1. Chebyshev Filter Design

SPECIFICATIONS:

Center frequency, f_0:	2.4GHz
3 dB bandwidth, BW_{3dB}:	10%
Maximum ripple:	<0.1dB
Stopband bandwidth:	$2BW_{3dB}$
Stopband attenuation:	≥36dB
Source impedance, R_S:	50Ω
Load impedance, R_L:	50Ω
Relative permittivity of substrate, ε_r:	2.31
Thickness of the substrate, h:	31.5mil
Thickness of the conductor:	1.2mil

2. DESIGN STEPS

a. Find The Order Of Chebyshev Filter Needed

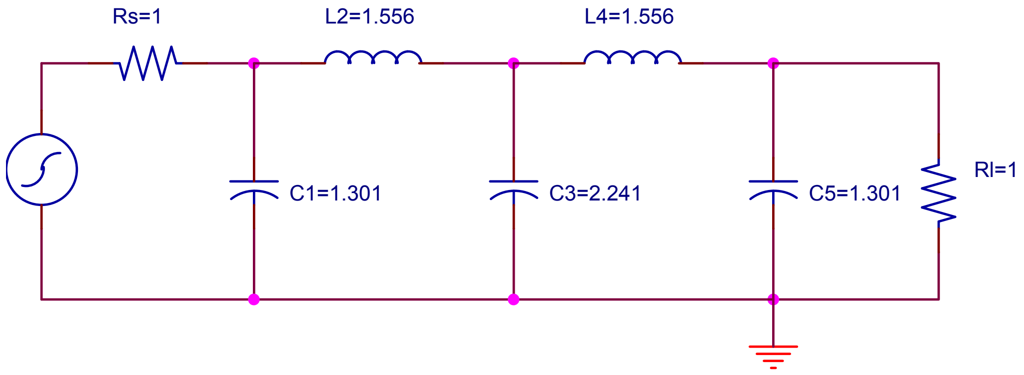
$$BW_{3dB} = 10\% \times f_0 = 240\text{MHz}$$

$$A_s = \frac{StopbandBW}{BW_{3dB}} = 2$$

Since the required stopband attenuation is at least 36dB, from the Attenuation characteristics curve for chebyshev filter with 0.1dB ripple, we find that the filter has to be at least 5th order.

The 5th order chebychev LPF prototype is presented in Figure 1.

Figure 1 5th order chebychev low pass filter prototype



b. Chebyshev BPF Using Discrete Components

The frequency-scaling factor is,
FSF = 2π BW = 2π × 240MHz
And the impedance scaling factor is Z=50.

Therefore, we can find the actual component values of C_1, L_2, C_3, L_4 and C_5.

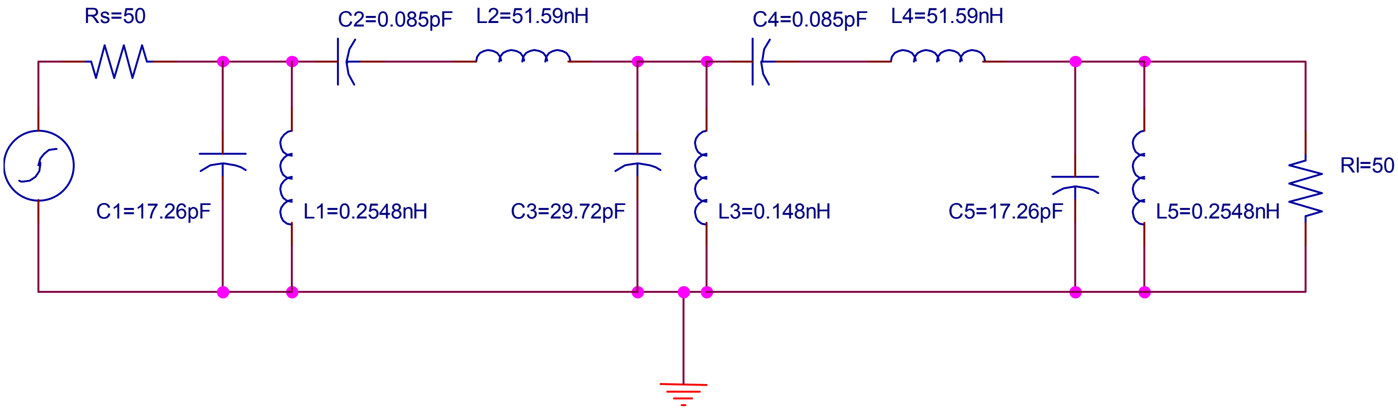
$$C_1 = C_5 = \frac{1.301}{FSF \times 50} = 17.26\text{pF}$$

$$L_2 = L_4 = \frac{1.556 \times 50}{FSF} = 51.59\text{nH}$$

$$C_3 = \frac{2.241}{FSF \times 50} = 29.72\text{pF}$$

To convert this LPF prototype to a BPF, we need to find the parallel L for each C and a series C for each L element, as shown in figure 2.

Figure 2 Chebychev 5th order BPF using discrete components



Where,

$$L_1 = L5 = \frac{1}{(2\times\pi\times f_0)^2 \times C_1} = \frac{1}{(2\times\pi\times f_0)^2 \times 17.26\,pF} = 0.2548\text{nH}$$

$$C_2 = C_4 = \frac{1}{(2\times\pi\times f_0)^2 \times L_2} = \frac{1}{(2\times\pi\times f_0)^2 \times 51.59\,nH} = 0.085\text{pF}$$

$$L_3 = \frac{1}{(2\times\pi\times f_0)^2 \times C_3} = \frac{1}{(2\times\pi\times f_0)^2 \times 29.72\,pF} = 0.148\text{nH}$$

c. Microstrip BPF Design

From the LFP prototype we have,

$K_1 = K_5 = 1.301$
$K_2 = K_4 = 1.556$
$K_3 = 2.241$

$\Omega = BW_{3dB}/f_0 = 0.1$

Therefore, we get,

$$J_{01}' = [\frac{\pi \times \Omega}{2 \times K_0 \times K_1}]^{0.5} = [\frac{\pi \times 0.1}{2 \times 1 \times 1.301}]^{0.5} = 0.347$$

$$J_{12}' = \frac{\pi \times \Omega}{2} \times \frac{1}{\sqrt{K_1 \times K_2}} = \frac{\pi \times 0.1}{2} \times \frac{1}{\sqrt{1.301 \times 1.556}} = 0.1104$$

$$J_{23}' = \frac{\pi \times \Omega}{2} \times \frac{1}{\sqrt{K_2 \times K_3}} = \frac{\pi \times 0.1}{2} \times \frac{1}{\sqrt{1.556 \times 2.241}} = 0.084$$

$$J_{34}' = \frac{\pi \times \Omega}{2} \times \frac{1}{\sqrt{K_3 \times K_4}} = \frac{\pi \times 0.1}{2} \times \frac{1}{\sqrt{2.241 \times 1.556}} = 0.084$$

$$J_{45}' = \frac{\pi \times \Omega}{2} \times \frac{1}{\sqrt{K_4 \times K_5}} = \frac{\pi \times 0.1}{2} \times \frac{1}{\sqrt{1.556 \times 1.301}} = 0.1104$$

$$J_{56}' = [\frac{\pi \times \Omega}{2 \times K_5 \times K_6}]^{0.5} = [\frac{\pi \times 0.1}{2 \times 1.301 \times 1}]^{0.5} = 0.347$$

Given, $\varepsilon_r = 2.31$ and h = 31.5 mil.
Using ADS tools, the “LineCal” function, we can find that $W^{50} = 92$ mil.

From Figure 9.25 of the reference material, we have,
For $J_{01}' = J_{56}' = 0.347$,
$\log_{10}(S/h) = -0.85$ ➔ S = 4.45 mil
$\frac{W}{W^{50}} = 0.754$ ➔ W=69.368 mil

For $J_{12}' = J_{45}' = 0.1104$,
$\mathrm{Log}_{10}(S/h) = 0.04 \Rightarrow S = 34.54$ mil
$\frac{W}{W^{50}} = 0.974 \Rightarrow W=89.608$ mil

For $J_{23}' = J_{34}' = 0.084$,
$\mathrm{Log}_{10}(S/h) = 0.16 \Rightarrow S = 45.53$ mil
$\frac{W}{W^{50}} = 0.982 \Rightarrow W=90.3$ mil

d. Simulation Using ADS Tools

i. *Simulation Circuit And Results For The BPF Prototype*

The BPF prototype circuit is shown in Figure 3.

The S-parameter simulation is done for a frequency range from 2.1GHz to 2.7GHz. The simulation results can be found in Figure 4.

Marker 1 and 2 show the –3dB frequencies. The 3dB BW is calculated to be 240MHz. The band separation of Marker 3 and 4 is 480MHz and the attenuations are -38dB and –44dB, respectively.

From the figure we also can see that the maximum passband ripple is equal to 0.1dB.

ii. *Simulation Circuit And Results For Microstrip BPF*

The microstrip BPF circuit is constructed as shown in Figure 5.

The value of the width and separation of every microstrip line calculated in section 3 were used at the beginning. The loss tangent was set to zero for simplicity. The circuit was simulated. The result showed a big ripple in passband and the center frequency was not at 2.4GHz.

Later on, some optimization was done to bring the center frequency back to 2.4GHz and to minimize the passband ripple. The length, width and separation of all the microstrip lines were set as tunable variables for optimization. The optimization goals were set to achieve 2.4GHz as the center frequency, 0.1dB passband ripple and to set 2.28GHz and 2.52GHz as the –3dB frequencies.

The simulation results (shown in Figure 6) were much satisfactory after the optimization.

The final circuit of the microstrip BPF is shown in Figure 7 and the layout is shown in Figure 8.

e. Testing Of Fabricated Microstrip BPF

The fabricated microstrip BPF was tested. The measured waveforms can be found in the appendix A.

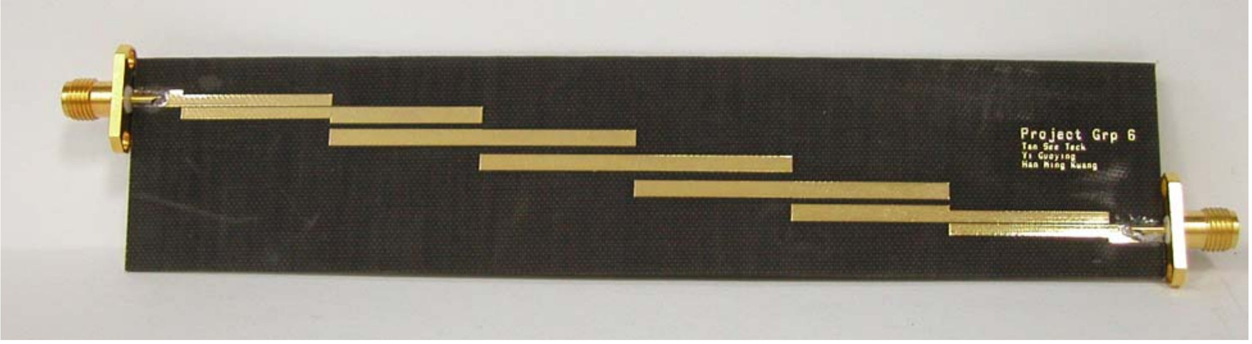
Table 1: Attenuation at different frequencies

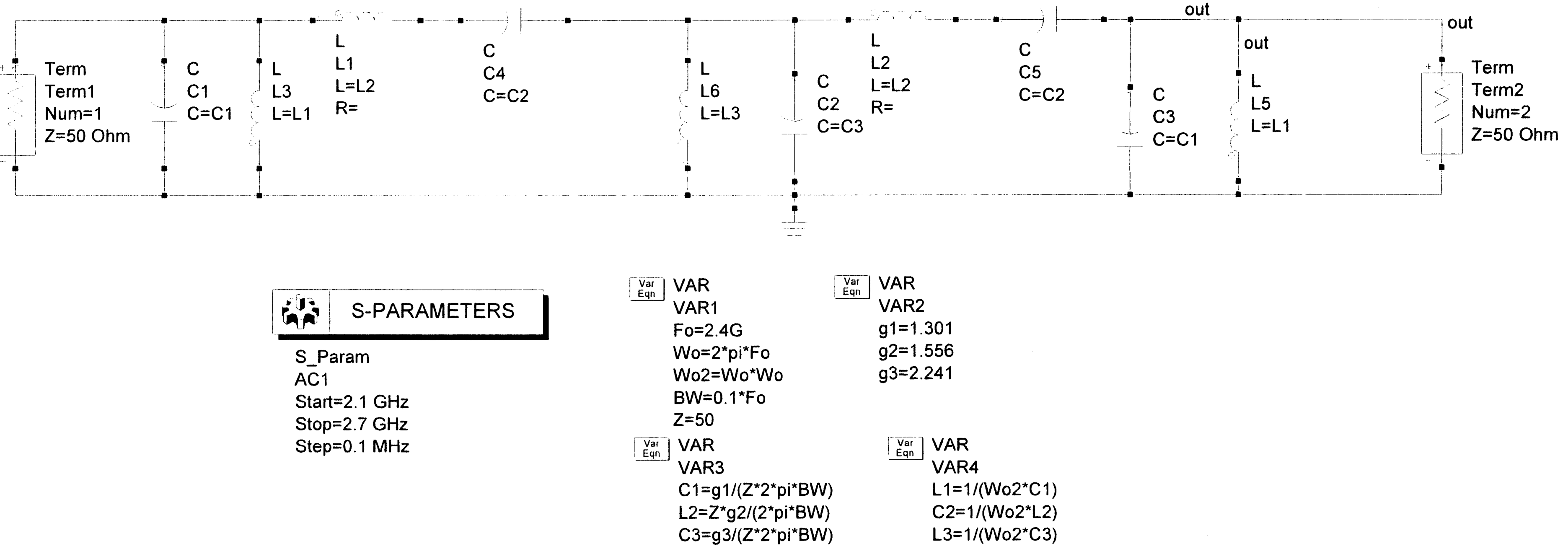
	2.4GHz	***2.28GHz***	***2.52GHz***	***2.16GHz***	***2.64GHz***
Actual attenuation	2.8262 dB	5.6721 dB	8.3403 dB	35.1 dB	37.859 dB
Attenuation except the insertion loss		2.846 dB	5.514 dB	32.27 dB	35.03 dB

From the above data, we can see that the actual filter performance is different from the design simulation.

In the design we have steeper roll off at the lower frequency side. But the above data shows that the high frequency side has more attenuation. Therefore, we suspect that the center frequency is shifted to the lower frequency side.

We also can see that the 3dB BW is narrower than the requirement. But the stop band didn't provide more than 36dB attenuation.





S_Param
AC1
Start=2.1 GHz
Stop=2.7 GHz
Step=0.1 MHz

VAR
VAR1
Fo=2.4G
Wo=2*pi*Fo
Wo2=Wo*Wo
BW=0.1*Fo
Z=50

VAR
VAR2
g1=1.301
g2=1.556
g3=2.241

VAR
VAR3
C1=g1/(Z*2*pi*BW)
L2=Z*g2/(2*pi*BW)
C3=g3/(Z*2*pi*BW)

VAR
VAR4
L1=1/(Wo2*C1)
C2=1/(Wo2*L2)
L3=1/(Wo2*C3)

Figure 3: 5th order chebychev BPF prototype

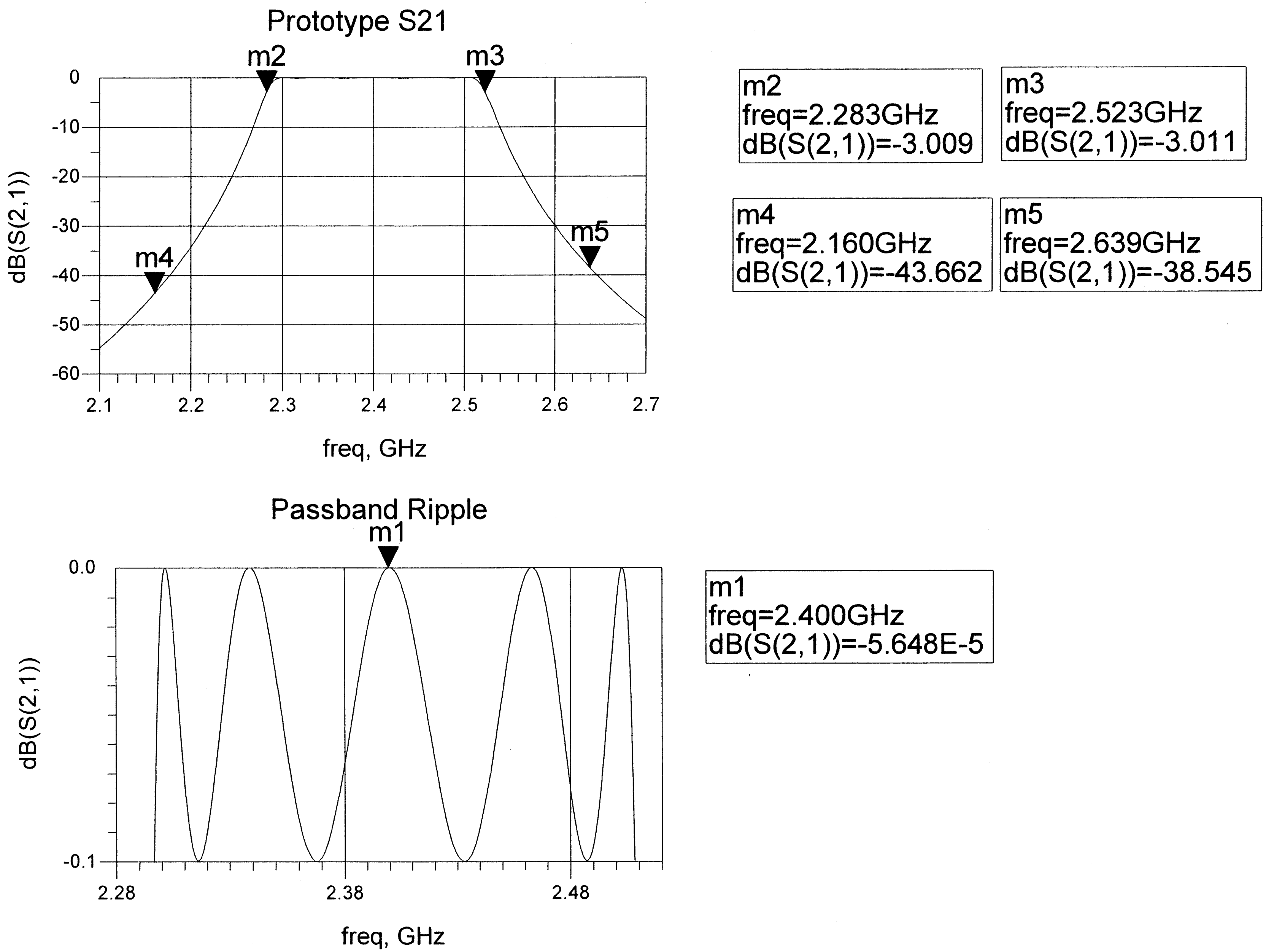
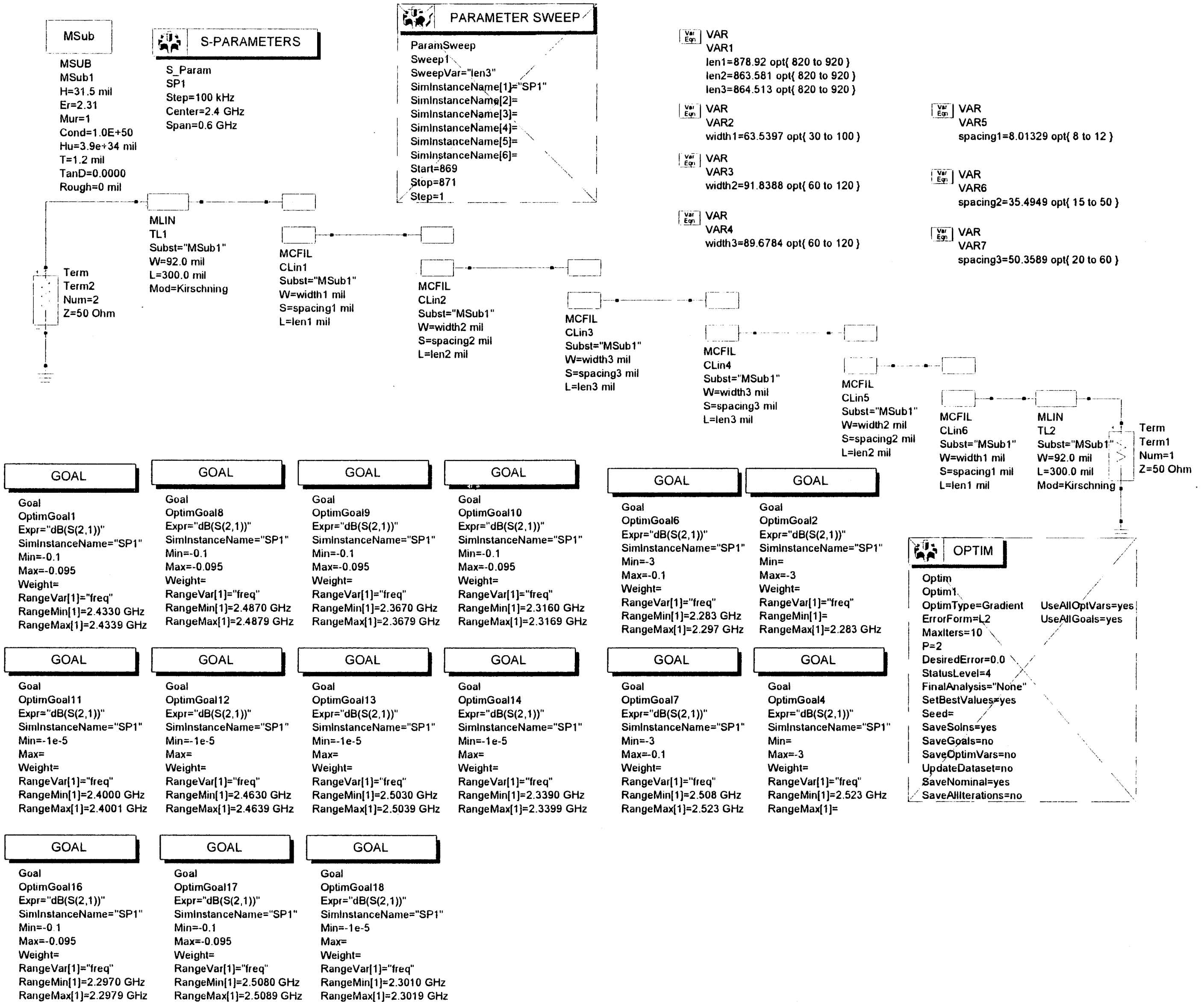


Figure 4 : Simulation result for prototype BPF



MSUB
MSub1
H=31.5 mil
Er=2.31
Mur=1
Cond=1.0E+50
Hu=3.9e+34 mil
T=1.2 mil
TanD=0.0000
Rough=0 mil

S_Param
SP1
Step=100 kHz
Center=2.4 GHz
Span=0.6 GHz

ParamSweep
Sweep1
SweepVar="len3"
SimInstanceName[1]="SP1"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=869
Stop=871
Step=1

VAR
VAR1
len1=878.92 opt(820 to 920)
len2=863.581 opt(820 to 920)
len3=864.513 opt(820 to 920)

VAR
VAR2
width1=63.5397 opt(30 to 100)

VAR
VAR3
width2=91.8388 opt(60 to 120)

VAR
VAR4
width3=89.6784 opt(60 to 120)

VAR
VAR5
spacing1=8.01329 opt(8 to 12)

VAR
VAR6
spacing2=35.4949 opt(15 to 50)

VAR
VAR7
spacing3=50.3589 opt(20 to 60)

Term
Term2
Num=2
Z=50 Ohm

MLIN
TL1
Subst="MSub1"
W=92.0 mil
L=300.0 mil
Mod=Kirschning

MCFIL
CLin1
Subst="MSub1"
W=width1 mil
S=spacing1 mil
L=len1 mil

MCFIL
CLin2
Subst="MSub1"
W=width2 mil
S=spacing2 mil
L=len2 mil

MCFIL
CLin3
Subst="MSub1"
W=width3 mil
S=spacing3 mil
L=len3 mil

MCFIL
CLin4
Subst="MSub1"
W=width3 mil
S=spacing3 mil
L=len3 mil

MCFIL
CLin5
Subst="MSub1"
W=width2 mil
S=spacing2 mil
L=len2 mil

MCFIL
CLin6
Subst="MSub1"
W=width1 mil
S=spacing1 mil
L=len1 mil

MLIN
TL2
Subst="MSub1"
W=92.0 mil
L=300.0 mil
Mod=Kirschning

Term
Term1
Num=1
Z=50 Ohm

Goal
OptimGoal1
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.4330 GHz
RangeMax[1]=2.4339 GHz

Goal
OptimGoal8
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.4870 GHz
RangeMax[1]=2.4879 GHz

Goal
OptimGoal9
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.3670 GHz
RangeMax[1]=2.3679 GHz

Goal
OptimGoal10
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.3160 GHz
RangeMax[1]=2.3169 GHz

Goal
OptimGoal6
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-3
Max=-0.1
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.283 GHz
RangeMax[1]=2.297 GHz

Goal
OptimGoal2
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=
Max=-3
Weight=
RangeVar[1]="freq"
RangeMin[1]=
RangeMax[1]=2.283 GHz

Goal
OptimGoal11
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-1e-5
Max=
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.4000 GHz
RangeMax[1]=2.4001 GHz

Goal
OptimGoal12
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-1e-5
Max=
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.4630 GHz
RangeMax[1]=2.4639 GHz

Goal
OptimGoal13
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-1e-5
Max=
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.5030 GHz
RangeMax[1]=2.5039 GHz

Goal
OptimGoal14
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-1e-5
Max=
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.3390 GHz
RangeMax[1]=2.3399 GHz

Goal
OptimGoal7
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-3
Max=-0.1
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.508 GHz
RangeMax[1]=2.523 GHz

Goal
OptimGoal4
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=
Max=-3
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.523 GHz
RangeMax[1]=

Goal
OptimGoal16
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.2970 GHz
RangeMax[1]=2.2979 GHz

Goal
OptimGoal17
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-0.1
Max=-0.095
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.5080 GHz
RangeMax[1]=2.5089 GHz

Goal
OptimGoal18
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=-1e-5
Max=
Weight=
RangeVar[1]="freq"
RangeMin[1]=2.3010 GHz
RangeMax[1]=2.3019 GHz

Optim
Optim1
OptimType=Gradient
ErrorForm=L2
MaxIters=10
P=2
DesiredError=0.0
StatusLevel=4
FinalAnalysis="None"
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=no
SaveOptimVars=no
UpdateDataset=no
SaveNominal=yes
SaveAllIterations=no
UseAllOptVars=yes
UseAllGoals=yes

Figure 5: Microstrip BPF design

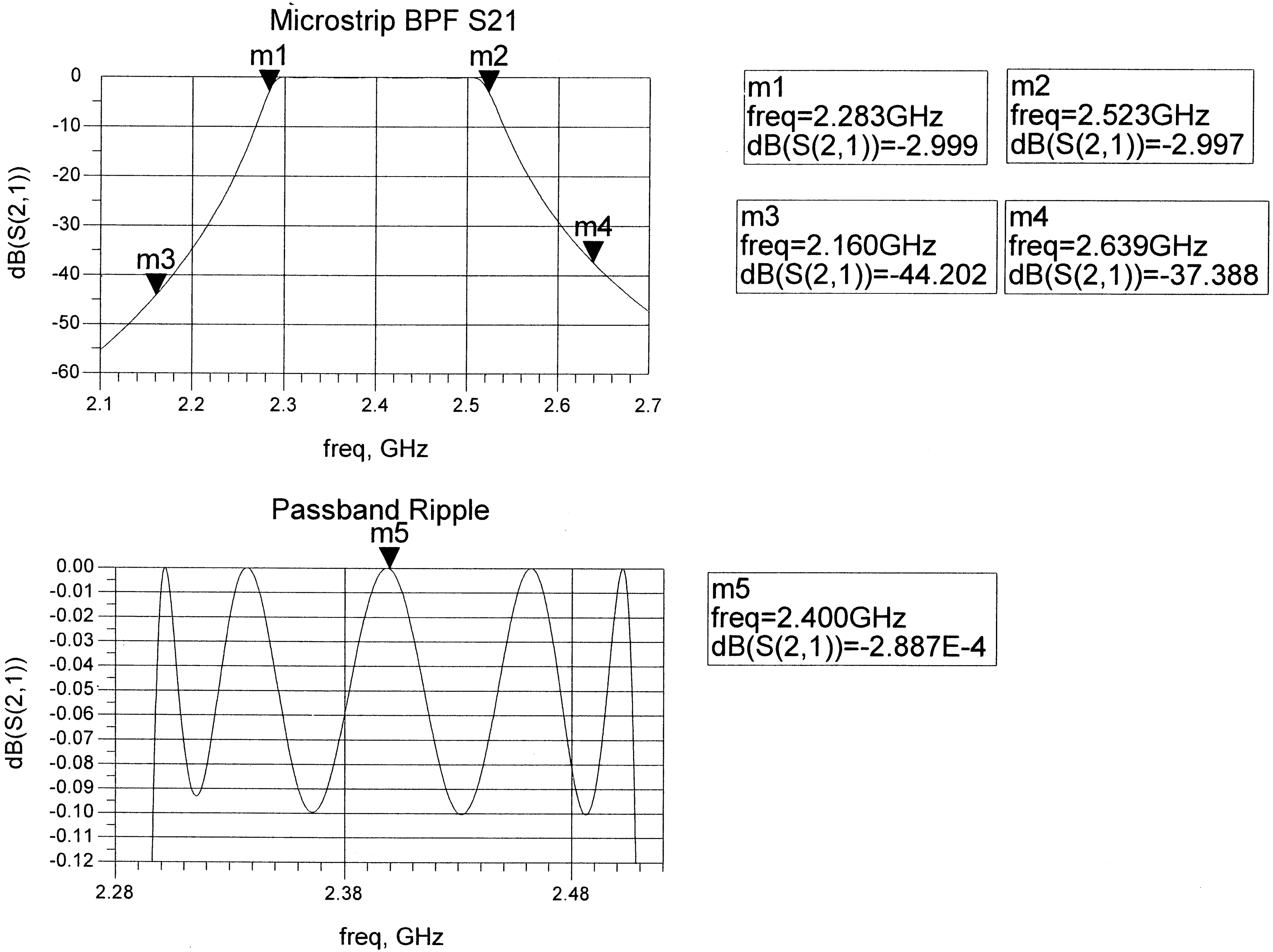


Figure 6: Microstrip BPF simulation results

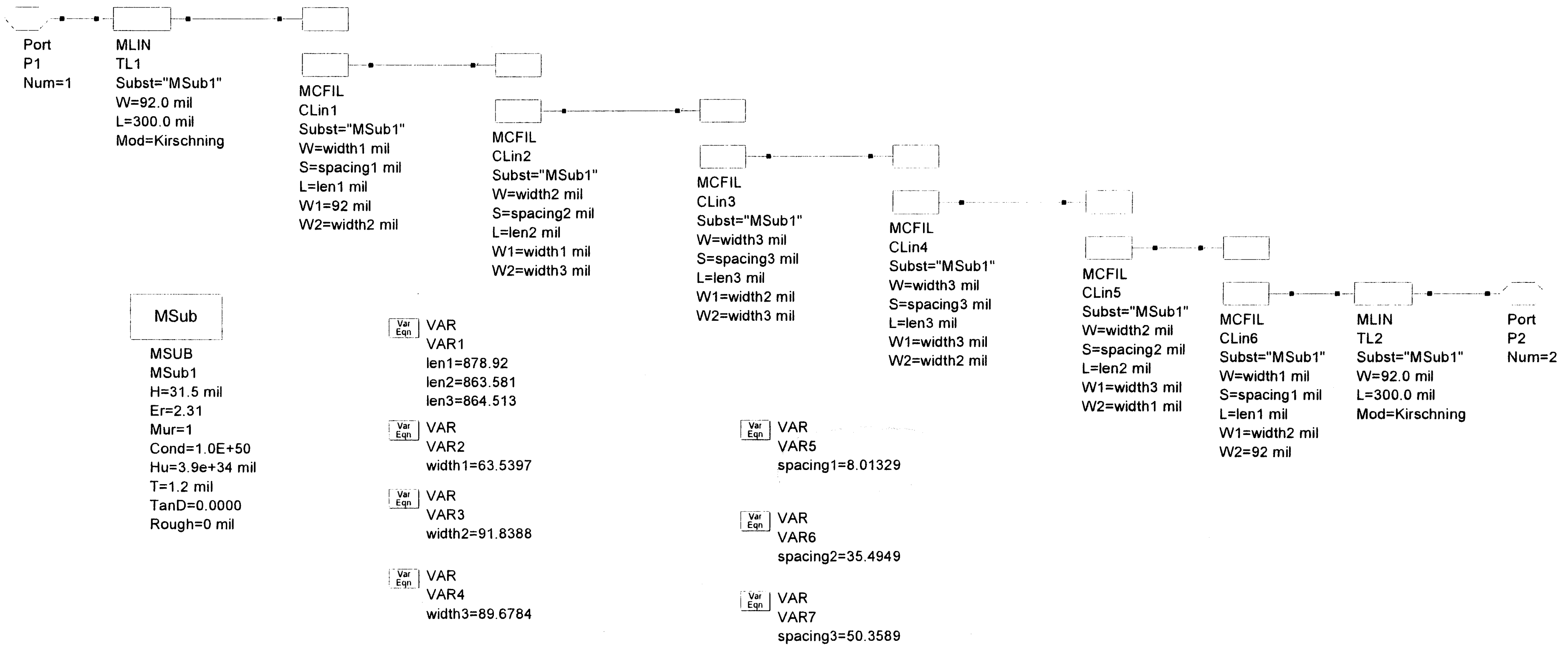
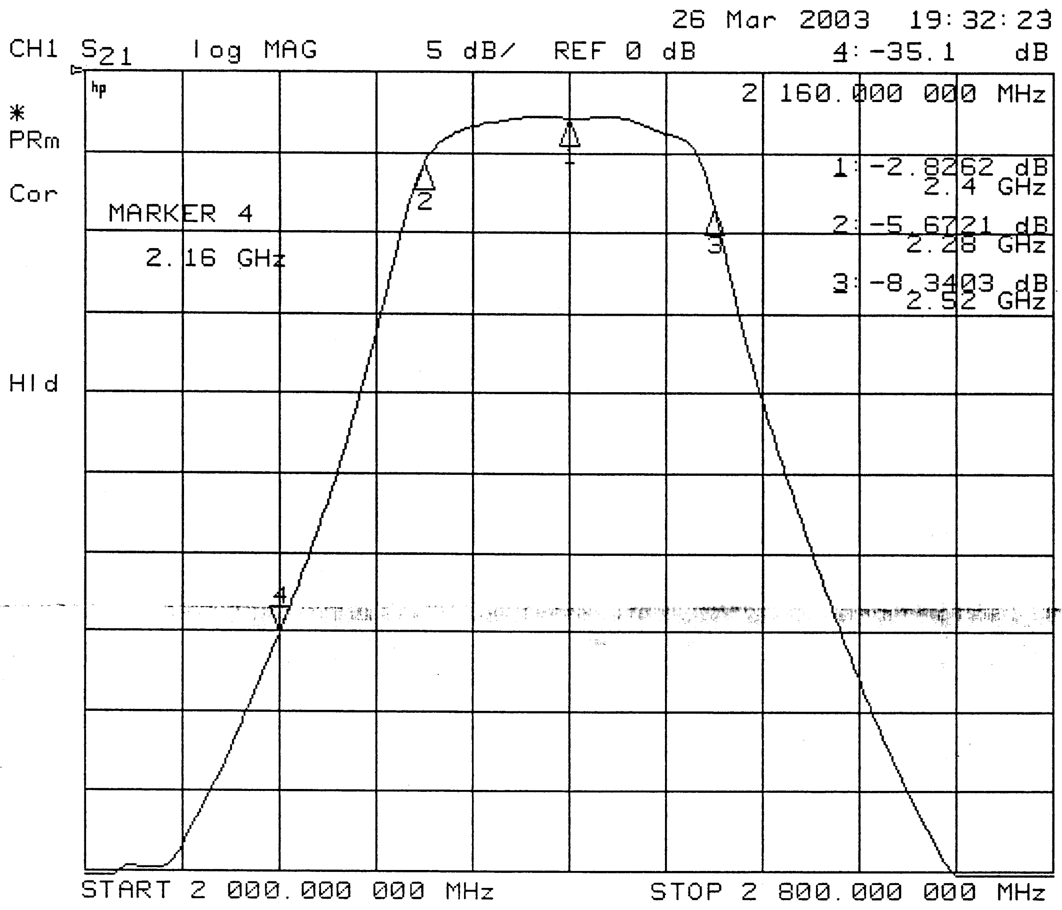
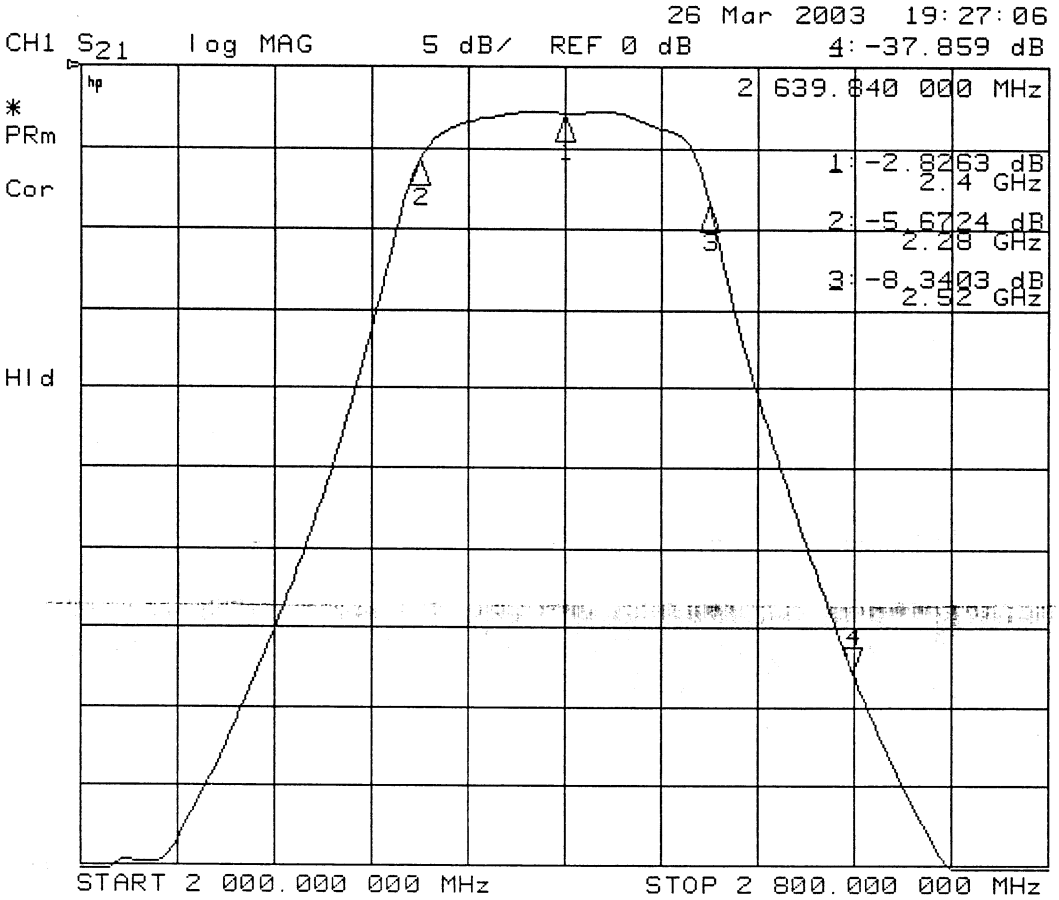


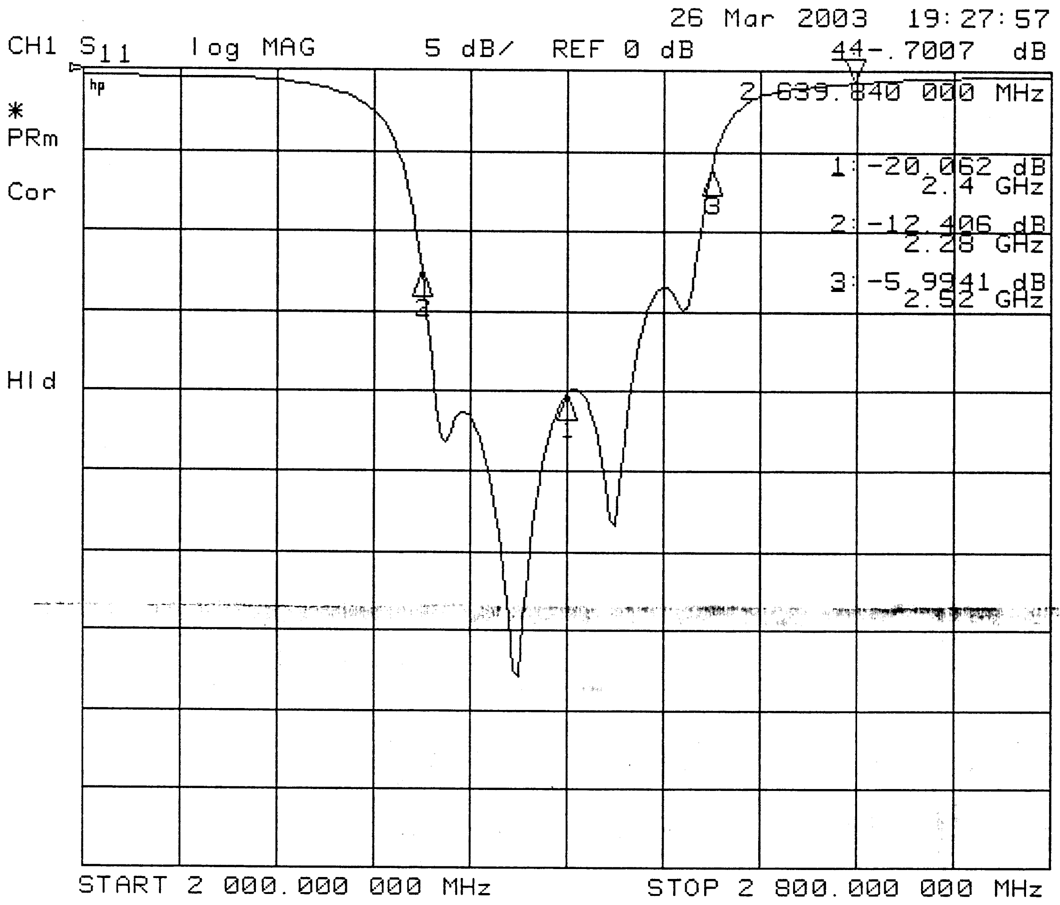
Figure 7: Final microstrip BPF schematic

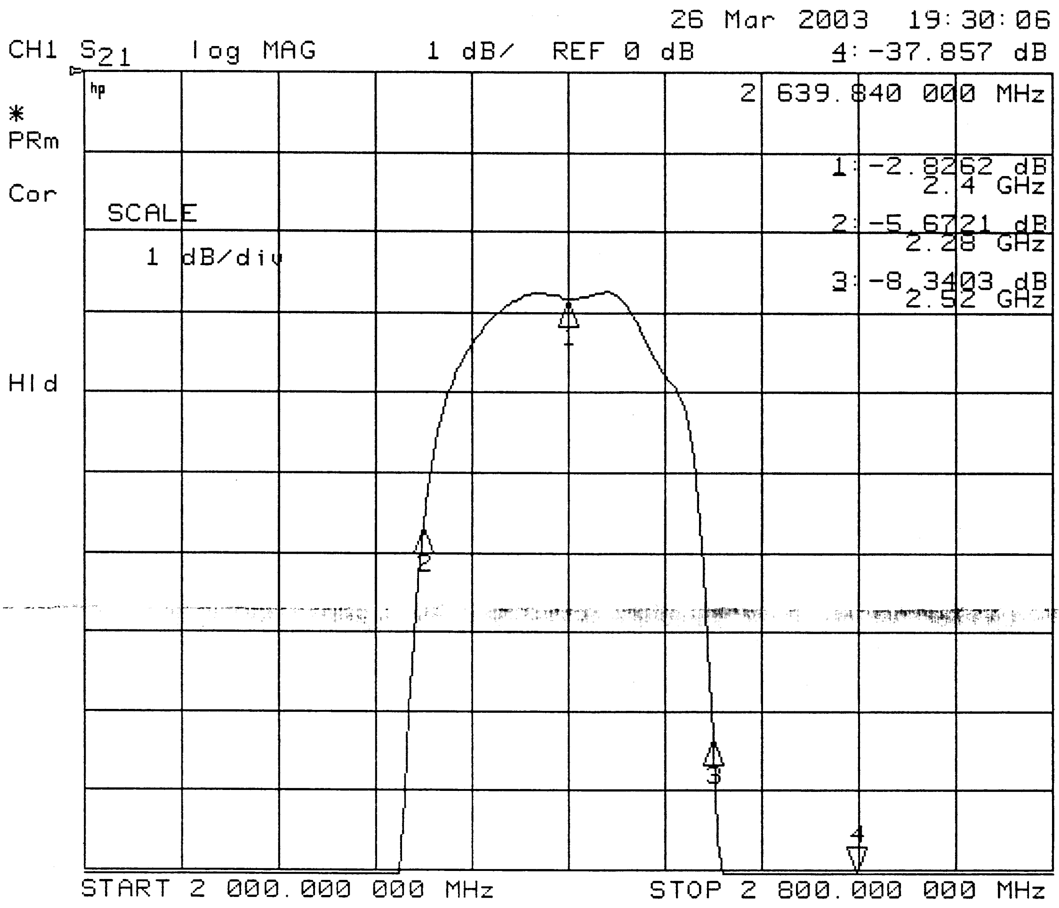
APPENDIX A

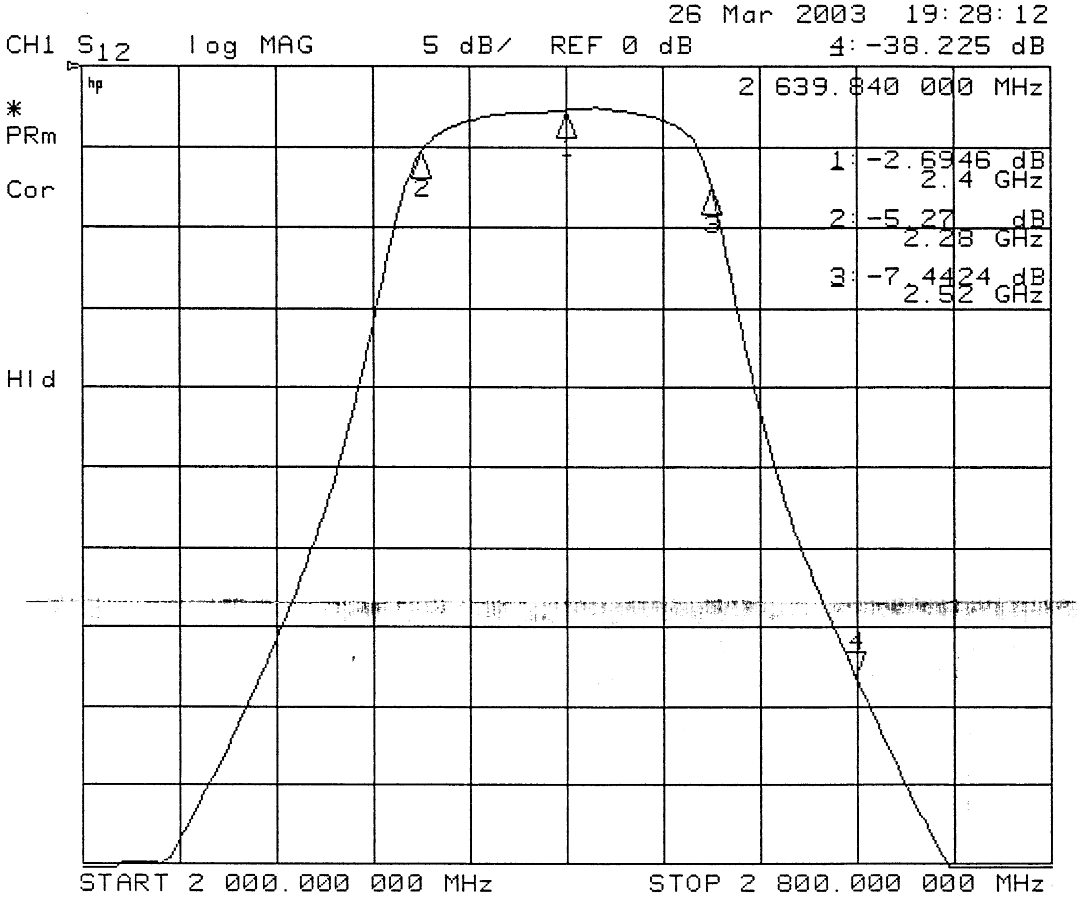
TESTING RESULTS FOR MICROSTRIP CHEBYCHEV BAND PASS FILTER

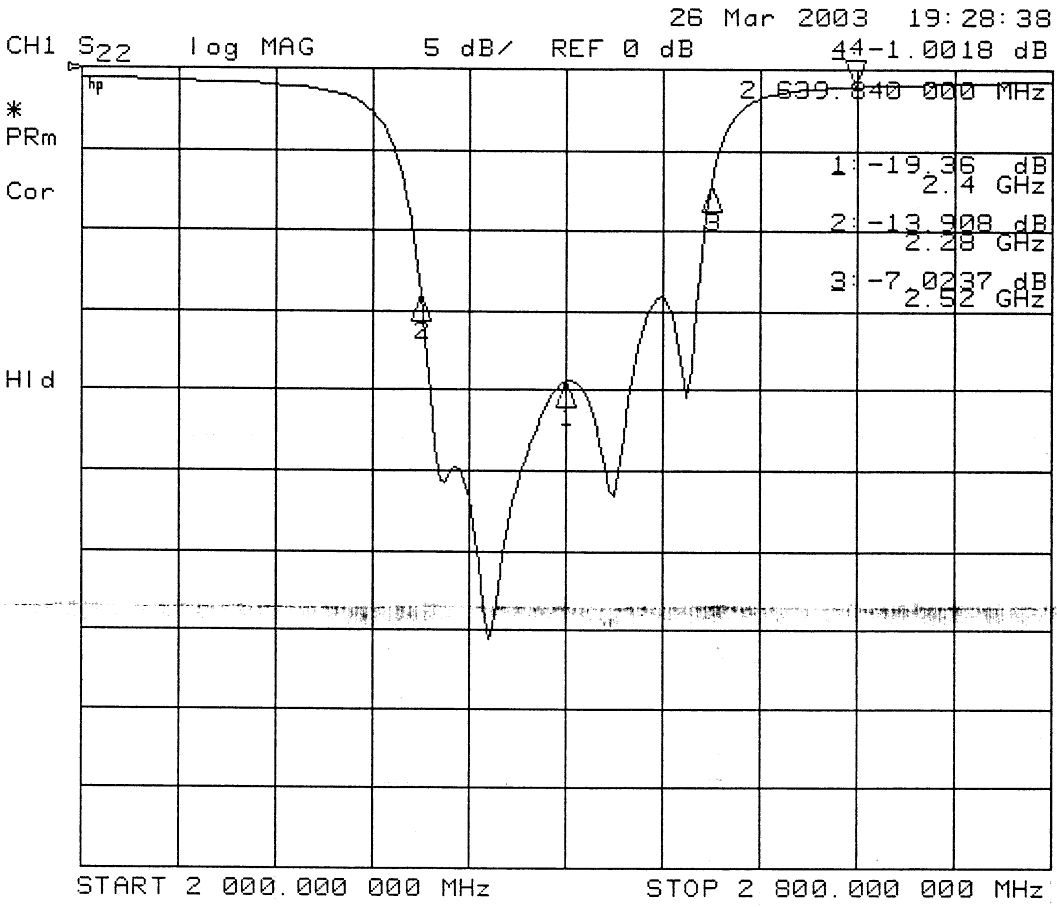

26 Mar 2003 19:32:23
CH1 S_{21} log MAG 5 dB/ REF 0 dB 4: -35.1 dB
2 160.000 000 MHz
hp
*
PRm
Cor
HId
MARKER 4
2.16 GHz
1: -2.8262 dB
2.4 GHz
2: -5.6721 dB
2.28 GHz
3: -8.3403 dB
2.52 GHz
1
2
3
4
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz


26 Mar 2003 19:27:06
CH1 S21 log MAG 5 dB/ REF 0 dB 4: -37.859 dB
2 639.840 000 MHz
hp
*
PRm
Cor
Hld
1: -2.8263 dB
2.4 GHz
2: -5.6724 dB
2.28 GHz
3: -8.3403 dB
2.52 GHz
2
3
4
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz


26 Mar 2003 19:27:57
CH1 S_{11} log MAG 5 dB/ REF 0 dB
4 -.7007 dB
2 639.840 000 MHz
*
PRm
Cor
Hld
hp
1: -20.062 dB
2.4 GHz
2: -12.406 dB
2.28 GHz
3: -5.9941 dB
2.52 GHz
1
2
3
4
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz


26 Mar 2003 19:30:06
CH1 S21 log MAG 1 dB/ REF 0 dB 4:-37.857 dB
2 639.840 000 MHz
hp
*
PRm
Cor
SCALE
1 dB/div
Hld
1:-2.8262 dB
2.4 GHz
2:-5.6721 dB
2.28 GHz
3:-8.3403 dB
2.52 GHz
1
2
3
4
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz


26 Mar 2003 19:28:12
CH1 S12 log MAG 5 dB/ REF 0 dB 4:-38.225 dB
hp
2 639.840 000 MHz
*
PRm
Cor
Hld
1: -2.6946 dB
2.4 GHz
2: -5.27 dB
2.28 GHz
3: -7.4424 dB
2.52 GHz
1
2
3
4
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz


26 Mar 2003 19:28:38
CH1 S22 log MAG 5 dB/ REF 0 dB 44-1.0018 dB
2 639.840 000 MHz
*
PRm
Cor
Hld
hp
1: -19.36 dB
2.4 GHz
2: -13.908 dB
2.28 GHz
3: -7.0237 dB
2.52 GHz
1
2
3
START 2 000.000 000 MHz
STOP 2 800.000 000 MHz