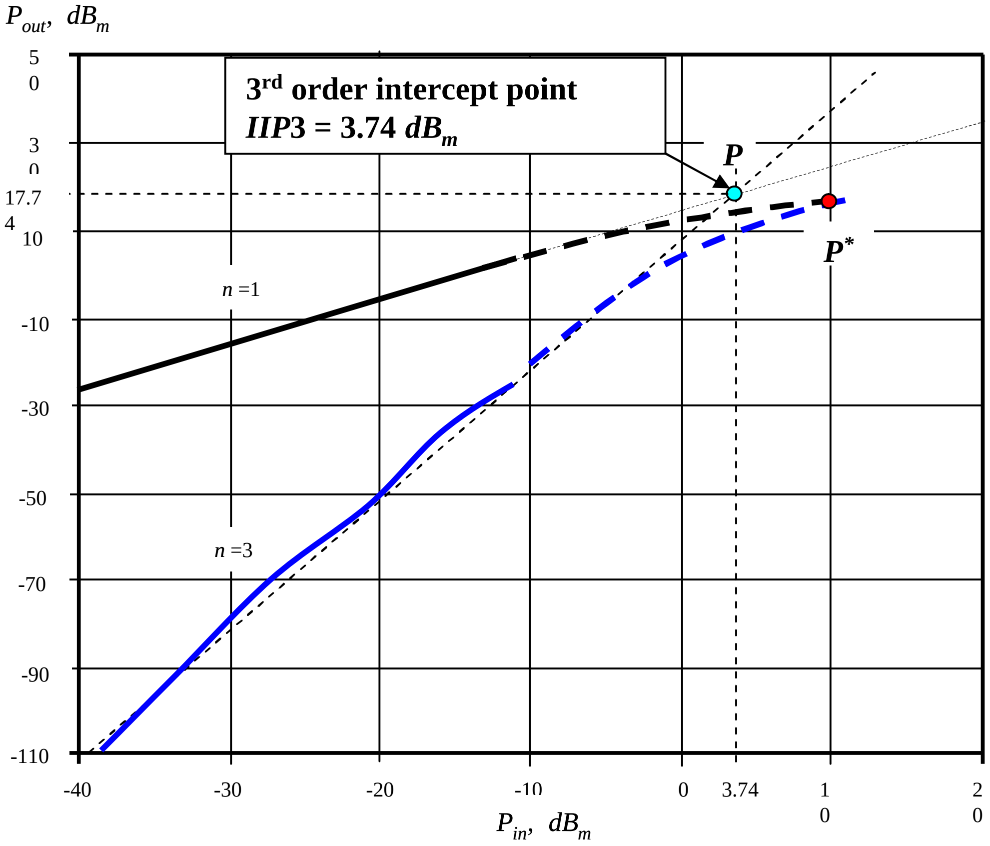


Figure 11.47 **3^{rd} order input intercept point when $f_o = 3.96$ GHz**

- **2^{nd} order Intercept Point**

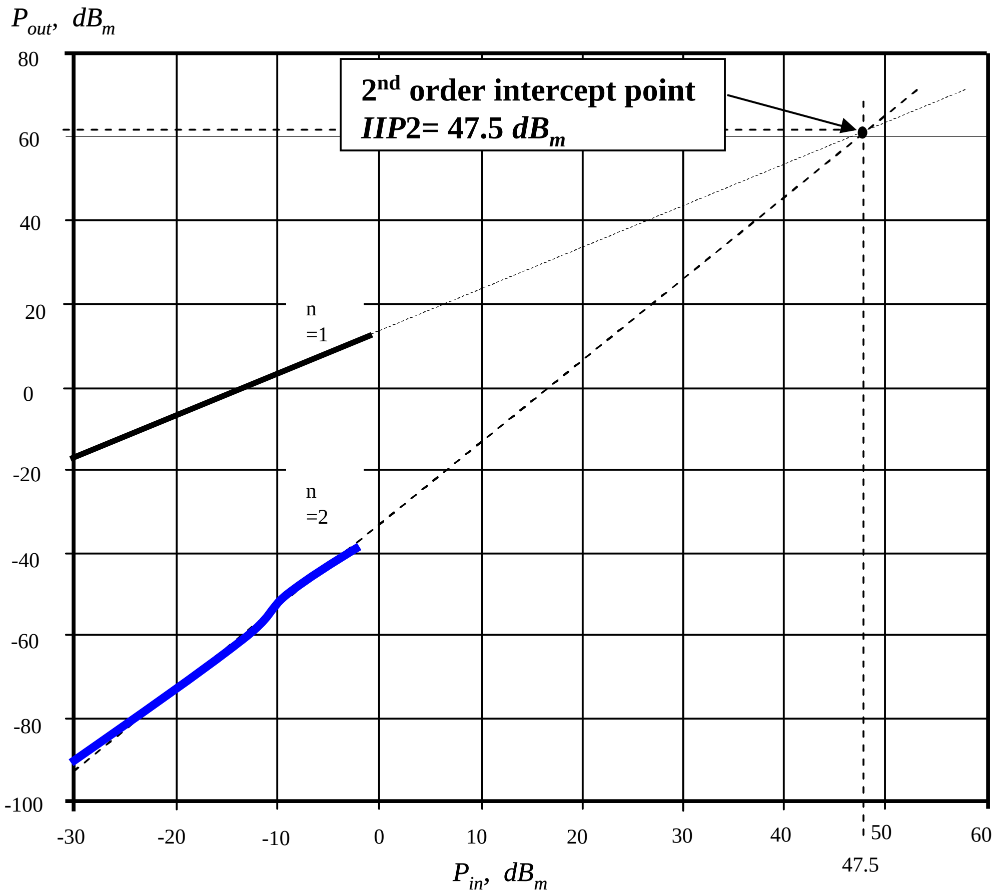


Figure 4.48 2^{nd} order input intercept point when $f_o = 3.96\ GHz$

o LNA with AGC (Automatic Gain Control)

* Variation of Field Strength around Antenna

- **Q: What does the 90 dB variation of the field strength around the antennamean?**
- **A: It means that the field strength is varied so many times, that is,**

$$2^{\frac{90}{3}} = 1,073,741,824 \quad !$$

* Implication of AGC

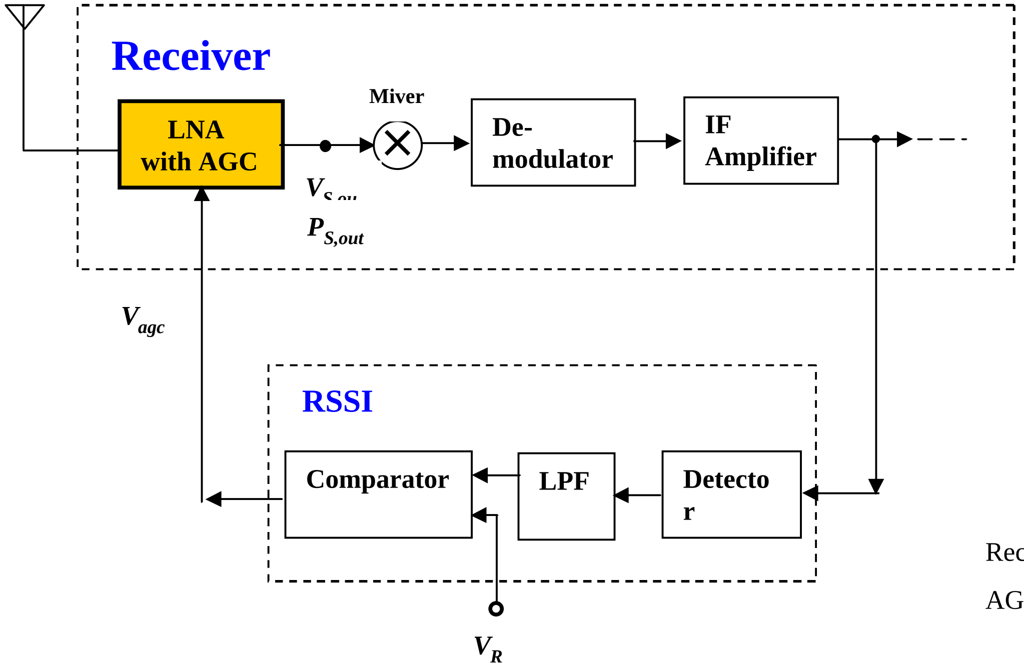


Figure 11.49 An AGC control loop in the receiver of a communication system

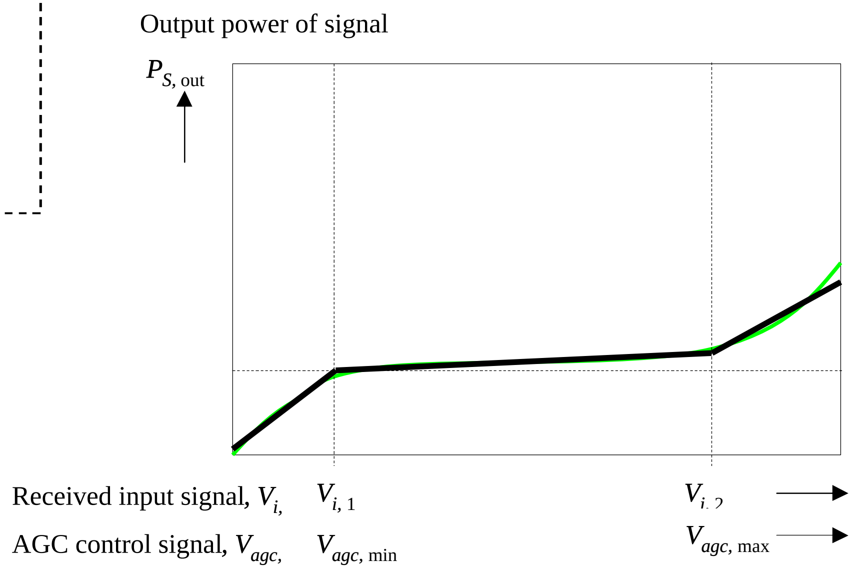
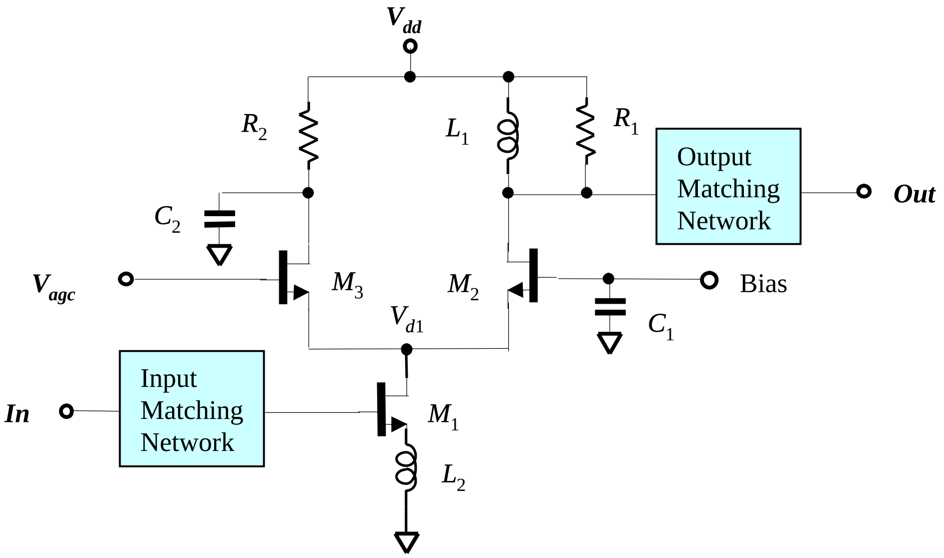


Figure 11.50 Expected Characteristics of AGC control

━ Ideal

━ Actual performance

* TradictionalLNA with AGC



M_1, M_2 -Cascodeddevices;
C_1, C_2 -ac short-circuited capacitor;
L_1 -Load inductor;
R_1 -Stability resistor;
L_2 -Degeneration inductor;
M_3 -AGC effective device;
R_2 -Current control resistor.

Figure 11.51 Traditional LNA with AGC

* Increase of AGC Dynamic Range

- **Diode Clamping**

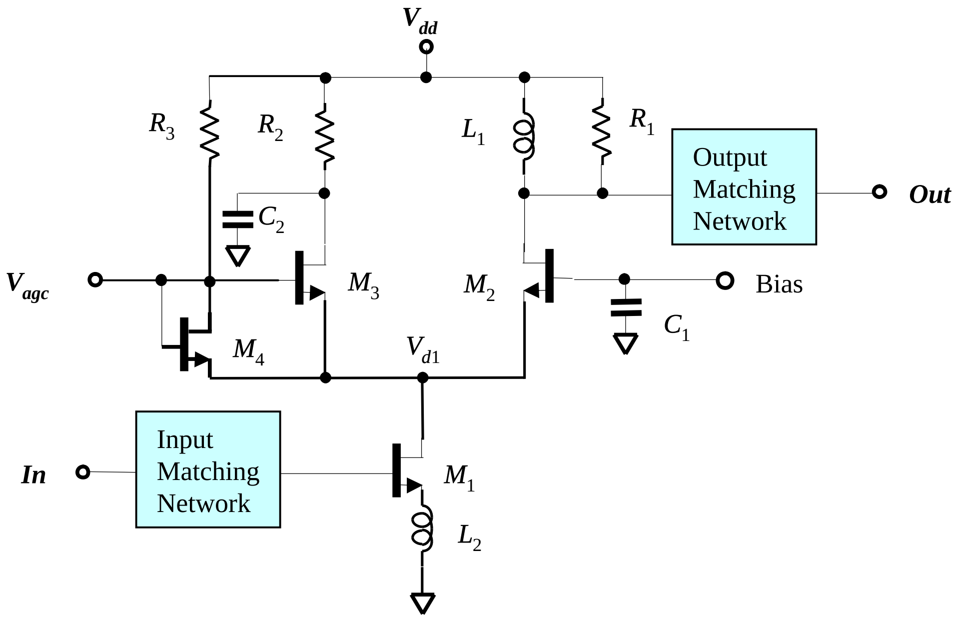


Figure 11.52 LNA with large dynamic range of AGC

- **To avoid RSSI operated as a current sink or source**

Addition of R_3 and M_4

- **Selection of big device M_3**

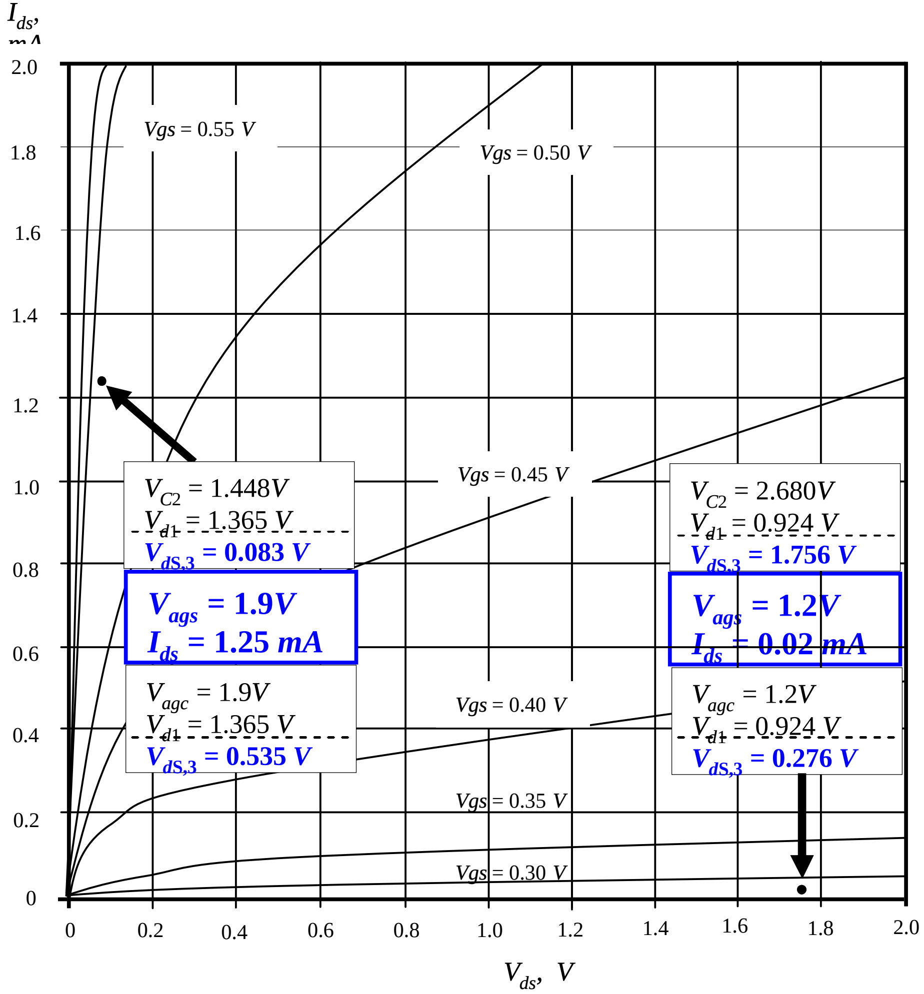


Figure 11.53 DC characteristics of transistor M_3

Table 11.2 Part list of LNA with AGC

Part	Value	
M_1	Fingers = 8	W_{total}= 128 μm
M_2	Fingers = 16	W_{total}= 256 μm
M_3	Fingers = 100	W_{total} = 1600 μm
M_4	Fingers = 16	W_{total}= 1256 μm
R_1	700 Ω	
R_2	1 $k\Omega$	
R_3	10 $k\Omega$	
C_1	20 pF	
C_2	40 pF	
L_1	50 nH	
L_2	30 nH	

Table 11.3 Goals, simulation, and performance of a LNA with AGC

	Goal	Simulation	Performance	
DC power supply, *V*	**3.0**	**3.0**	**3.0**	***V***
Frequency, *f*	**460 to 470**	**460 to 470**	**460 to 470**	***MHz***
RSSI Control voltage, *Vagc*	**1.2 to 1.9**	**1.2 to 1.9**	**1.2 to 1.9**	***V***
AGC dynamic range, *DRagc*	**0.00 to -40**	**0.00 to -43.7**	**0.0 to -42**	***dB***
Current drain, *Ids*	**2.0 to ***	**1.87 to 1.48**	**2.0 to 1.4**	***mA***
Gain, *G*	**12.0 to -28**	**12.6 to -31.1**	**15.0 to -27.0**	***dB***
Noise Figure, *NF*	**2.0 to ***	**1.26 to 29.4**	**2.7 to ***	***dB***
***3rd order intercept point, IIP*3**	**-15.0 to ***	**-10.2 to -7.5**	**-10.5 to -8.0**	***dBm***
Input Return Loss, *S*11	*** to ***	**-15.3 to -10.4**	*** to ***	***dB***
Output Return Loss, *S*22	*** to ***	**-23.2 to -11.7**	*** to ***	***dB***

Discussion

- Key points to approach G_{max} and NF_{min}.
- Advantages and disadvantages of CS-CG or CE-CB cascodeLNA
- Why AGC?
- Why differential?

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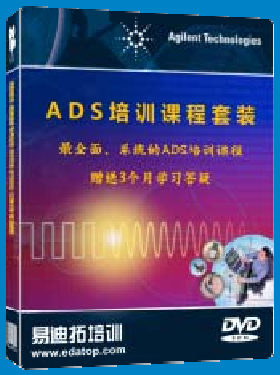

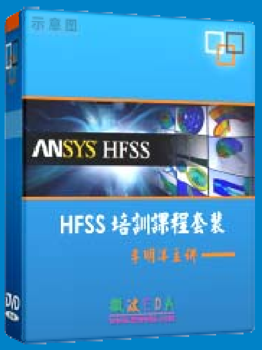

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