1. RF Amplifier Design

This report describes the design of a RF amplifier operating at 2.4GHz.

Below are the design specifications: -

Centre Frequency	2.4 GHz
Bandwidth	± 5 %
Noise Figure	<3dB
Gain	As high as possible
Source impedance	50 Ω
Load impedance	50 Ω
Size of Circuit Layout	4” x 5”

The transistor used here is Fujitsu FHX35LG HEMT.

2. Design Procedure

The available power gain approach, where the output is assumed conjugate match, is used here.

a. Transistor performance

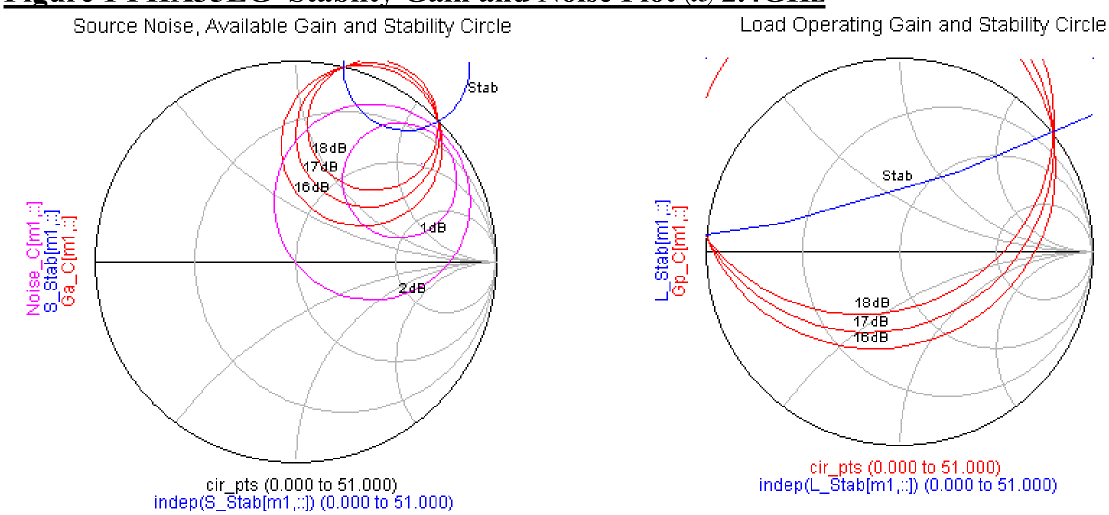
Firstly the performance of the FHX35LG transistor is evaluated.
Base on the S-parameter of the transistor at 2.4 GHz (Fig 2).

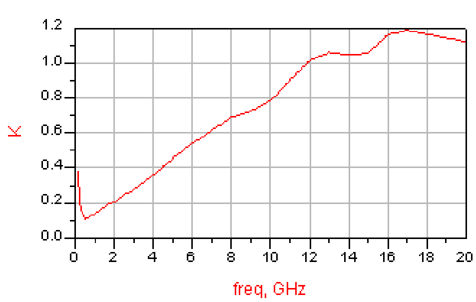
$$\Delta = S_{11}S_{22}-S_{12}S_{21}$$
$$= 0.464\angle -71.7°$$
$$|\Delta| = 0.464 < 1$$

$$K = (1+|\Delta|^2-|S_{11}|^2-|S_{22}|^2) / (2*|S_{12}S_{21}|)$$
$$= 0.239 <1$$

Therefore the transistor is conditionally stable at 2.4GHz. It is also found that the transistor is conditional stable up to 12GHz as shown in Fig 1. This will present difficulty in the amplifier design, as the microstrip matching network designed for 2.4GHz may not ensure stability at other frequencies thus resulting oscillations.

Figure 1 FHX35LG Stabilty Gain and Noise Plot @ 2.4GHz





freq	K	Δ Delta
1.900GHz	0.204	0.480
2.000GHz	0.209	0.477
2.100GHz	0.217	0.474
2.200GHz	0.225	0.471
2.300GHz	0.232	0.467
2.400GHz	0.239	0.464
2.500GHz	0.246	0.460
2.600GHz	0.252	0.457
2.700GHz	0.258	0.453
2.800GHz	0.264	0.450
2.900GHz	0.270	0.446

Figure 2 Transistor S Parameter @ 2.4GHz

S(1,1)[m1]	S(1,2)[m1]	S(2,1)[m1]	S(2,2)[m1]
0.935 / -52.660	0.049 / 52.580	4.193 / 131.980	0.492 / -44.760

Therefore it is necessary to stabilize the transistor using external component. Firstly, output series resistor of 30 ohm will be used to stabilize the high frequency performance. Secondly, to reduce the Q of the matching network a microstrip line is used to shift the gain and stability circles closer to the real axis. Thirdly, a 36-ohm shunt resistor at the input will be used to stabilize the low frequency performance.

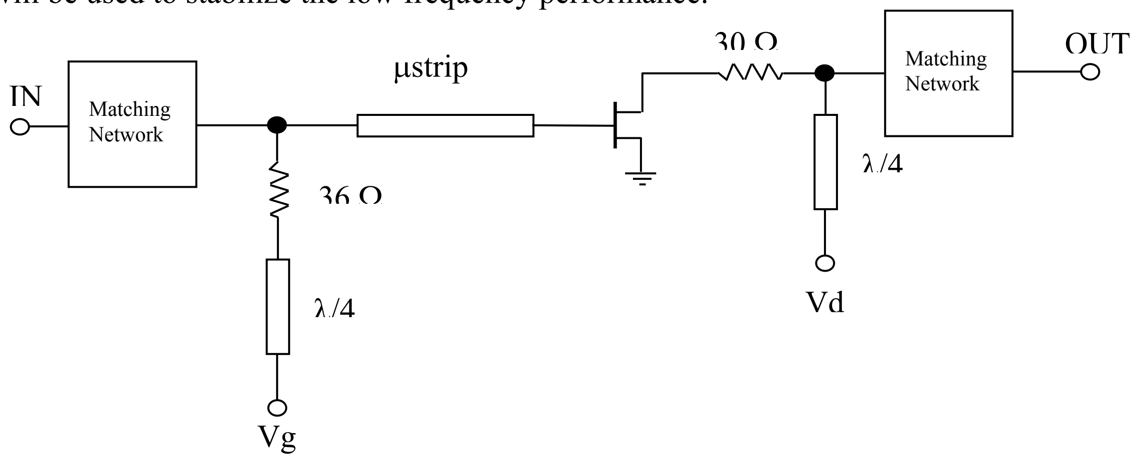
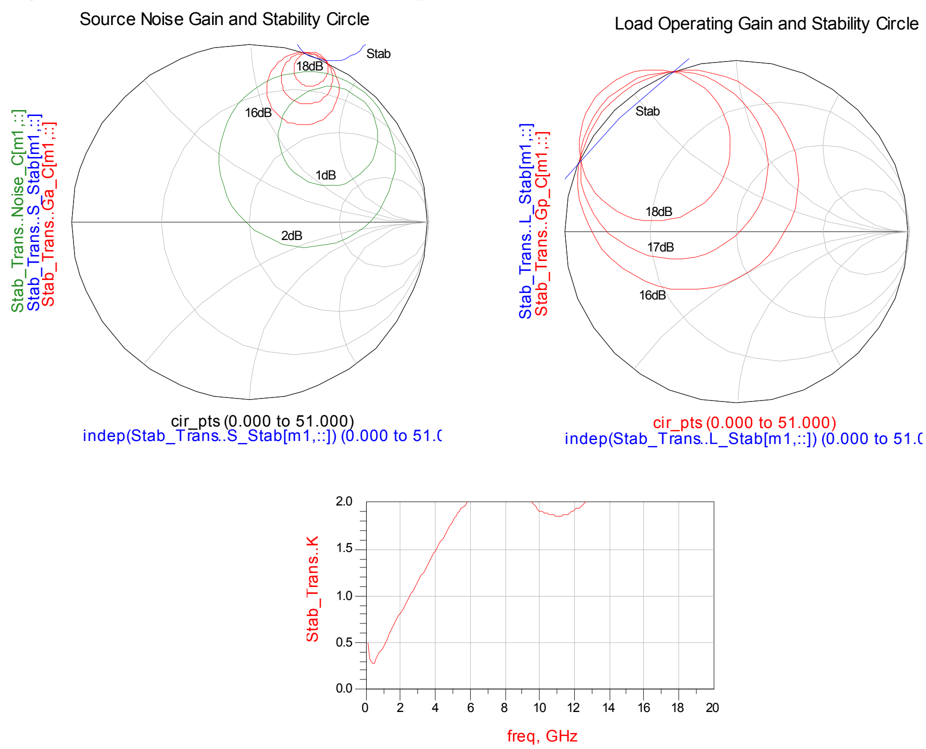
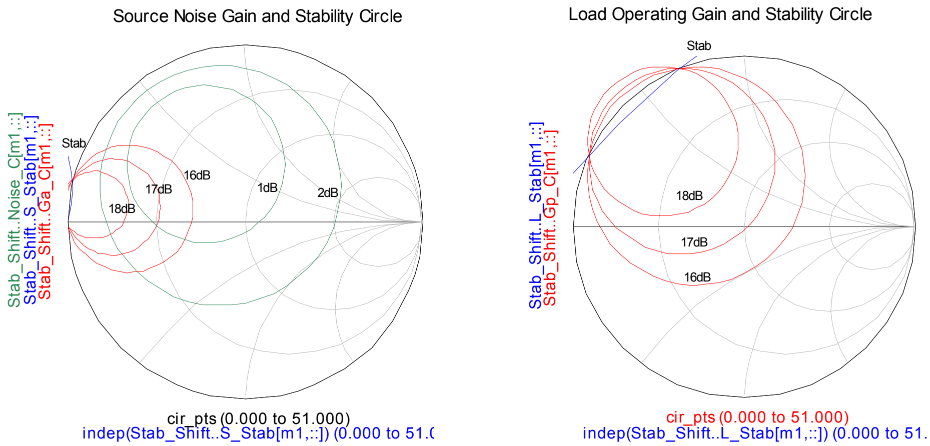


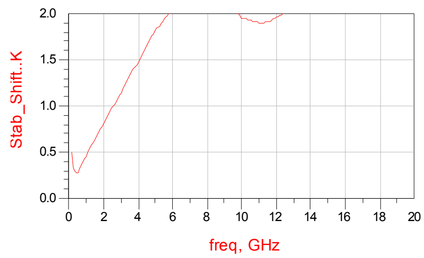
Figure 3 Performance with output series resistance



Observation : Gain circle radius reduced and K value improved for higher frequencies.

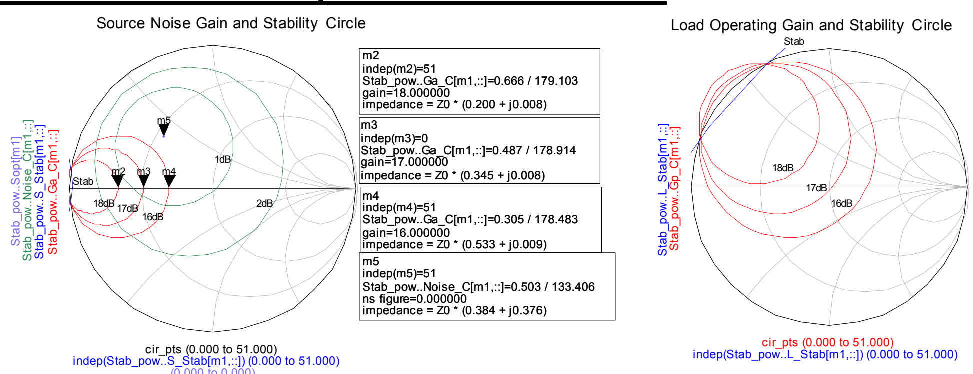
Figure 4 Performance with 330 mils micro strip

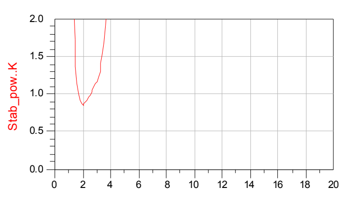




Observation : Both noise and gain circles shift closer to the real axis.

Figure 5 Performance with input shunt resistor 36 ohm





freq	Stab_pow..K	Stab_pow..Delta
1.500GHz	1.374	0.407
1.600GHz	1.143	0.421
1.700GHz	0.998	0.430
1.800GHz	0.913	0.433
1.900GHz	0.871	0.431
2.000GHz	0.858	0.427
2.100GHz	0.870	0.419
2.200GHz	0.893	0.411
2.300GHz	0.923	0.403
2.400GHz	0.956	0.395
2.500GHz	0.990	0.388
2.600GHz	1.024	0.382
2.700GHz	1.058	0.377
2.800GHz	1.093	0.373
2.900GHz	1.131	0.370
3.000GHz	1.174	0.368
3.100GHz	1.234	0.365
3.200GHz	1.308	0.363
3.300GHz	1.404	0.361

Observation: K value improved for the lower frequencies.

Figure 6 S-parameter of final stabilized circuit

Stab_pow..S(1,1)[m1]	Stab_pow..S(1,2)[m1]	Stab_pow..S(2,1)[m1]	Stab_pow..S(2,2)[m1]
0.729 / -171.699	0.056 / -32.734	4.881 / 41.870	0.317 / -76.703

$\Delta = S_{11}S_{22} - S_{12}S_{21}$
$= 0.394\angle 154.2°$
$|\Delta| = 0.394 < 1$
$K = (1+|\Delta|^2-|S_{11}|^2-|S_{22}|^2) / (2*|S_{12}S_{21}|)$
$= 0.957 < 1$

Input stability Circle :

$r_s = |S_{12}S_{21}| / |(|S_{11}|^2-|\Delta|^2)|$
$= 0.726$
$C_s = (S_{11}^*-\Delta^* S_{22}) / (|S_{11}|^2-|\Delta|^2)$
$= 1.708\angle 179.25°$

Output stability Circle :

$r_L = |S_{12}S_{21}| / |(|S_{22}|^2-|\Delta|^2)|$
$= 4.99$

$C_L = (S_{22}^*-\Delta^* S_{11}) / (|S_{22}|^2-|\Delta|^2)$
$= 4.04\angle -41.8°$

Noise Circle @ 1dB :

$N_i = (F_i - F_{min}) * |1 + \Gamma_o|^2 / 4r_n$
$= (1.26 - 1.139) * |1+0.503\angle 133.4°|^2 / (4*0.063)$
$= 0.270$

$C_{Fi} = \Gamma_o / (1 + N_i)$
$= 0.396\angle 133.4°$

$r_{Fi} = \sqrt{(N_i^2+N_i(1-|\Gamma_o|^2)} / (1+N_i)$
$= 0.4126$

From Fig 5, Γ_s of $0.487\angle 179°$ is chosen.

$\Gamma_{out} = (S_{22} - \Delta\Gamma_S) / (1- S_{11}\Gamma_S)$
$= 0.3738\angle -109.9°$ ===> Located within the load stable region

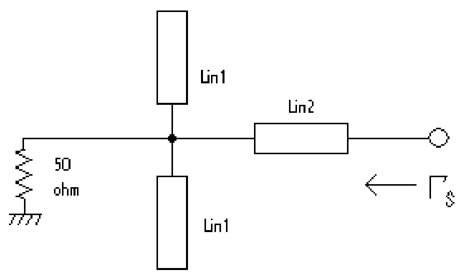
Therefore Γ_s of $0.487\angle 179°$ is OK.

b. Input Matching Network

Two step approach is used here. Initial design is done using smithchart than the values are tuned using ADS. A balanced double stud is used here.

Fig 7 shows the input matching network adopted and Page 7 shows the smith chart matching calculation and working.

Figure 7 Simplified Input Matching Network



The calculated value are Lin1=287 mils
Lin2=302 mils

This value are fine tuned using ADS to give
Lin1=260 mils
Lin2=285 mils

Schematic and results are shown in page 8 & 9.

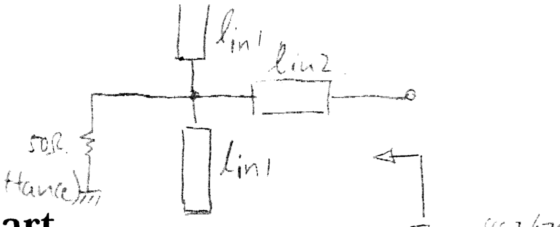
$\lambda = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}}$

$\lambda = 3510$ mils (From Line Calc)

$\therefore l_{in1} = 287$ mils

$\therefore l_{in2} = 302.28$ mils

Input Matching Network (Admittance)



The Complete Smith Chart

Black Magic Design

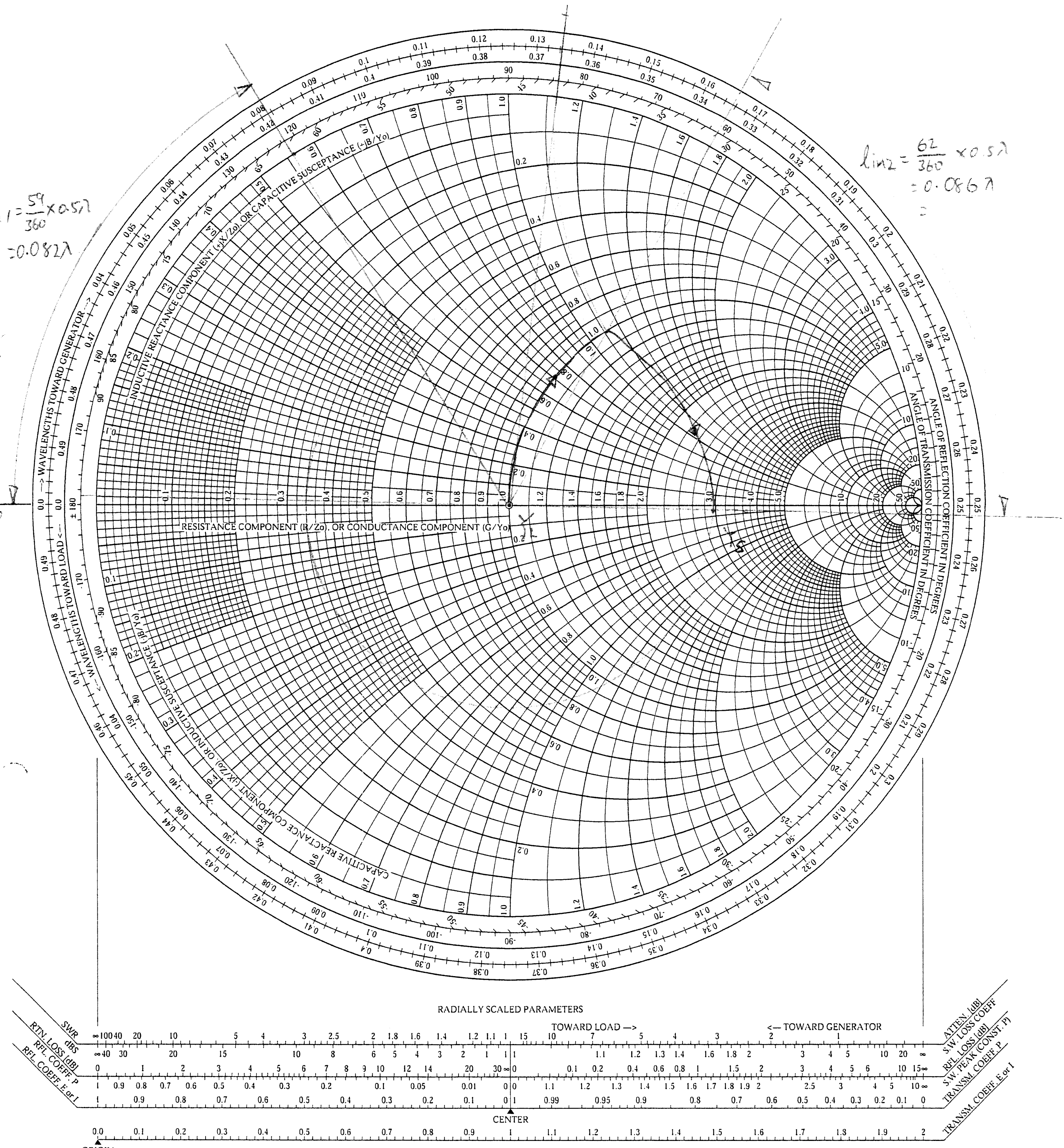


Figure 8 Input Matching Network

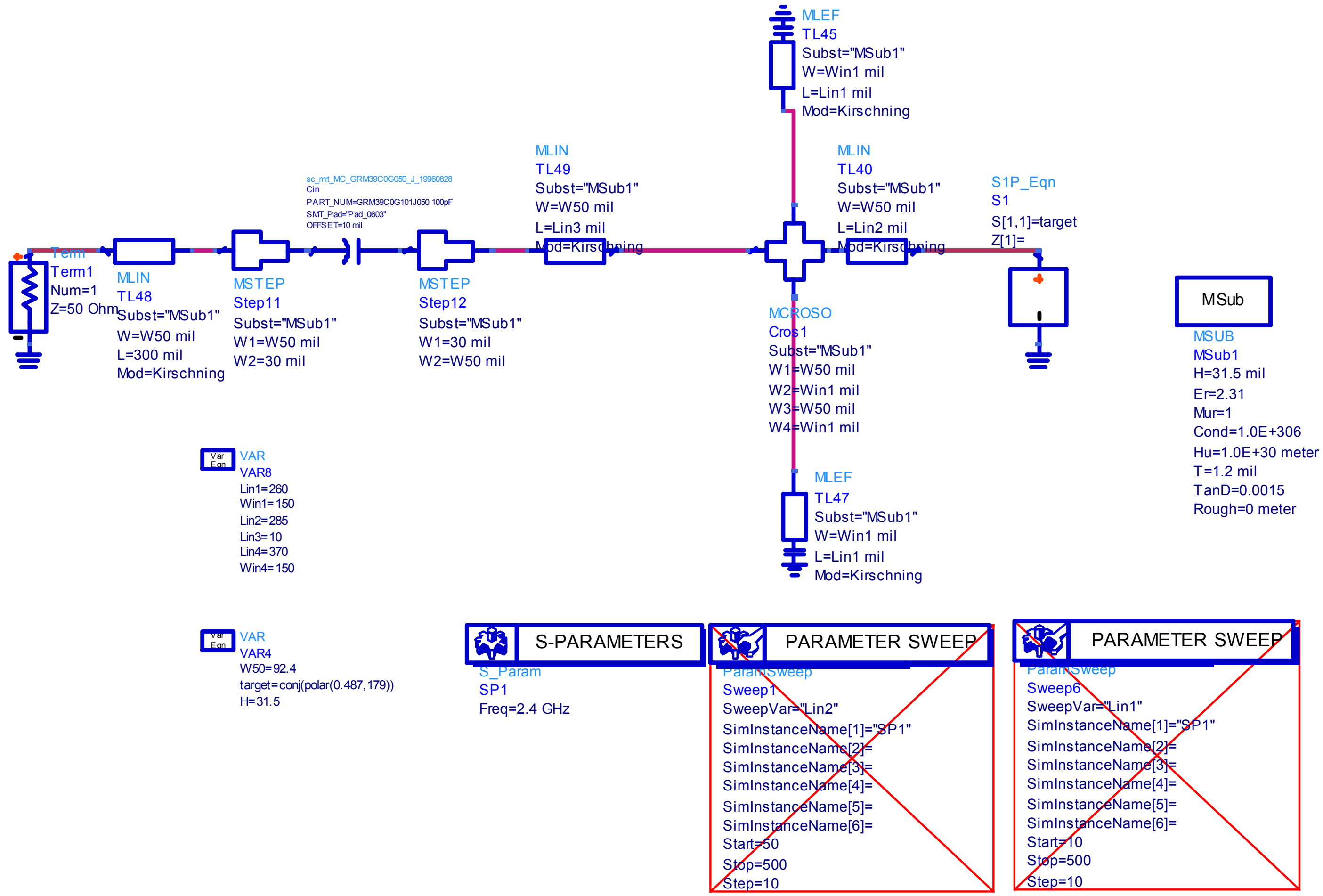
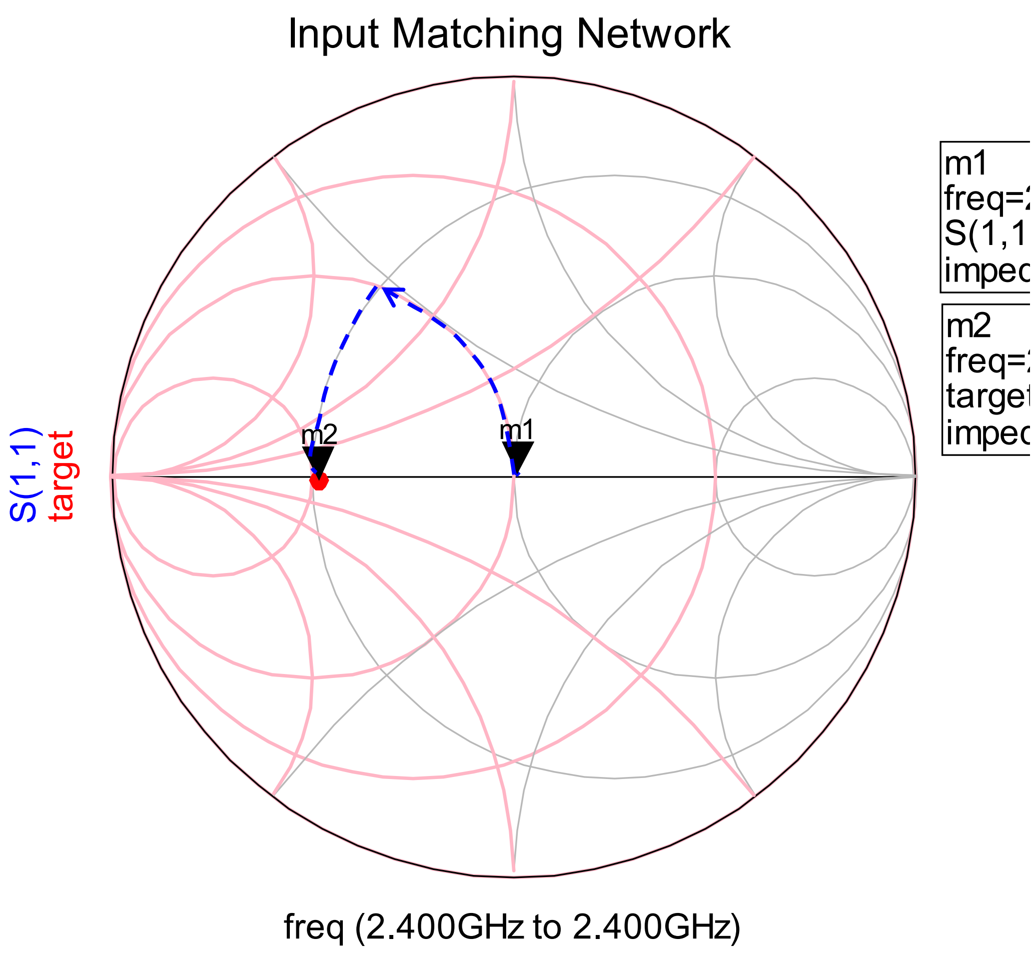


Figure 9 Input Matching Smith Chart



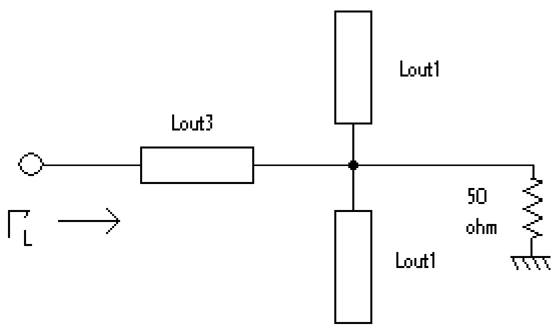
c. Output Matching Network

The designed input matching network is combined with the stabilized transistor network to simulate the resulting Γ_{out} . (Pg 11 & 12)

$\Gamma_{out} = 0.384\angle -110°$ (Calculated $\Gamma_{out} = 0.3738\angle -109.9°$)

Fig 10 shows the output-matching network adopted and Page 13 shows the smith chart matching calculation and working.

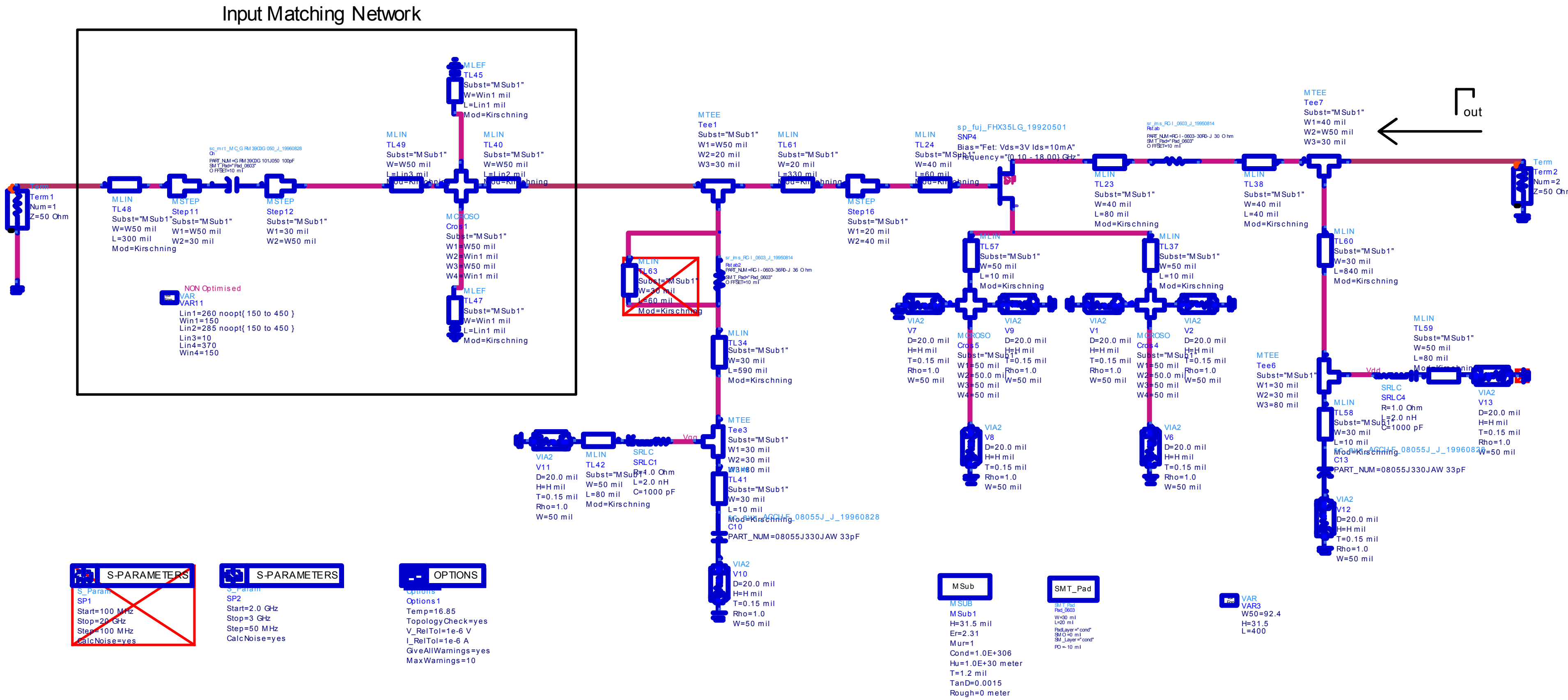
Figure 10 Simplified Output Matching Network

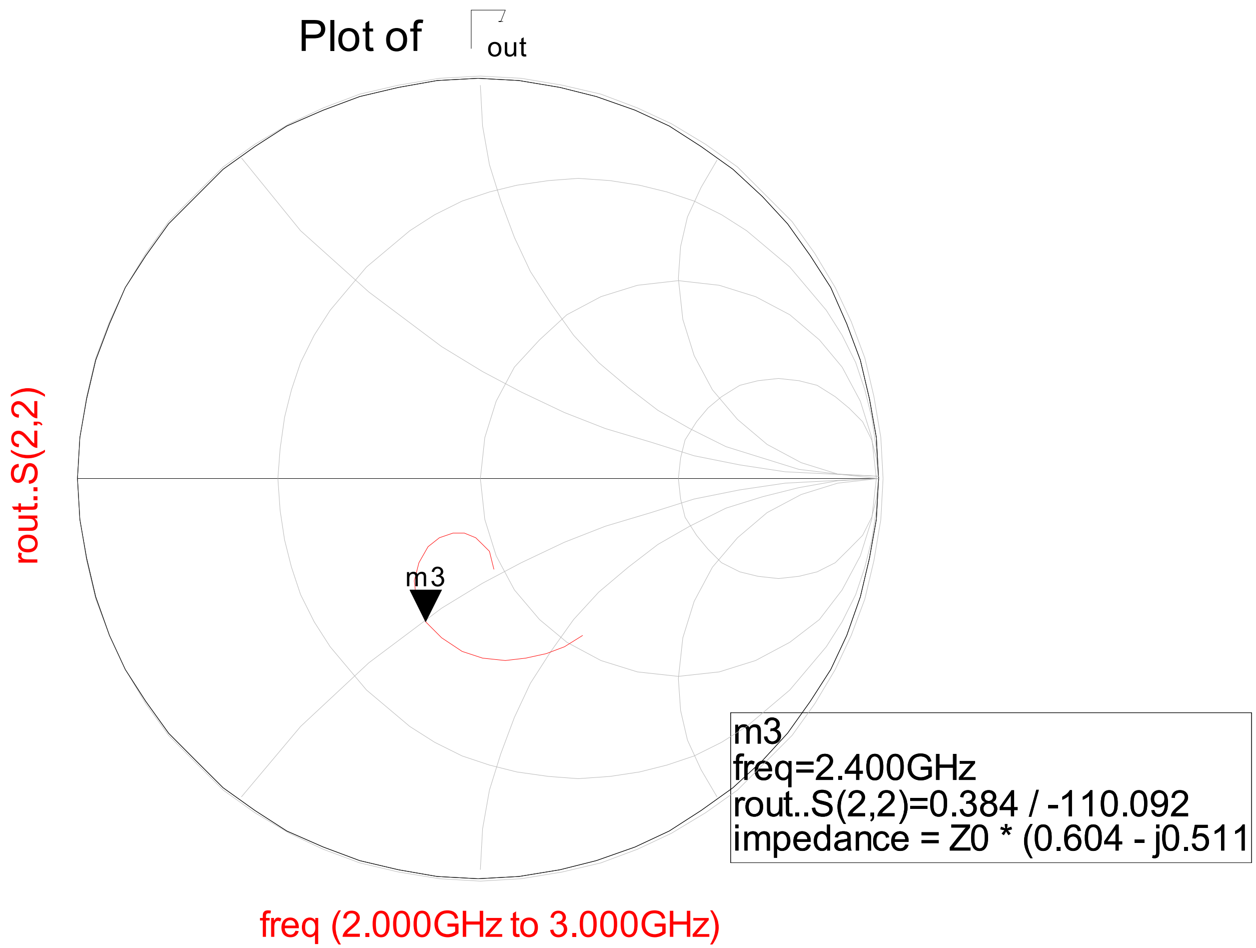


The calculated value are Lout1=224 mils
Lout3=667 mils

This value are fine tuned using ADS to give
Lout3=195 mils
Lout3=660 mils

Schematic and results are shown in page 14 & 15.


Input Matching Network
Γout
MLEF
TL45
Subst="MSub1"
W=Win1 mil
L=Lin1 mil
Mod=Kirschning
MLIN
TL48
Subst="MSub1"
W=W50 mil
L=300 mil
Mod=Kirschning
MSTEP
Step11
Subst="MSub1"
W1=W50 mil
W2=30 mil
MSTEP
Step12
Subst="MSub1"
W1=30 mil
W2=W50 mil
MLIN
TL49
Subst="MSub1"
W=W50 mil
MLIN
TL40
Subst="MSub1"
W=W50 mil
MCROSO
Cros1
Subst="MSub1"
W1=W50 mil
W2=Win1 mil
W3=W50 mil
W4=Win1 mil
MLEF
TL47
Subst="MSub1"
W=Win1 mil
L=Lin1 mil
Mod=Kirschning
NON Optimised
VAR
VAR11
Lin1=260 noopt{ 150 to 450 }
Win1=150
Lin2=285 noopt{ 150 to 450 }
Lin3=10
Lin4=370
Win4=150
Term1
Num=1
Z=50 Ohm
MTEE
Tee1
Subst="MSub1"
W1=W50 mil
W2=20 mil
W3=30 mil
MLIN
TL61
Subst="MSub1"
W=20 mil
L=330 mil
MSTEP
Step16
Subst="MSub1"
W1=20 mil
W2=40 mil
MLIN
TL24
W=40 mil
L=60 mil
sp_fuj_FHX35LG_19920501
SNP4
Bias="Fet: Vds=3V Ids=10mA"
MLIN
TL63
Mod=Kirschning
MLIN
TL34
Subst="MSub1"
W=30 mil
L=590 mil
Mod=Kirschning
MTEE
Tee3
Subst="MSub1"
W1=30 mil
W2=30 mil
TL41
Subst="MSub1"
W=30 mil
L=10 mil
C10
PART_NUM=08055J330JAW 33pF
VIA2
V10
D=20.0 mil
H=H mil
T=0.15 mil
Rho=1.0
W=50 mil
VIA2
V11
D=20.0 mil
H=H mil
T=0.15 mil
Rho=1.0
W=50 mil
MLIN
TL42
Subst="MSub1"
W=50 mil
L=80 mil
Mod=Kirschning
SRLC
SRLC1
R=4.0 Ohm
L=2.0 nH
C=1000 pF
Vgg
MLIN
TL23
Subst="MSub1"
W=40 mil
L=80 mil
Mod=Kirschning
MLIN
TL38
Subst="MSub1"
W=40 mil
L=40 mil
Mod=Kirschning
MTEE
Tee7
Subst="MSub1"
W1=40 mil
W2=W50 mil
W3=30 mil
Term
Term2
Num=2
Z=50 Ohm
MLIN
TL57
Subst="MSub1"
W=50 mil
L=10 mil
Mod=Kirschning
MLIN
TL37
Subst="MSub1"
W=50 mil
L=10 mil
Mod=Kirschning
MLIN
TL60
Subst="MSub1"
W=30 mil
L=840 mil
Mod=Kirschning
MCROSO
Cros5
MCROSO
Cros4
VIA2
V7
VIA2
V9
VIA2
V1
VIA2
V2
VIA2
V8
VIA2
V6
MLIN
TL59
Subst="MSub1"
W=50 mil
L=80 mil
MTEE
Tee6
Subst="MSub1"
W1=30 mil
W2=30 mil
W3=80 mil
SRLC
SRLC4
R=1.0 Ohm
L=2.0 nH
C=1000 pF
Vdd
VIA2
V13
MLIN
TL58
Subst="MSub1"
W=30 mil
L=10 mil
Mod=Kirschning
C13
PART_NUM=08055J330JAW 33pF
VIA2
V12
D=20.0 mil
H=H mil
T=0.15 mil
Rho=1.0
W=50 mil
S-PARAMETERS
S_Param
SP1
Start=100 MHz
Stop=20 GHz
Step=100 MHz
CalcNoise=yes
S-PARAMETERS
S_Param
SP2
Start=2.0 GHz
Stop=3 GHz
Step=50 MHz
CalcNoise=yes
OPTIONS
Options
Options1
Temp=16.85
TopologyCheck=yes
V_RelTol=1e-6 V
I_RelTol=1e-6 A
GiveAllWarnings=yes
MaxWarnings=10
MSub
MSUB
MSub1
H=31.5 mil
Er=2.31
Mur=1
Cond=1.0E+306
Hu=1.0E+30 meter
T=1.2 mil
TanD=0.0015
Rough=0 meter
SMT_Pad
VAR
VAR3
W50=92.4
H=31.5
L=400

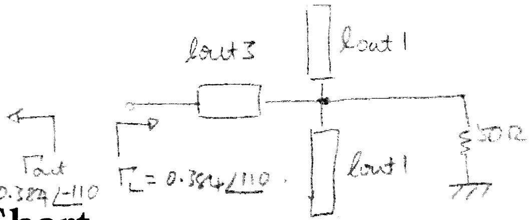

Plot of Γout
rout..S(2,2)
m3
m3
freq=2.400GHz
rout..S(2,2)=0.384 / -110.092
impedance = Z0 * (0.604 - j0.511
freq (2.000GHz to 3.000GHz)

$\lambda = 3510$

lout1 = 224 mils

lout3 = 667.9 mils

Output Matching Network



The Complete Smith Chart

Black Magic Design

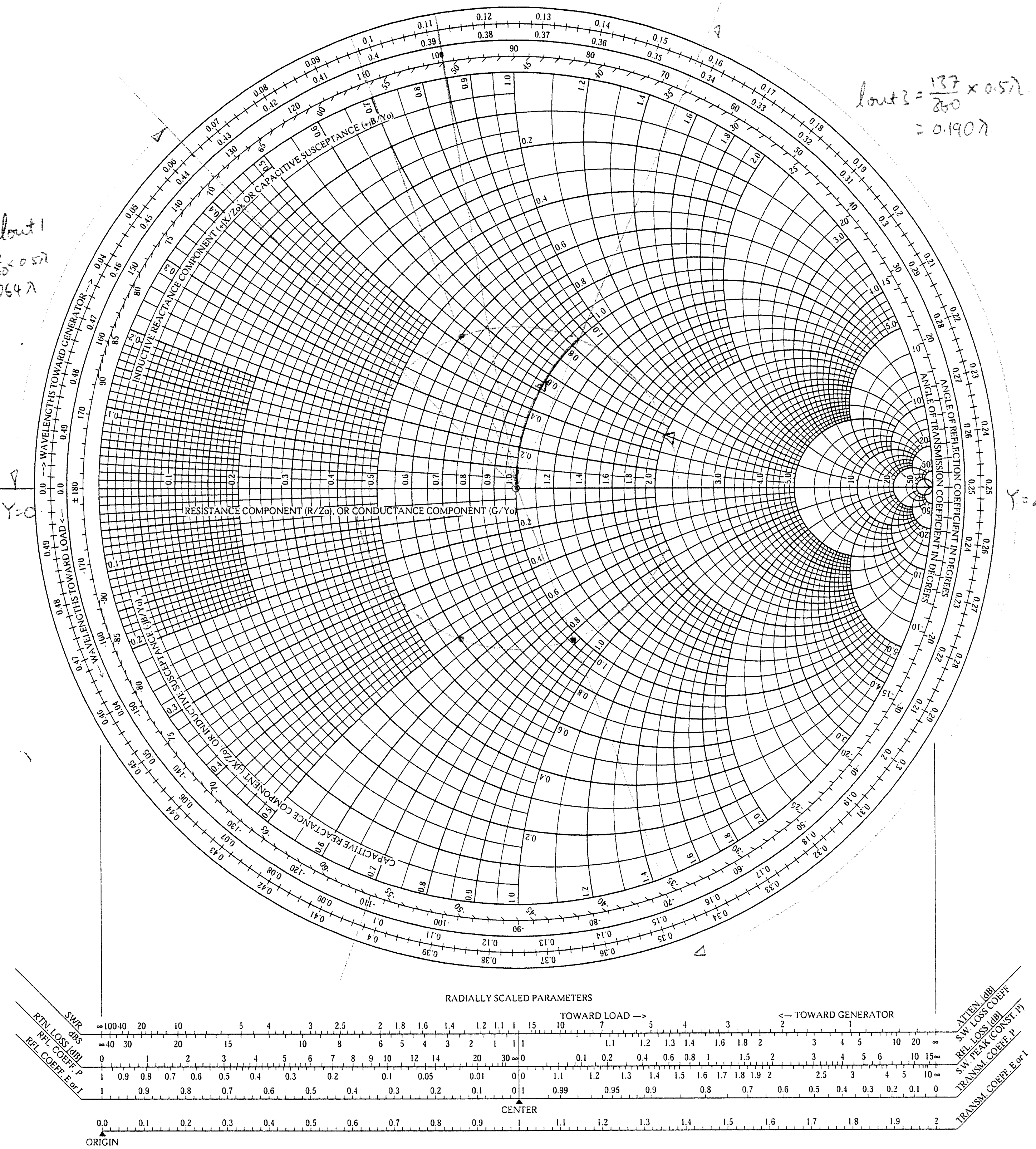
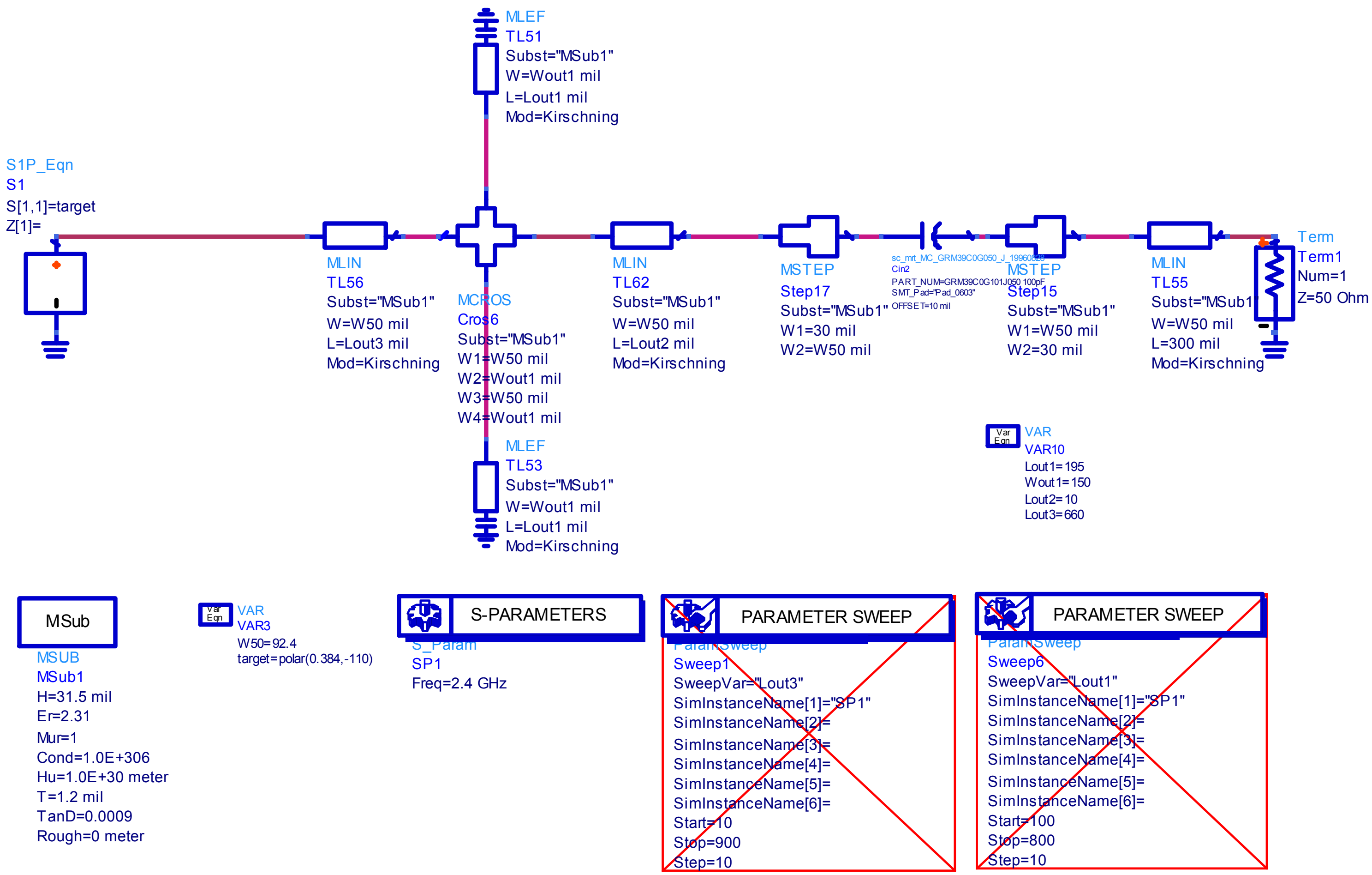
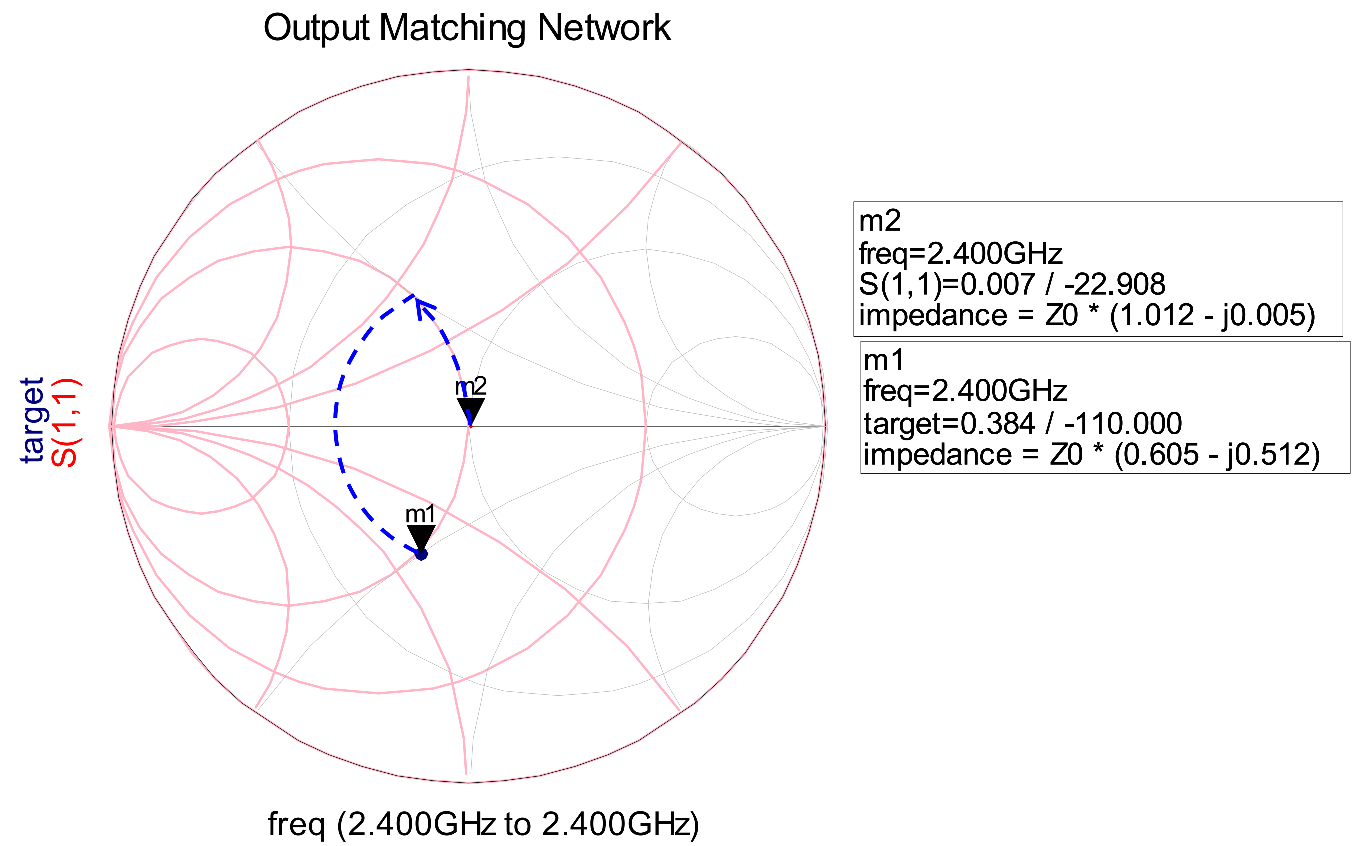


Figure 11 Output Matching Network




Output Matching Network
target
S(1,1)
m2
m1
m2
freq=2.400GHz
S(1,1)=0.007 / -22.908
impedance = Z0 * (1.012 - j0.005)
m1
freq=2.400GHz
target=0.384 / -110.000
impedance = Z0 * (0.605 - j0.512)
freq (2.400GHz to 2.400GHz)

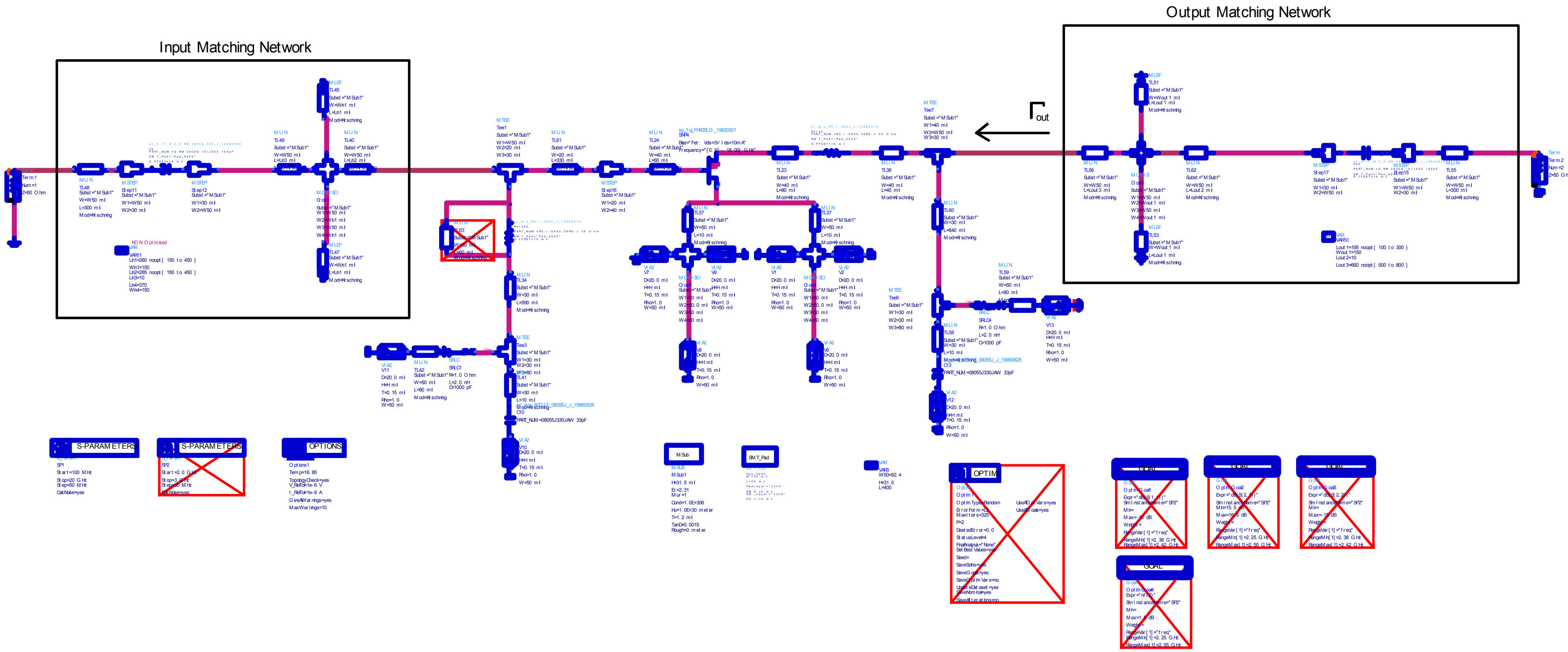
d. Final Amplifier Schematic

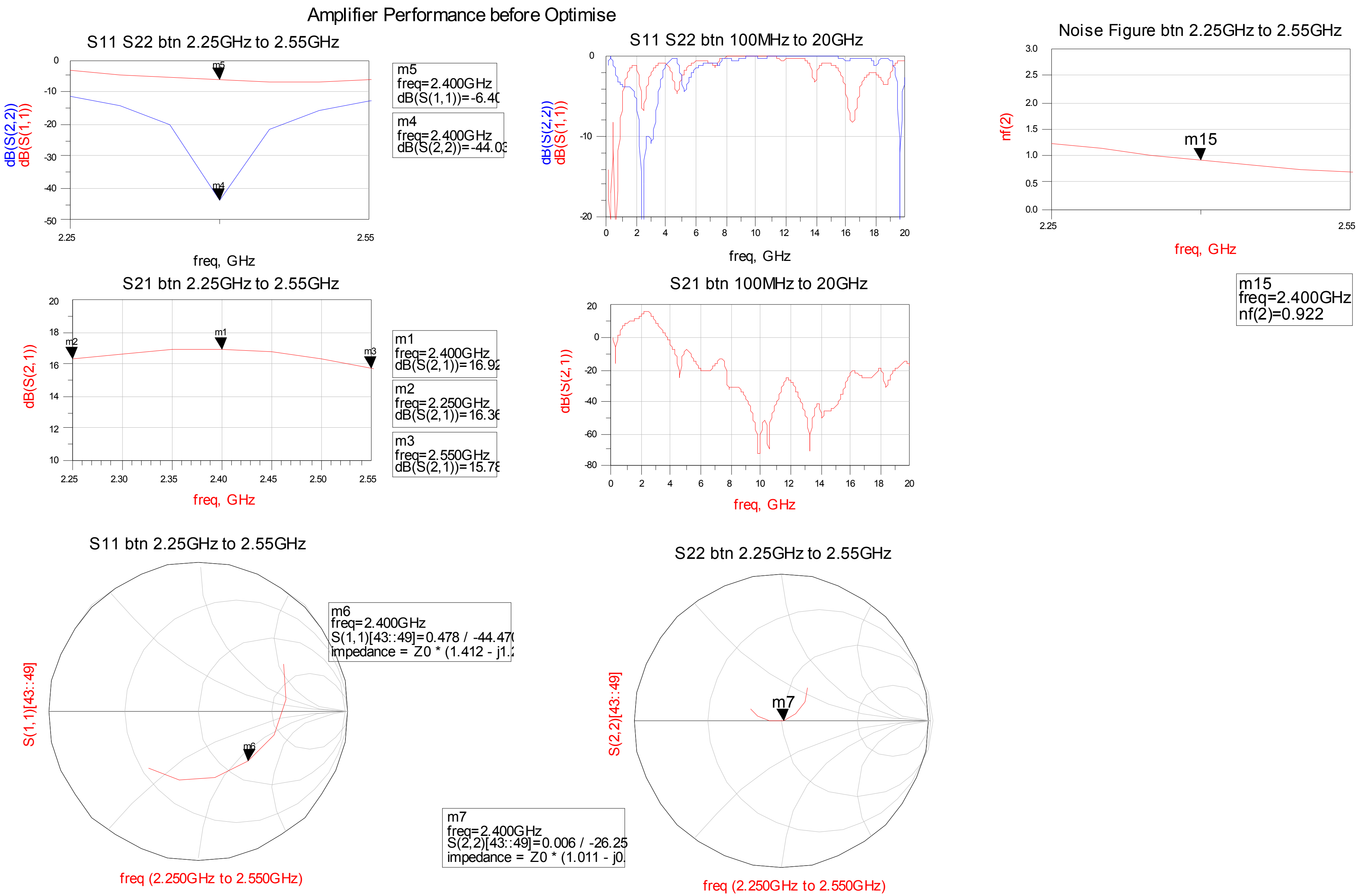
The designed input and output-matching network are finally combined together with the transistor and simulated.

Page 18 shows the performance of the amplifier using the parameters before optimization.
Page 19 shows the performances after optimization.

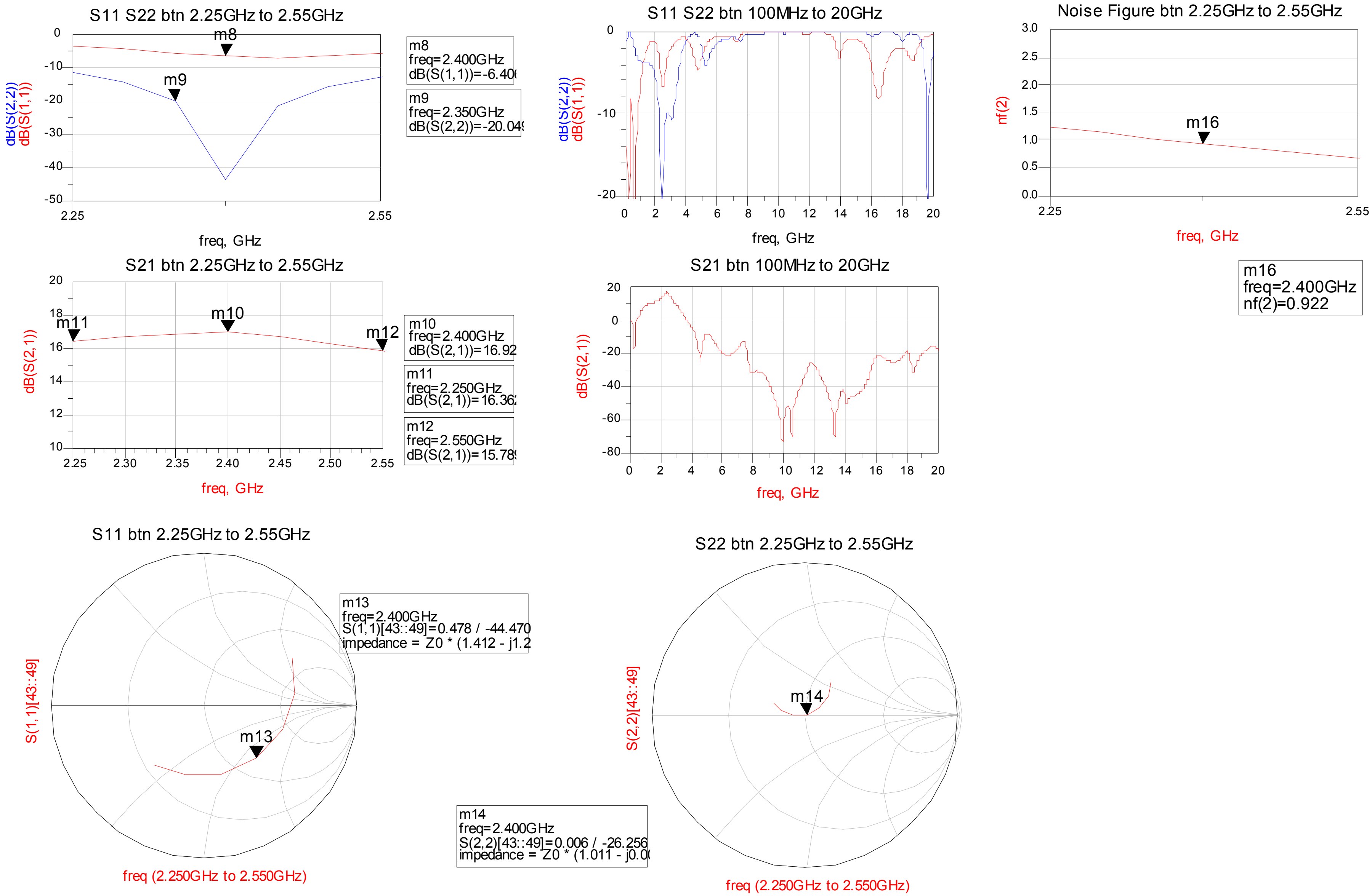
Final optimized matching network parameters are

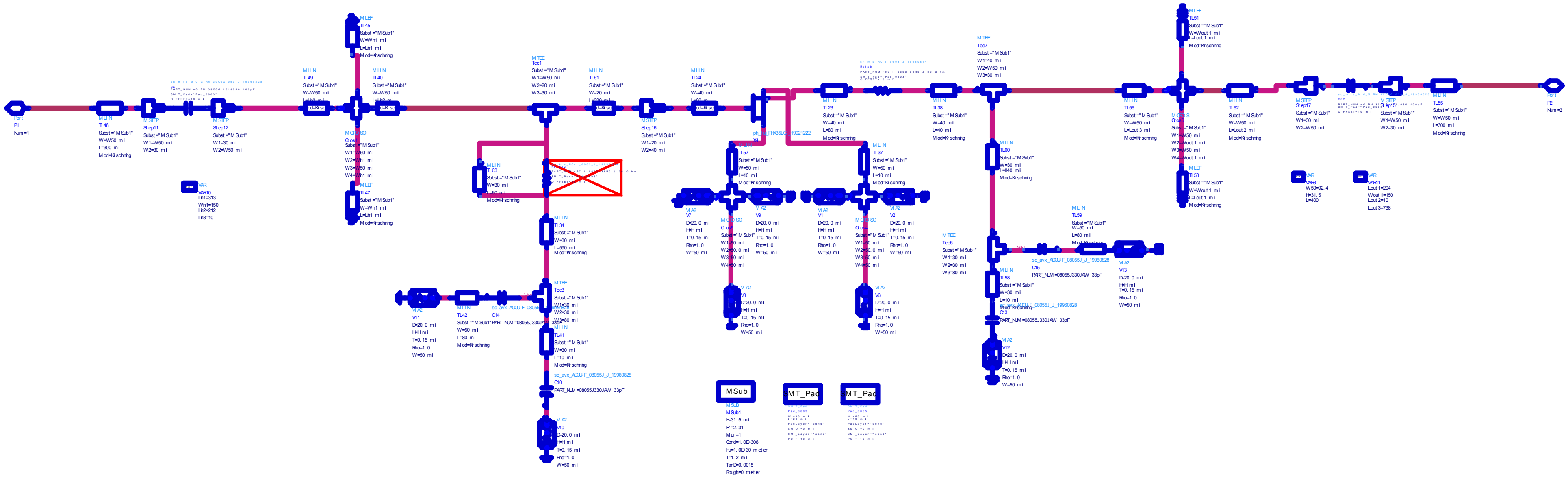
Lin1 = 313 mils Lin2 = 212 mils
Lout3 = 204 mils Lout3 = 738 mils


Input Matching Network
Output Matching Network
Γout


Amplifier Performance before Optimise
S11 S22 btn 2.25GHz to 2.55GHz
dB(S(2,2))
dB(S(1,1))
freq, GHz
m5
freq=2.400GHz
dB(S(1,1))=-6.40
m4
freq=2.400GHz
dB(S(2,2))=-44.03
S11 S22 btn 100MHz to 20GHz
Noise Figure btn 2.25GHz to 2.55GHz
nf(2)
m15
freq=2.400GHz
nf(2)=0.922
S21 btn 2.25GHz to 2.55GHz
dB(S(2,1))
m1
freq=2.400GHz
dB(S(2,1))=16.92
m2
freq=2.250GHz
dB(S(2,1))=16.36
m3
freq=2.550GHz
dB(S(2,1))=15.78
S21 btn 100MHz to 20GHz
S11 btn 2.25GHz to 2.55GHz
S(1,1)[43::49]
m6
freq=2.400GHz
S(1,1)[43::49]=0.478 / -44.47
impedance = Z0 * (1.412 - j1.
freq (2.250GHz to 2.550GHz)
S22 btn 2.25GHz to 2.55GHz
S(2,2)[43::49]
m7
freq=2.400GHz
S(2,2)[43::49]=0.006 / -26.25
impedance = Z0 * (1.011 - j0.
freq (2.250GHz to 2.550GHz)

Amplifier Performance After Optimise





Note : Final schematic and layout will exclude the input stabilizing resistor (36 ohm) for the time being. If low frequency oscillation is observed, it will be added.

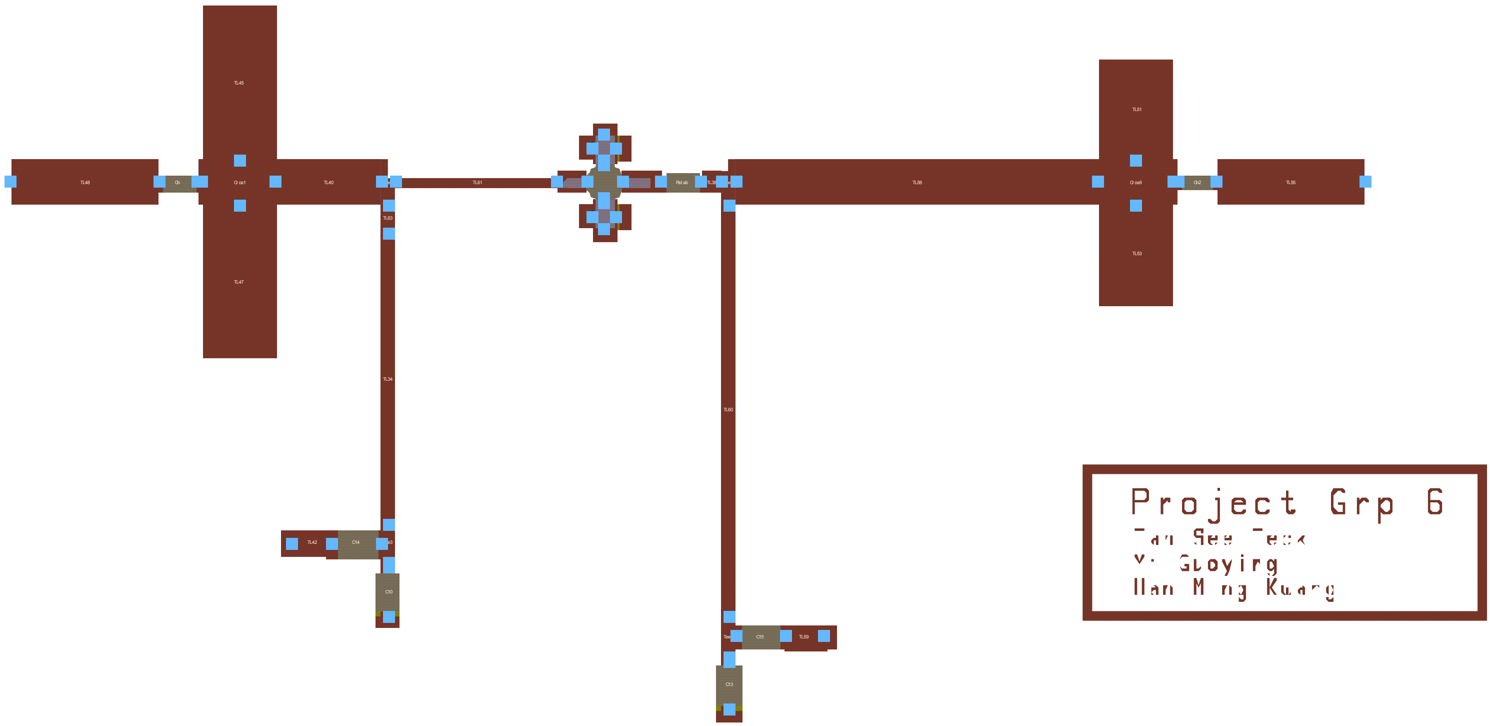
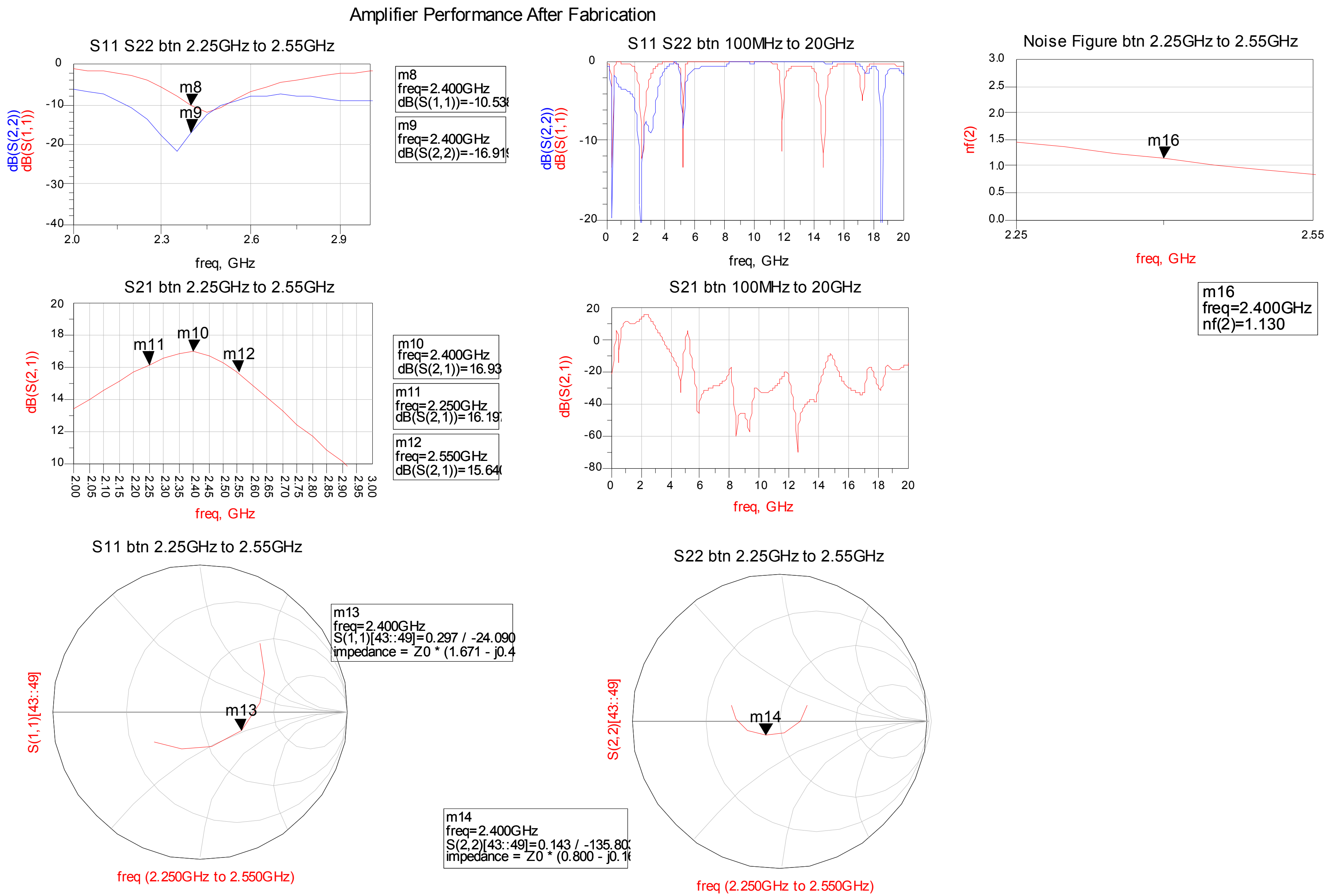

Project Grp 6

Figure 12 Resimulated Result using 33 ohm output stabilizing resistor



Appendix B shows the results from the fabricated amplifier design. We were unable to measure NF as the equipment is not available. Also due to the lack of exact value for the output stabilizing resistor, 33 ohm was chosen instead of the 30 ohm designed. Input stabilizing resistor of 36 ohm is also not soldered because no significant oscillation at low frequencies are observed.

Using the actual value of components used in the fabrication, the design is re-simulated and the result presented in Fig 12.

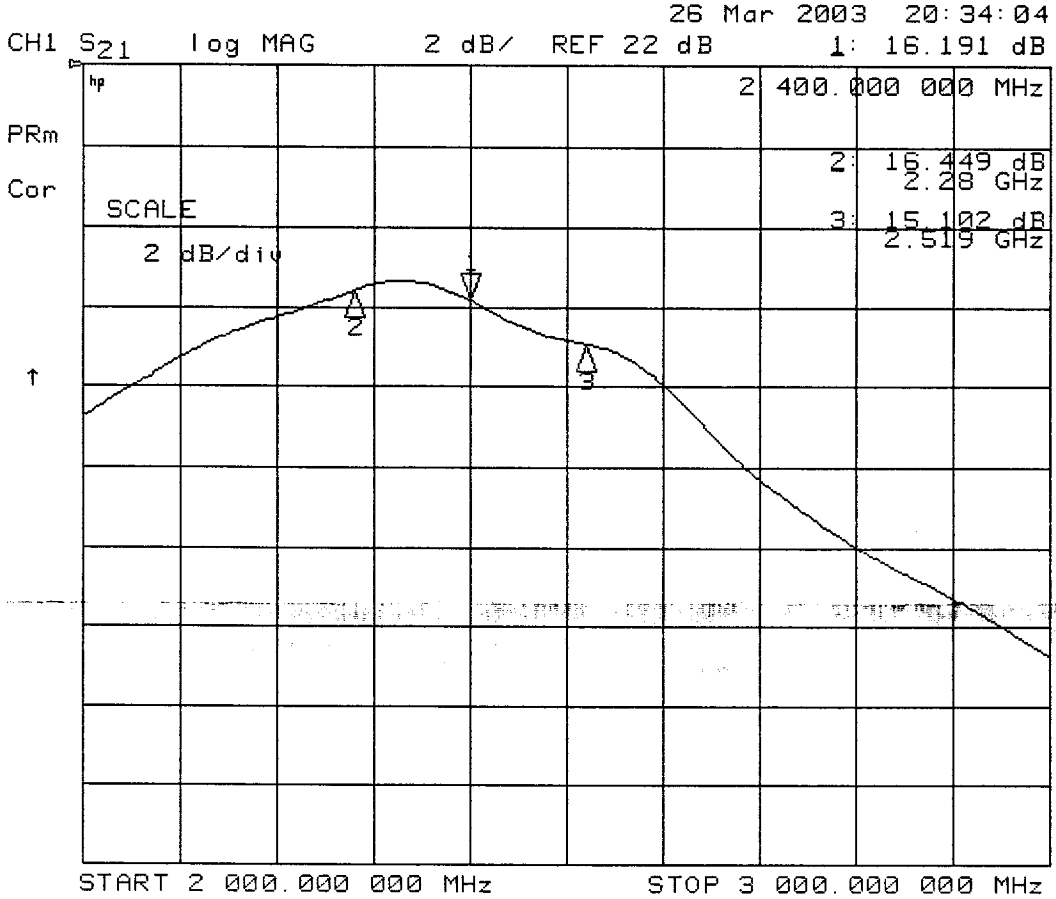
Comparison

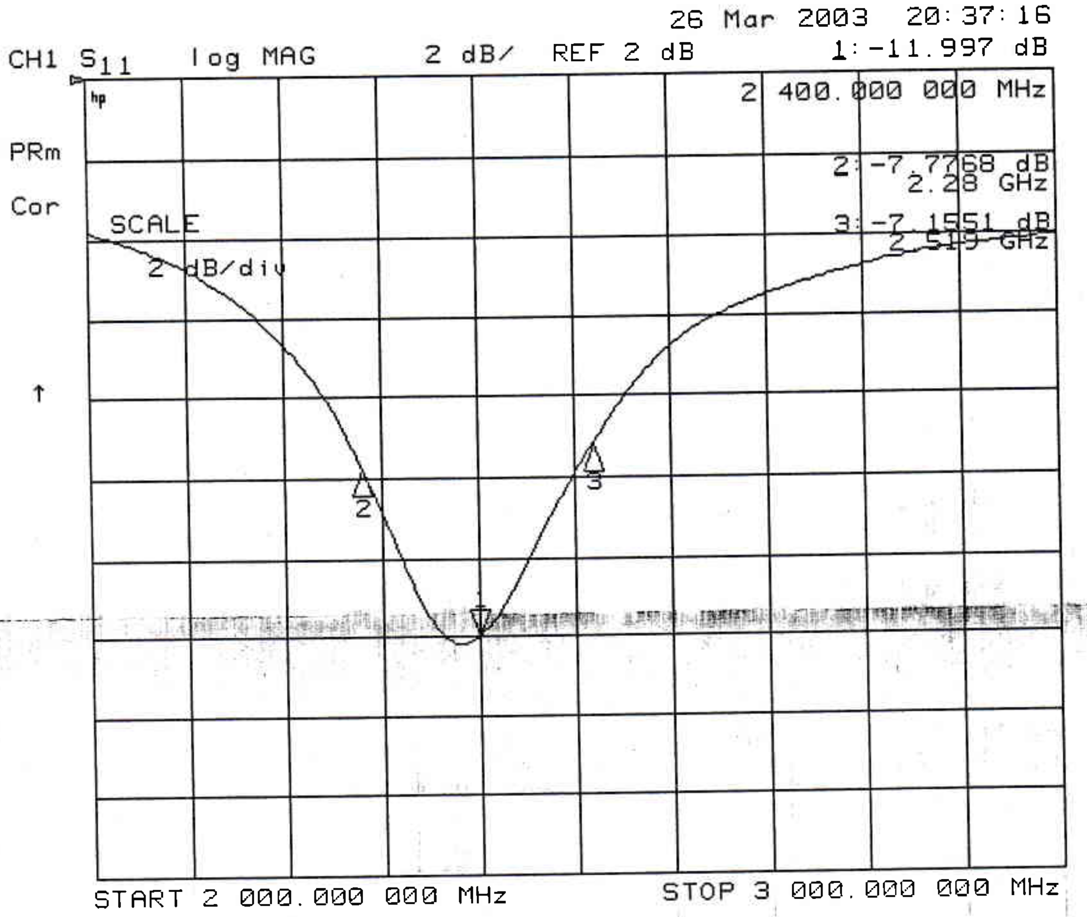
	Simulated	Actual	Difference
S21	16.932 dB	16.191 dB	0.741 dB
S11	-10.538 dB	-11.997 dB	1.459 dB
S22	-16.919 dB	-15.134 dB	-1.785 dB

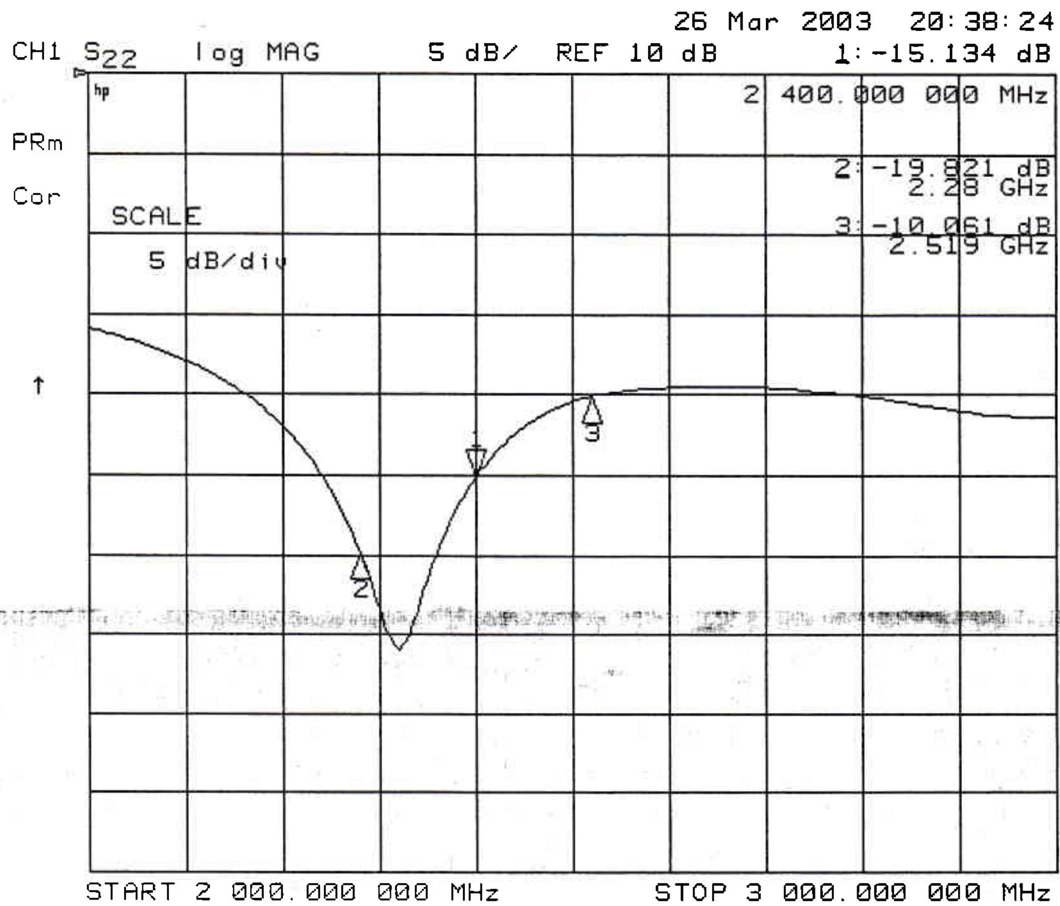
As expected output match is better than input match (S22<S11). S21 has only 0.741 dB difference between actual and simulated.

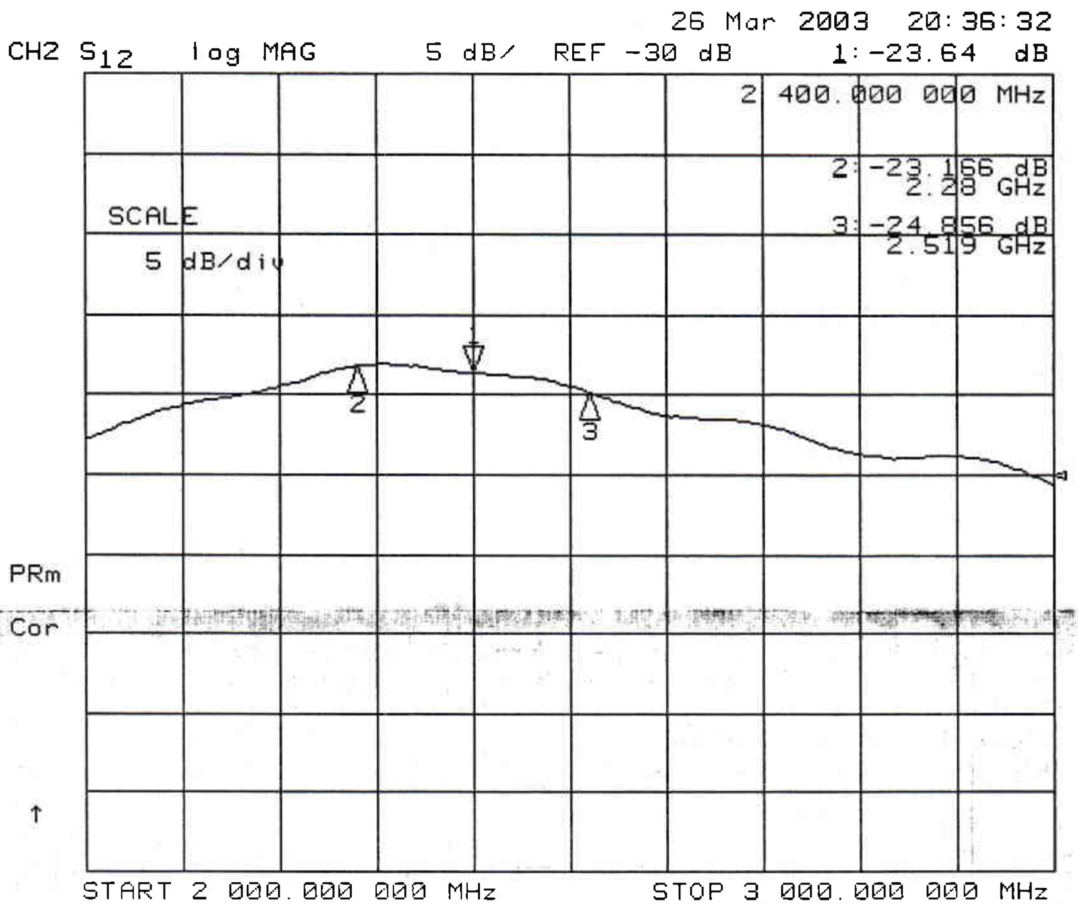
Figure 13 Group 6 RF Amplifier 2.4GHz

Appendix B


26 Mar 2003 20:34:04
CH1 S21 log MAG 2 dB/ REF 22 dB 1: 16.191 dB
2 400.000 000 MHz
PRm
Cor
SCALE
2 dB/div
2: 16.449 dB
2.28 GHz
3: 15.102 dB
2.519 GHz
START 2 000.000 000 MHz
STOP 3 000.000 000 MHz


26 Mar 2003 20:37:16
CH1 S11 log MAG 2 dB/ REF 2 dB 1:-11.997 dB
2 400.000 000 MHz
PRm
Cor
2:-7.7768 dB
2.28 GHz
3:-7.1551 dB
2.519 GHz
SCALE
2 dB/div
START 2 000.000 000 MHz
STOP 3 000.000 000 MHz


26 Mar 2003 20:38:24
CH1 S22 log MAG 5 dB/ REF 10 dB 1:-15.134 dB
2 400.000 000 MHz
PRm
Cor
2:-19.821 dB
2.28 GHz
3:-10.061 dB
2.519 GHz
SCALE
5 dB/div
START 2 000.000 000 MHz
STOP 3 000.000 000 MHz



26 Mar 2003 20:36:32
CH2 S12 log MAG 5 dB/ REF -30 dB 1:-23.64 dB
2 400.000 000 MHz
2:-23.166 dB
2.28 GHz
3:-24.856 dB
2.519 GHz
SCALE
5 dB/div
PRm
Cor
START 2 000.000 000 MHz
STOP 3 000.000 000 MHz