Table of Contents

Specifications:

Microstrip dielectric constant: $\varepsilon_r = 2.5$
Design center frequency: $f_0 = 3.4\ GHz$
Fractional bandwidth: $FBW = 1/3$
Maximum VSWR at band edge: $VSWR_m = 1.046$
Generator impedance: $Z_o = 50\ \Omega$
Load impedance: $Z_L = 100\ \Omega$
Circuit board dielectric thickness: $H = 60\ mils$
Circuit board metal: Copper ($\sigma \approx 5.96 * 10^7 S/m$)
Circuit board metal thickness: $T = 1.4\ mils$

A. Theoretical Air Transmission Line and Microstrip Model

$$\rho_m = \frac{VSWR_m - 1}{VSWR_m + 1} = \frac{1.046 - 1}{1.046 + 1} = 0.02248289$$

$$FBW = \frac{\Delta f}{f_0} = 2\left(1 - \frac{2}{\pi}\theta_m\right)$$

$$\rightarrow \theta_m = \frac{\pi}{4}(2 - FBW) = \frac{\pi}{4}(2 - 1/3) = \frac{5\pi}{12}$$

$$\theta_m = \cos^{-1}\left[\left|\frac{\rho_m}{\frac{Z_L - Z_o}{Z_L + Z_o}}\right|^{\frac{1}{N}}\right]$$

$$\rightarrow \cos^N \theta_m = \left|\frac{\rho_m}{\frac{Z_L - Z_o}{Z_L + Z_o}}\right|$$

$$\cos^N \frac{5\pi}{12} = \left|\frac{0.02248289}{\frac{100 - 50}{100 + 50}}\right|$$

$$\cos^N \frac{5\pi}{12} = |0.06744867|$$

$$\rightarrow N = \frac{\log|0.06744|}{\log\left(\cos\frac{5\pi}{12}\right)} = 1.9950168$$

Try $N = 2$

$n = 0$

$$\ln\left(\frac{Z_{o1}}{Z_o}\right) = \left(\frac{1}{2}\right)^2 C_0{}^2 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{1}{4}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o1} = Z_o e^{\frac{1}{4}\ln(2)} = 50 * e^{\frac{1}{4}\ln(2)} = 59.460355\ \Omega$$

$$Z_{o1} = 59.460355 = \frac{120\pi}{\frac{W}{H} + 2.42 - 0.44\frac{H}{W} + \left(1 - \frac{H}{W}\right)^6}\ [1]$$

$$\rightarrow \frac{W}{H} = 3.86781$$

$$\rightarrow W = 3.86781H = 3.86781 * 60\ mils = 232.068\ mils = 0.58945272\ cm$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10H}{W}\right)^{-1/2} = \frac{1+1}{2} + \frac{1-1}{2}\left(1 + \frac{10}{3.86781}\right)^{-1/2} = 1$$

$$L = \frac{\lambda}{4} = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} = \frac{c}{4 * 3.4 * 10^9\sqrt{1}} = 2.2043563\ cm$$

$n = 1$

$$\ln\left(\frac{Z_{o2}}{Z_{o1}}\right) = \left(\frac{1}{2}\right)^2 C_1{}^2 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{1}{2}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o2} = Z_{o1} e^{\frac{1}{2}\ln(2)} = 59.460355 * e^{\frac{1}{2}\ln(2)} = 84.089640\ \Omega$$

$$Z_{o2} = 84.089640 = \frac{120\pi}{\frac{W}{H} + 2.42 - 0.44\frac{H}{W} + \left(1 - \frac{H}{W}\right)^6}\ [1]$$

$$\rightarrow \frac{W}{H} = 2.23205$$

$$\rightarrow W = 2.23205H = 2.2320 * 60\ mils = 133.923\ mils = 0.34016442\ cm$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10H}{W}\right)^{-1/2} = \frac{1+1}{2} + \frac{1-1}{2}\left(1 + \frac{10}{2.23205}\right)^{-1/2} = 1$$

$$L = \frac{\lambda}{4} = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} = \frac{c}{4 * 3.4 * 10^9\sqrt{1}} = 2.2043563\ cm$$

N = 2

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
59.460355	1	0.58945272	2.2043563
84.089640	1	0.34016442	2.2043563

Fig A.1 N=2 Theoretical Air Transmission Line and Microstrip Parameters

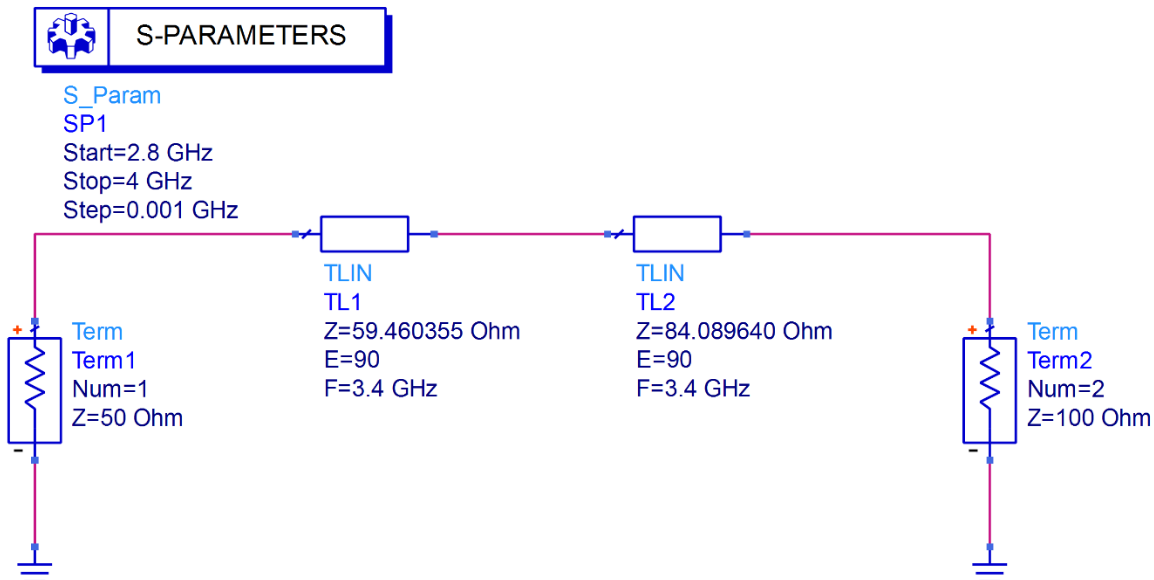


Fig A.2 N=2 Theoretical Air Transmission Line ADS Schematic

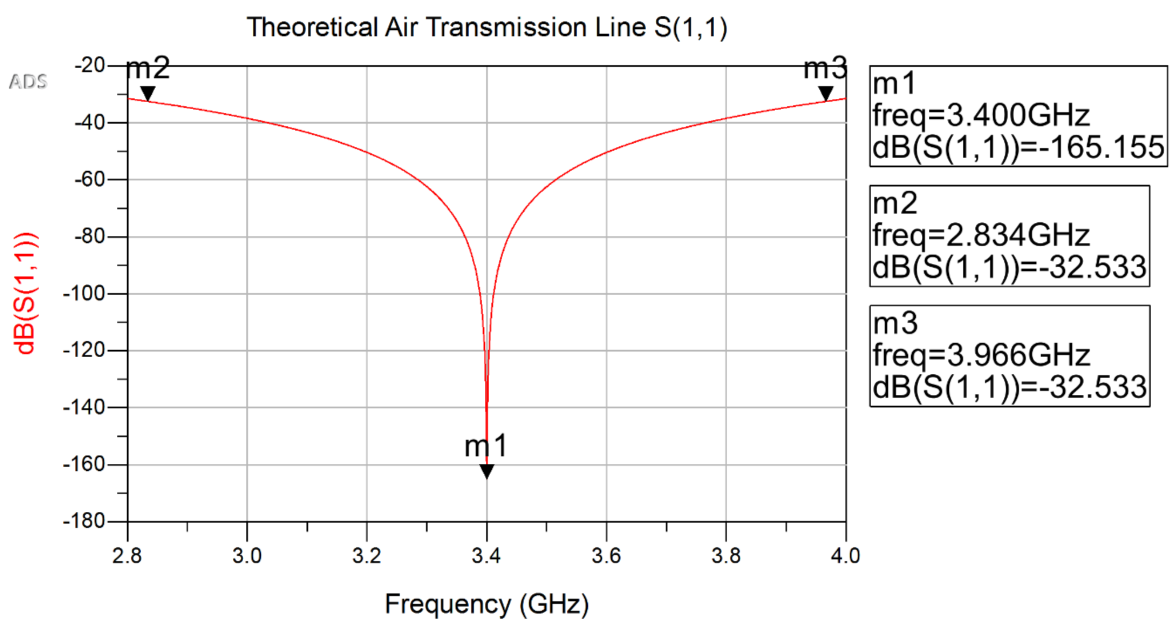


Fig A.3 N=2 Theoretical Air Transmission Line S(1,1) showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$$RL = 165.155\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{165.155}{-20}} = 5.2395332 * 10^{-9}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 5.2395332 * 10^{-9}}{1 - 5.2395332 * 10^{-9}} \approx 1$$

$f = f_{FBW\ edge} = 2.834\ GHz = 3.966\ GHz$

$$RL = 32.533\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{32.533}{-20}} = 0.02362381$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 0.02362381}{1 - 0.02362381} = 1.0483907 \nleq 1.046$$

Matched theoretical air transmission line but VSWR exceeds design maximum VSWR at band edge.

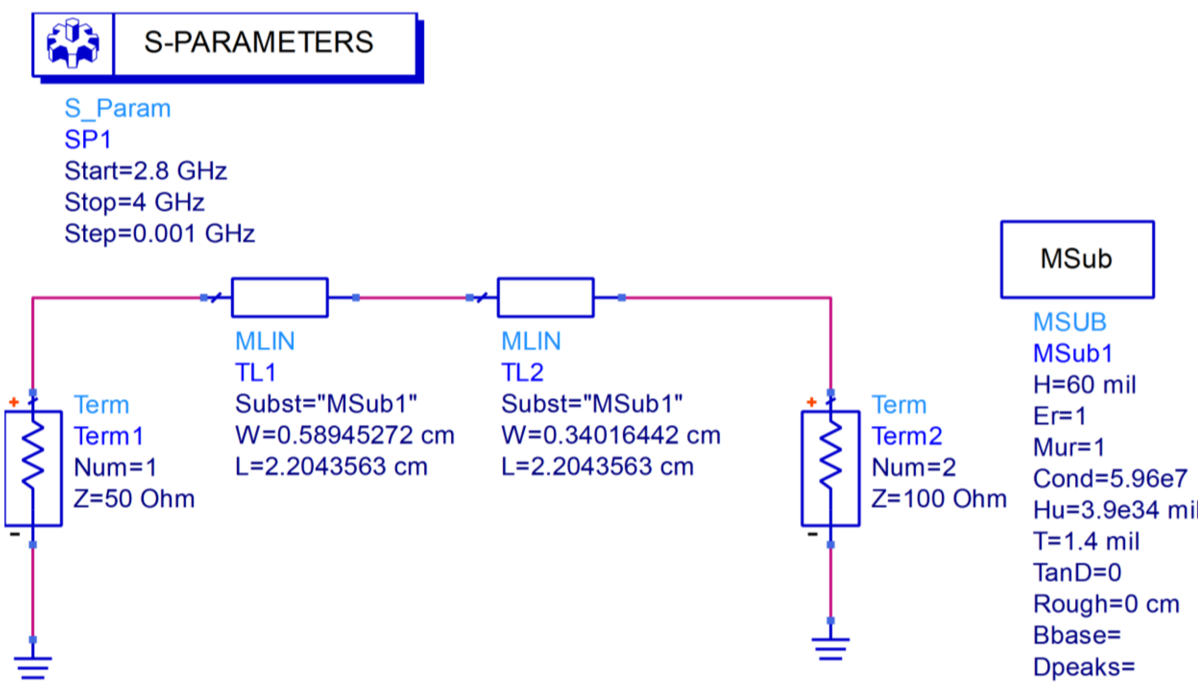


Fig A.4 N=2 Theoretical Air Microstrip ADS Schematic

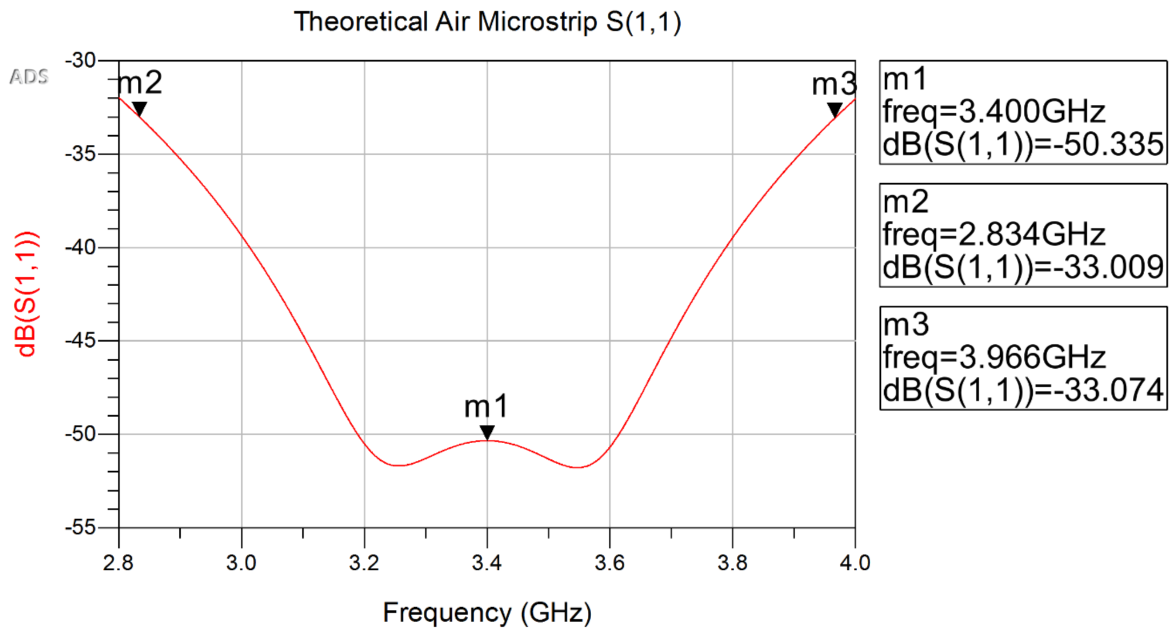


Fig A.5 N=2 Theoretical Air Microstrip S(1,1) showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$$RL = 50.335\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{50.335}{-20}} = 0.00304263$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+\ 0.00304263}{1-\ 0.00304263} \approx 1$$

$f = f_{FBW\ edge1} = 2.834\ GHz$

$$RL = 33.009\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{33.009}{-20}} = 0.02236402$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.02236402}{1-0.02236402} = 1.0457512 \leq 1.046$$

$f = f_{FBW\ edge2} = 3.966\ GHz$

$$RL = 33.074\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{33.074}{-20}} = 0.02219729$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.02219729}{1-0.02219729} = 1.0454023 \leq 1.046$$

Matched theoretical air microstrip and band edge VSWR meets specification.

Although the above results indicate that N=2 will meet the VSWR requirement in air, simulation using LineCalc derived parameters using $\varepsilon = 2.5$ will not met VSWRW requirements. See Appendix [A.1] for the simulation. Therefore, N=3 is chosen to be the selected number of sections.

For $N = 3$

$n = 0$

$$\ln\left(\frac{Z_{o1}}{Z_o}\right) = \left(\frac{1}{2}\right)^3 C_0{}^3 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{1}{8}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o1} = Z_o e^{\frac{1}{8}\ln(2)} = 50 * e^{\frac{1}{8}\ln(2)} = 54.525386\ \Omega$$

$$Z_{o1} = 54.525386 = \frac{120\pi}{\frac{W}{H} + 2.42 - 0.44\frac{H}{W} + \left(1 - \frac{H}{W}\right)^6}\ [1]$$

$$\rightarrow \frac{W}{H} = 4.383$$

$$\rightarrow W = 4.383H = 4.383 * 60\ mils = 262.98\ mils = 0.6679692\ cm$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10H}{W}\right)^{-1/2} = \frac{1+1}{2} + \frac{1-1}{2}\left(1 + \frac{10}{4.383}\right)^{-1/2} = 1$$

$$L = \frac{\lambda}{4} = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} = \frac{c}{4 * 3.4 * 10^9\sqrt{1}} = 2.2043563\ cm$$

$n = 1$

$$\ln\left(\frac{Z_{o2}}{Z_{o1}}\right) = \left(\frac{1}{2}\right)^3 C_1{}^3 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{3}{8}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o2} = Z_{o1} e^{\frac{3}{8}\ln(2)} = 54.525386 * e^{\frac{3}{8}\ln(2)} = 70.710677\ \Omega$$

$$Z_{o2} = 70.710677 = \frac{120\pi}{\frac{W}{H} + 2.42 - 0.44\frac{H}{W} + \left(1 - \frac{H}{W}\right)^6}\ [1]$$

$$\rightarrow \frac{W}{H} = 2.97391$$

$$\rightarrow W = 2.97391H = 2.97391 * 60\ mils = 178.4346\ mils = 0.45322388\ cm$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10H}{W}\right)^{-1/2} = \frac{1+1}{2} + \frac{1-1}{2}\left(1 + \frac{10}{2.97391}\right)^{-1/2} = 1$$

$$L = \frac{\lambda}{4} = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} = \frac{c}{4 * 3.4 * 10^9\sqrt{1}} = 2.2043563\ \ cm$$

$n = 2$

$$\ln\left(\frac{Z_{o3}}{Z_{o2}}\right) = \left(\frac{1}{2}\right)^3 C_2{}^3 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{3}{8}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o2} = Z_{o2}e^{\frac{3}{8}\ln(2)} = 70.710677 * e^{\frac{3}{8}\ln(2)} = 91.700402\ \Omega$$

$$Z_{o2} = 91.700402 \quad = \frac{120\pi}{\frac{W}{H} + 2.42 - 0.44\frac{H}{W} + \left(1 - \frac{H}{W}\right)^6} \quad [1]$$

$$\rightarrow \frac{W}{H} = 1.90982$$

$$\rightarrow W = 1.90982H = 1.90982 * 60\ mils = 114.5892\ mils = 0.29105656\ cm$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10H}{W}\right)^{-1/2} = \frac{1+1}{2} + \frac{1-1}{2}\left(1 + \frac{10}{1.90982}\right)^{-1/2} = 1$$

$$L = \frac{\lambda}{4} = \frac{c}{4f_0\sqrt{\varepsilon_{eff}}} = \frac{c}{4 * 3.4 * 10^9\sqrt{1}} = 2.2043563\ \ cm$$

N = 3

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
54.525386	1	0.6679692	2.2043563
70.710677	1	0.45322388	2.2043563
91.700402	1	0.29105656	2.2043563

Fig A.6 N=3 Theoretical Air Transmission Line and Microstrip Parameters

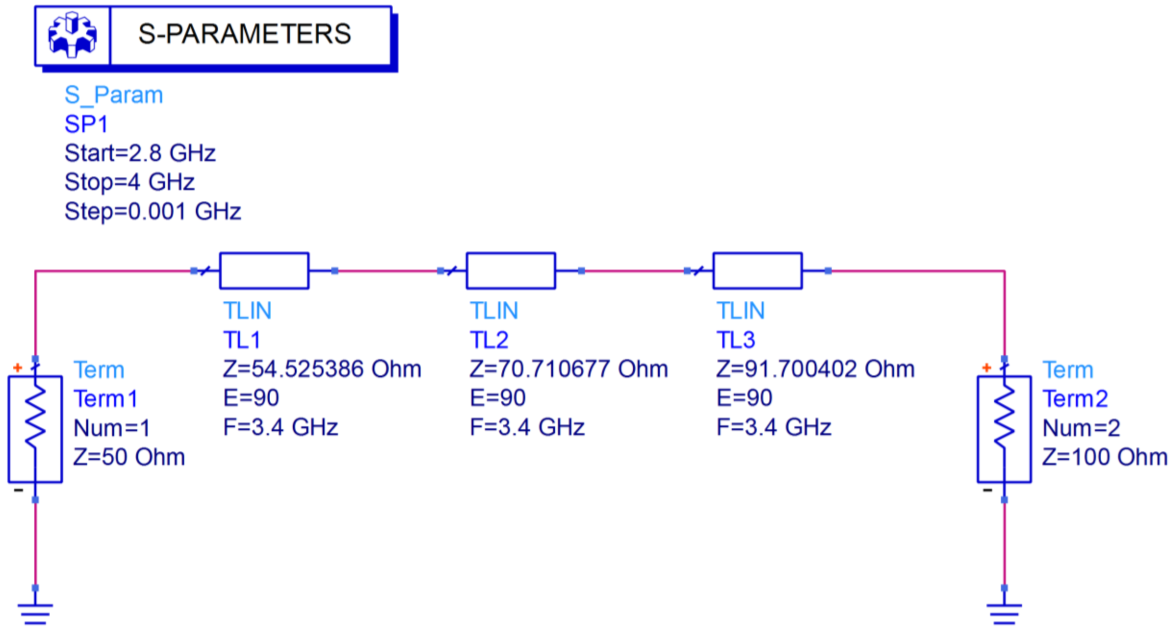


Fig A.7 N=3 Theoretical Air Transmission Line ADS Schematic

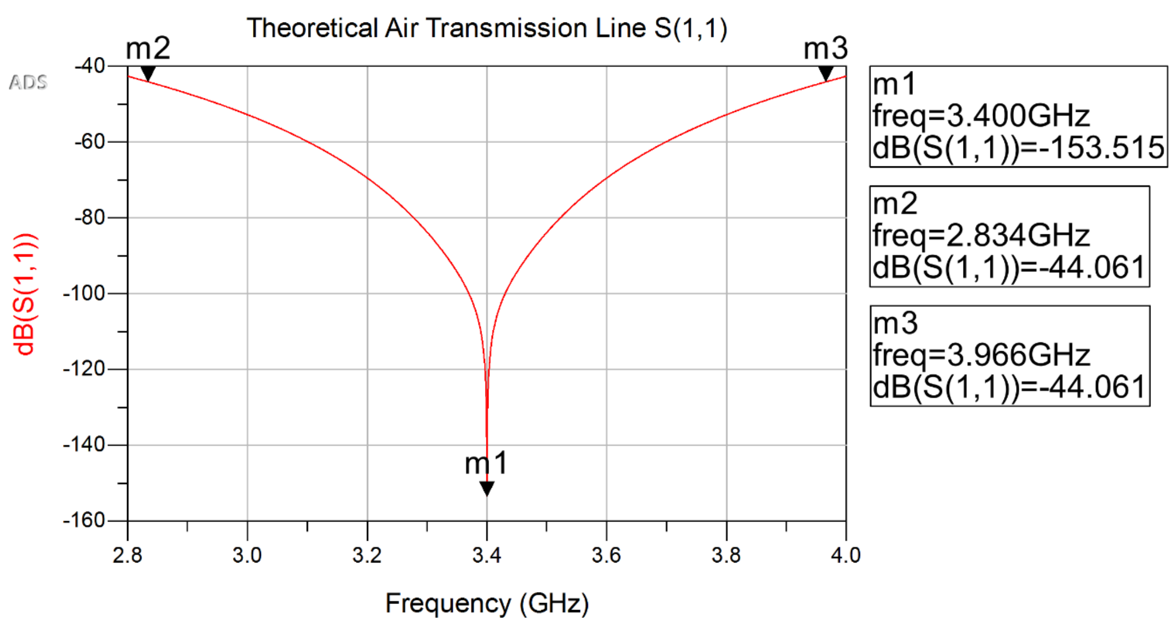


Fig A.8 N=3 Theoretical Air Transmission Line S(1,1) showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$$RL = 153.515\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{153.515}{-20}} = 2.1098423 * 10^{-8}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+2.1098423 * 10^{-8}}{1-2.1098423 * 10^{-8}} \approx 1$$

$$f = f_{FBW\ edge} = 2.834\ GHz = 3.966\ GHz$$

$$RL = 44.061\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{44.061}{-20}} = 0.00626541$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.00626541}{1-0.00626541} = 1.0012609 \ \leq 1.046$$

Matched theoretical air transmission line and band edge VSWR meets specification.

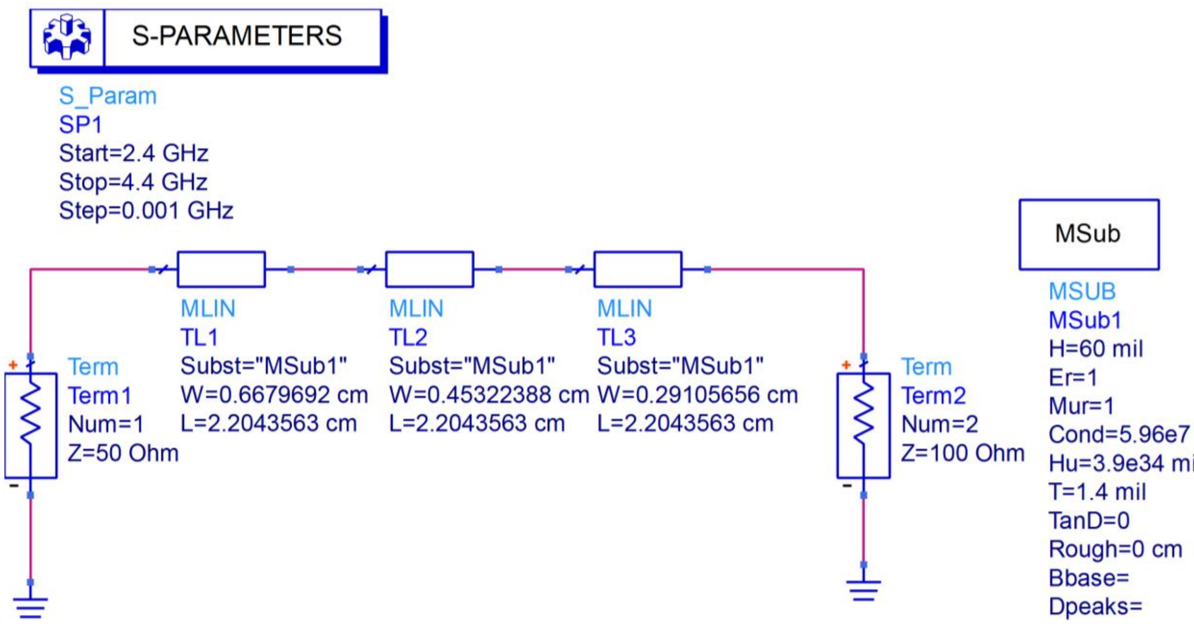


Fig A.9 N=3 Theoretical Air Microstrip ADS Schematic

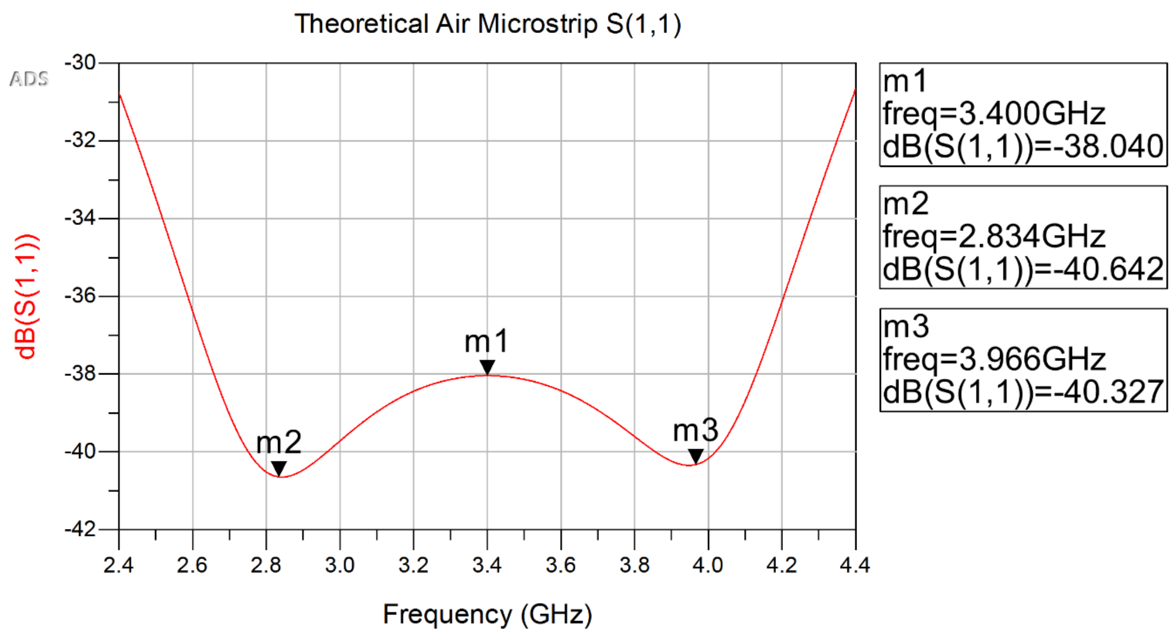


Fig A.10 N=3 Theoretical Air Microstrip S(1,1) showing markers at FBW edge and center frequency

$$f = f_0 = 3.4\ GHz$$

$$RL = 38.040\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{38.040}{-20}} = 0.0125314$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+\ 0.0125314}{1-\ 0.0125314} \approx 1$$

$$f = f_{FBW\ edge1} = 2.834\ GHz$$

$$RL = 40.642\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{40.642}{-20}} = 0.00928752$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.00928752}{1-0.00928752} = 1.0187491 \leq 1.046$$

$$f = f_{FBW\ edge2} = 3.966\ GHz$$

$$RL = 40.327\ dB$$

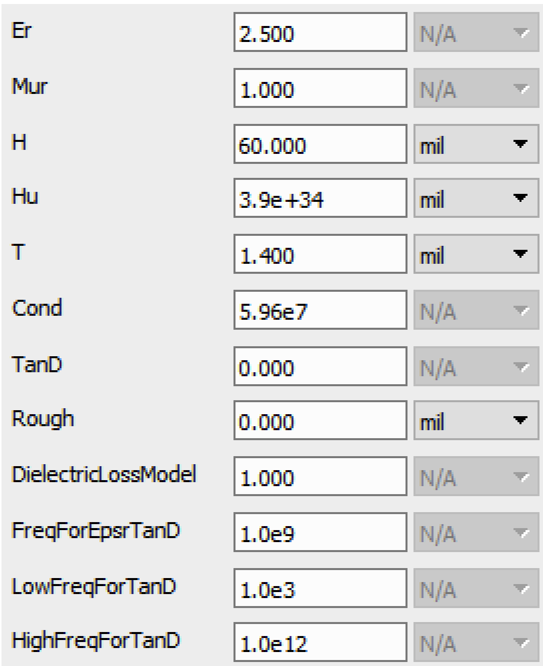
$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{40.327}{-20}} = 0.00963052$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+0.00963052}{1-0.00963052} = 1.0194483 \leq 1.046$$

Matched theoretical air microstrip and band edge VSWR meets specification.

B. Lossless Microstrip Model Parameters



Er	2.500	N/A
Mur	1.000	N/A
H	60.000	mil
Hu	3.9e+34	mil
T	1.400	mil
Cond	5.96e7	N/A
TanD	0.000	N/A
Rough	0.000	mil
DielectricLossModel	1.000	N/A
FreqForEpsrTanD	1.0e9	N/A
LowFreqForTanD	1.0e3	N/A
HighFreqForTanD	1.0e12	N/A

Fig B.1 Lossless Microstrip LineCalc Parameters

N = 3

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
54.525386	2.082	0.37406200	1.5276900
70.710677	2.018	0.23995700	1.5515200
91.700402	1.955	0.14224199	1.5764399

Fig B.2 N=3 Lossless Microstrip Parameters from LineCalc

C. Lossless Microstrip Model Simulation

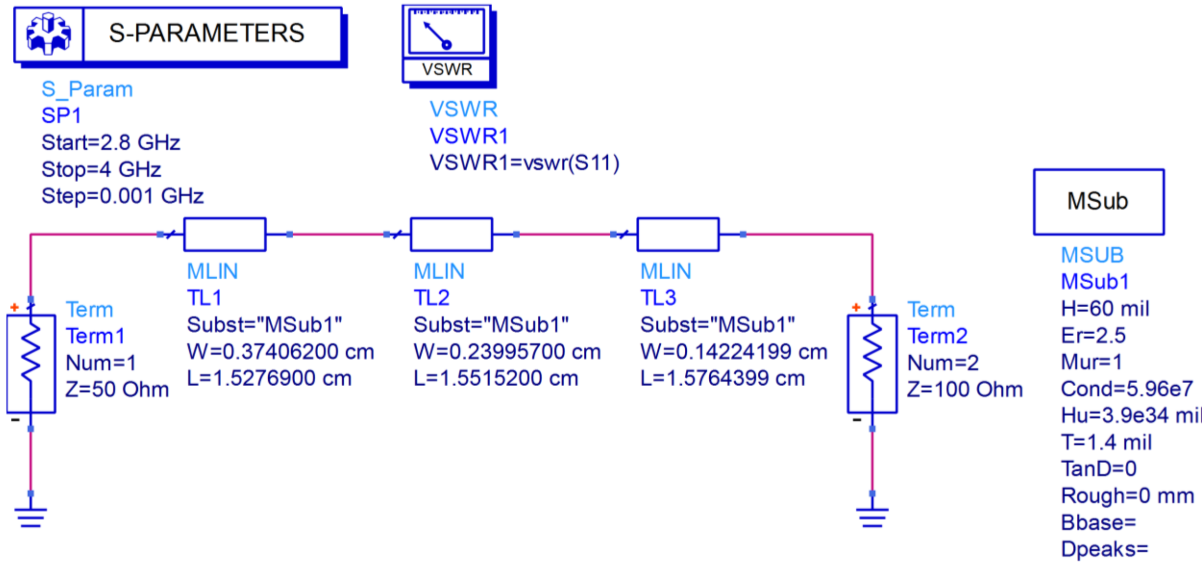


Fig C.1 Lossless Microstrip ADS Schematic

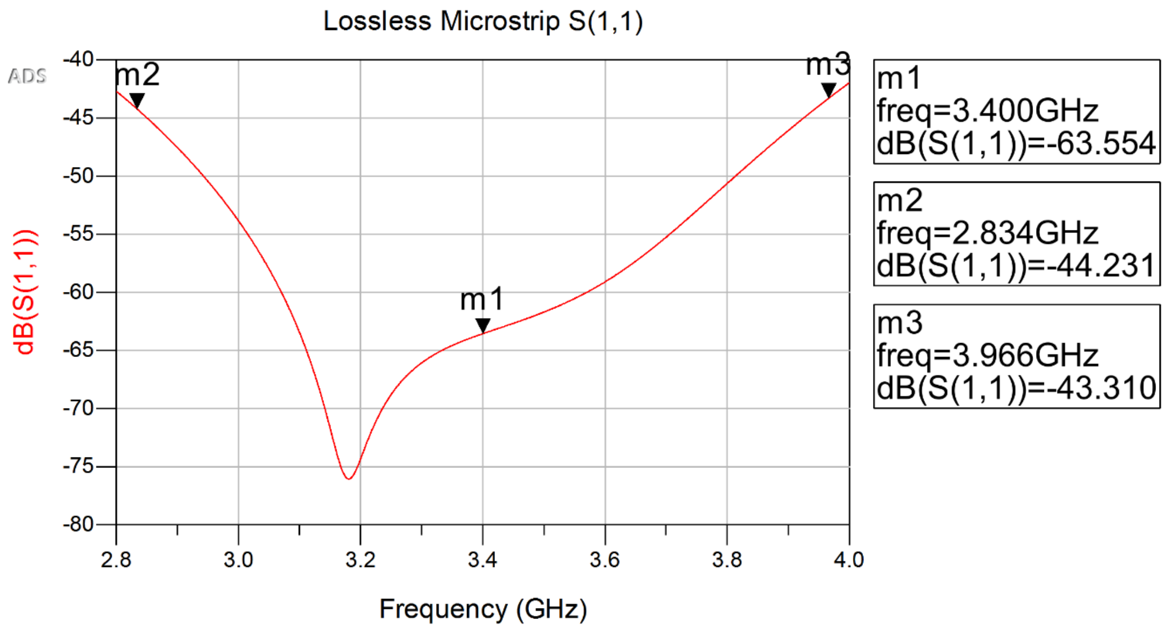


Fig C.2 Lossless Microstrip S(1,1) showing markers at FBW edge and center frequency

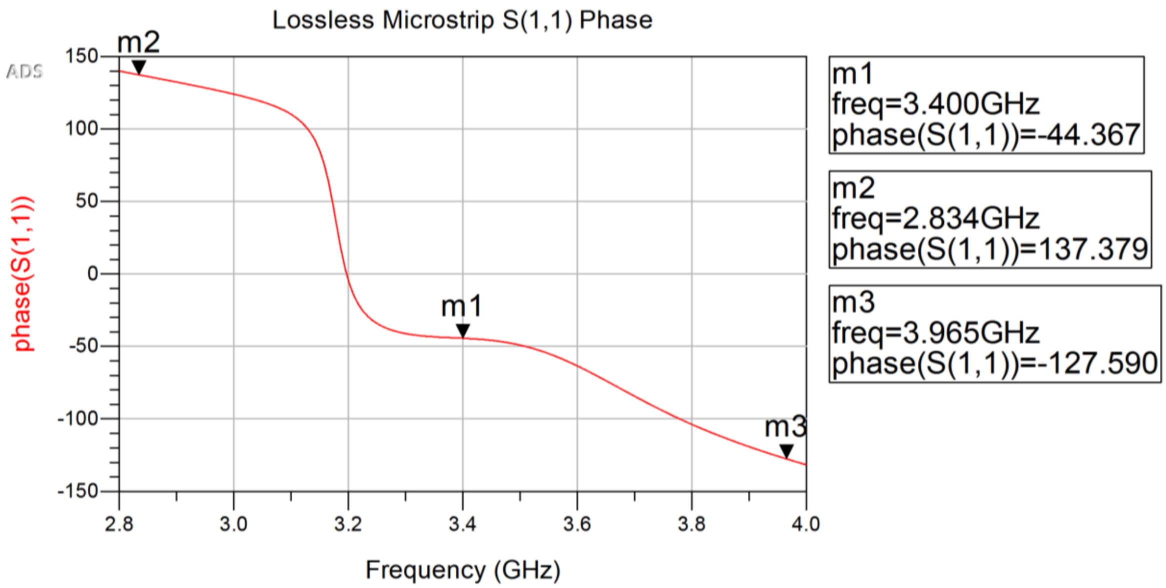


Fig C.3 Lossless Microstrip S(1,1) Phase showing markers at FBW edge and center frequency

$$f = f_0 = 3.4\ GHz$$

$$RL = 63.554\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{63.554}{-20}} = 6.6420172 * 10^{-4}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 6.6420172 * 10^{-4}}{1 - 6.6420172 * 10^{-4}} \approx 1$$

$$\angle\Gamma = -44.367°$$

$$f = f_{FBW\ edge1} = 2.834\ GHz$$

$$RL = 44.231\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{44.231}{-20}} = 0.00614398$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 0.00614398}{1 - 0.00614398} = 1.0123639\ \leq 1.046$$

$$\angle\Gamma = 137.379°$$

$$f = f_{FBW\ edge2} = 3.966\ GHz$$

$$RL = 43.310\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{43.310}{-20}} = 0.00683124$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 0.00683124}{1 - 0.00683124} = 1.0137564 \ \leq 1.046$$

$$\angle\Gamma = -127.590°$$

Matched lossless microstrip and band edge VSWR meets specification.

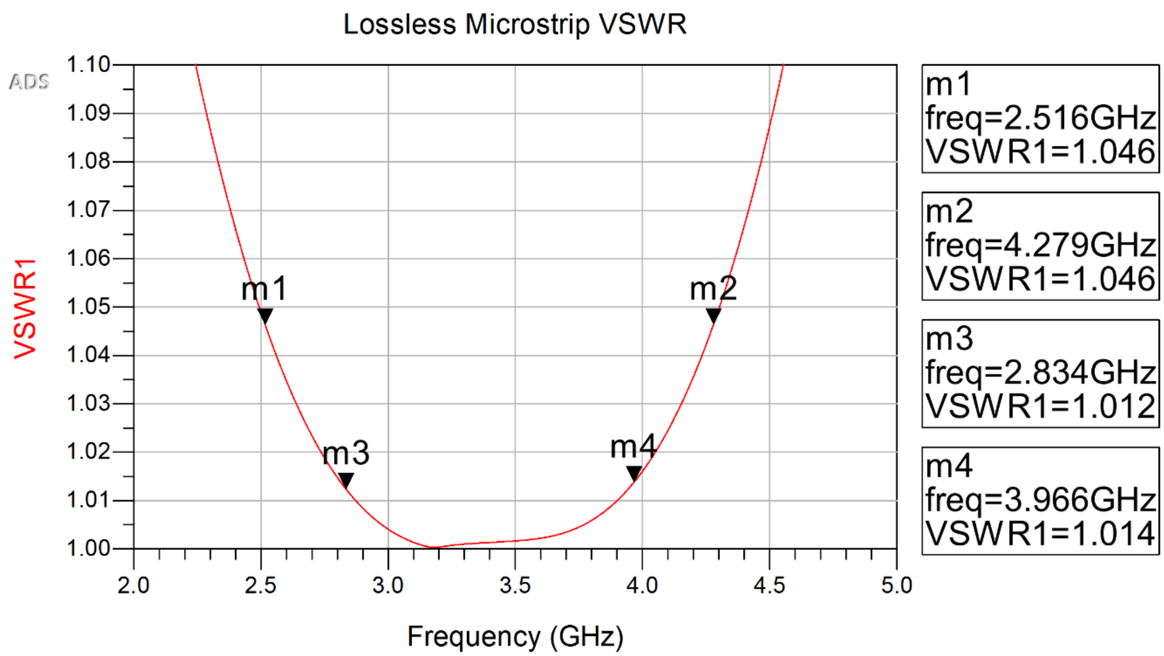


Fig C.4 Lossless Microstrip VSWR 1 to 1.1 Scale showing markers at BWs

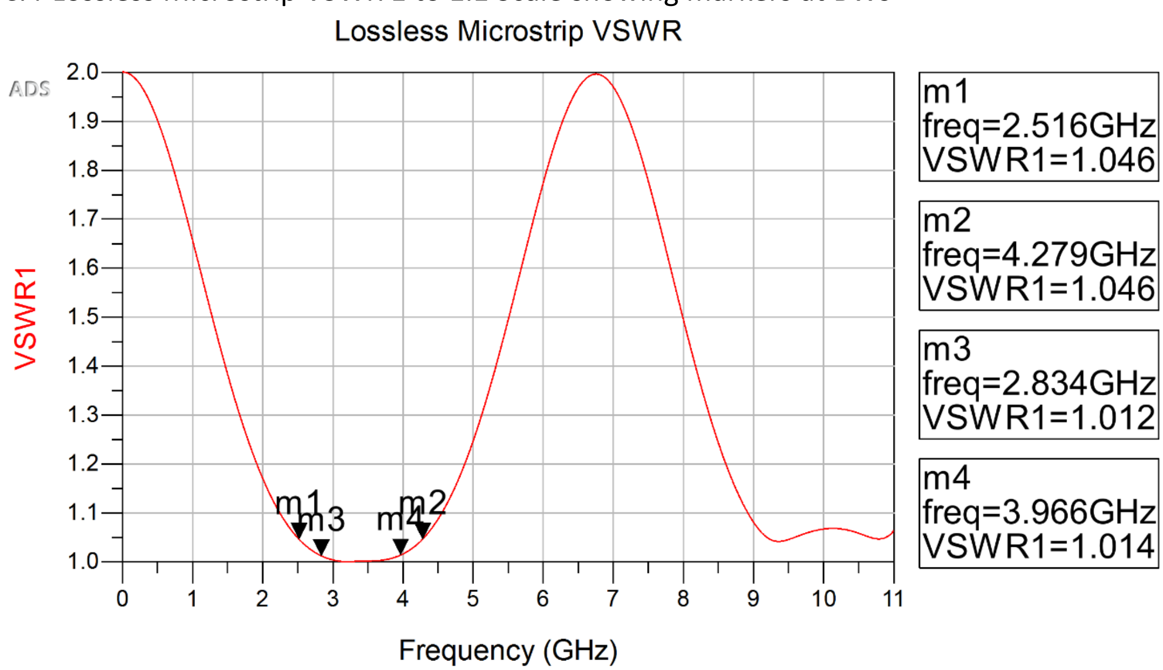


Fig C.5 Lossless Microstrip VSWR 1 to 2 Scale showing markers at BWs

A secondary resonance can be observed at around three times the center frequency point.

$BW_{prescribed} = m3 - m4 = 3.966 - 2.834 = 1.132\ GHz$

$BW_{computed} = m2 - m1 = 4.279 - 2.516 = 1.763\ GHz$

The computer bandwidth exceeds the prescribed bandwidth while meeting the VSWR band edge specifications.

D. Lossy Microstrip Model

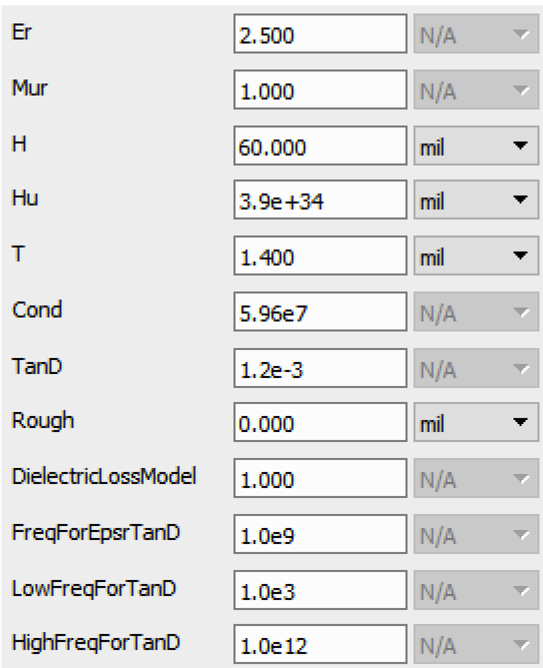


Fig D.1 Lossy Microstrip LineCalc Parameters $\delta = 0.0012$

N = 3

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
54.525386	2.080	0.37429799	1.5282699
70.710677	2.017	0.24012599	1.5520899
91.700402	1.953	0.14235899	1.5770100

Fig D.2 Lossy Microstrip Parameters $\delta = 0.0012$ from LineCalc

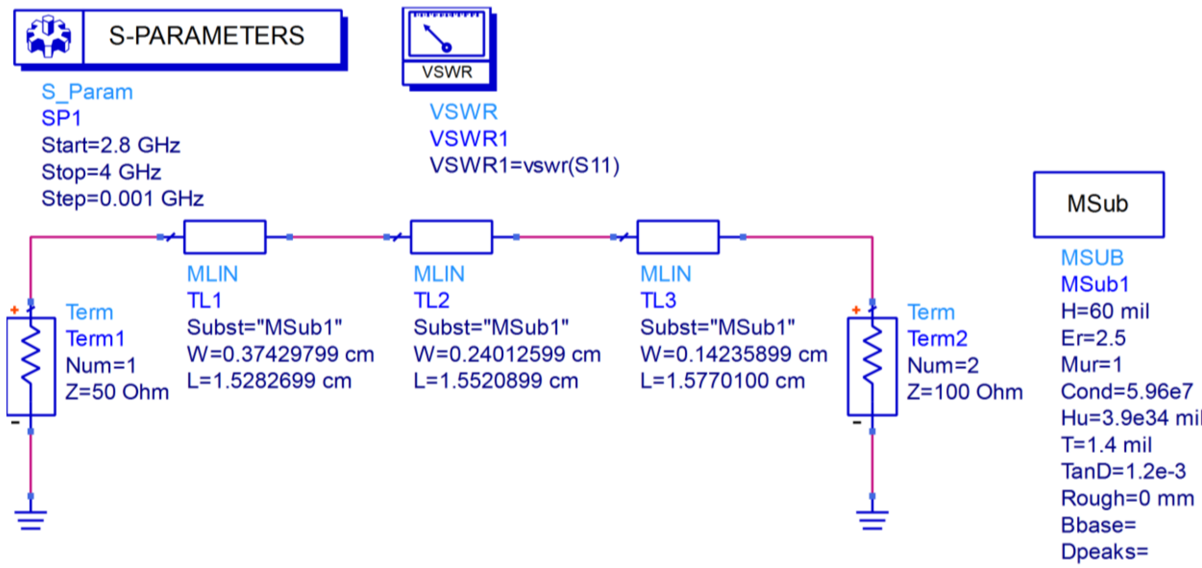


Fig D.3 Lossy Microstrip ADS Schematic

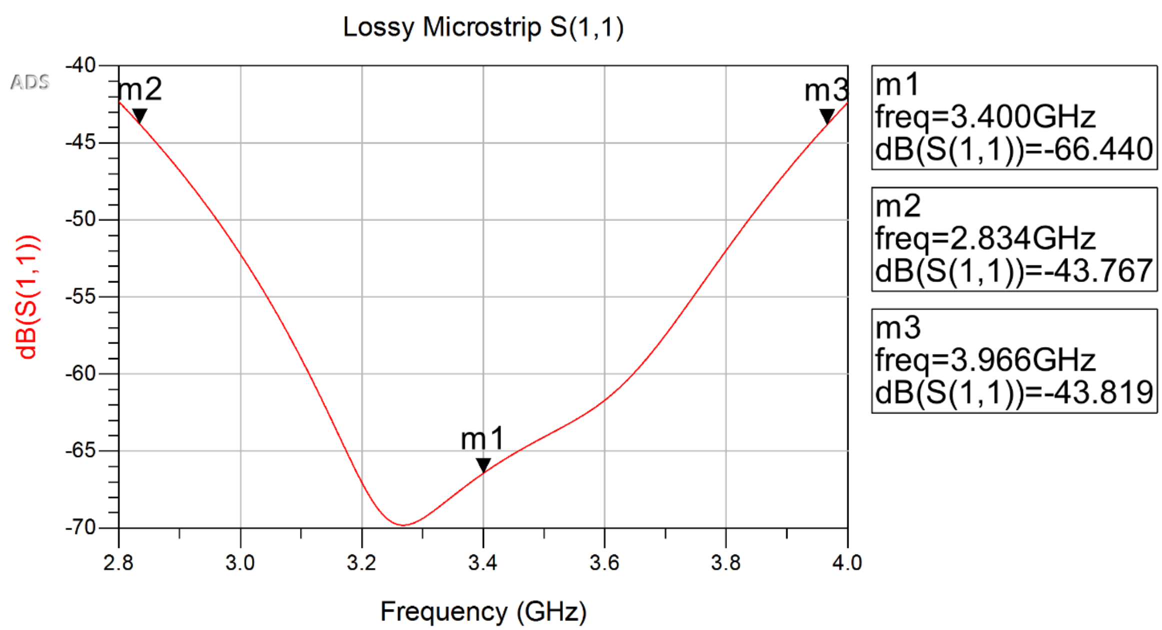


Fig D.4 Lossy Microstrip S(1,1) showing markers at FBW edge and center frequency

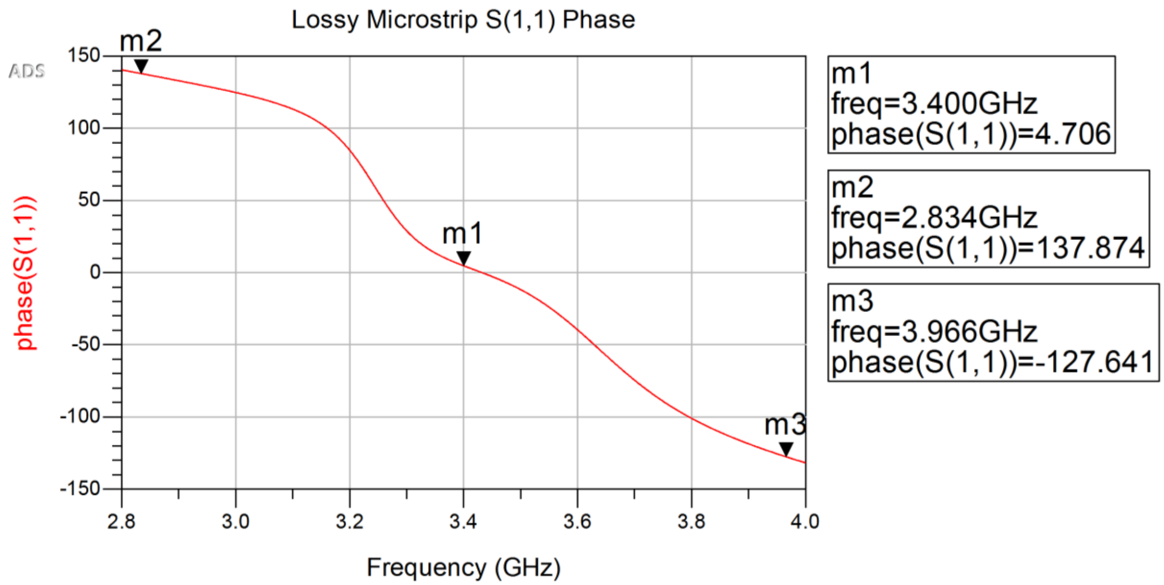


Fig D.5 Lossy Microstrip S(1,1) Phase showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$$RL = 66.440\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{66.440}{-20}} = 4.7643098 * 10^{-4}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 4.7643098 * 10^{-4}}{1 - 4.7643098 * 10^{-4}} \approx 1$$

$$\angle\Gamma = 4.706°$$

$f = f_{FBW\ edge1} = 2.834\ GHz$

$$RL = 43.767\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{43.767}{-20}} = 0.00648111$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+\ 0.00648111}{1-\ 0.00648111} = 1.0130467 \leq 1.046$$

$$\angle\Gamma = 137.874°$$

$f = f_{FBW\ edge2} = 3.966\ GHz$

$$RL = 43.819\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{43.819}{-20}} = 0.00644243$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+ \ 0.00644243}{1- \ 0.00644243} = 1.0133619 \ \leq 1.046$$

$$\angle\Gamma = -127.641°$$

Matched lossy microstrip and band edge VSWR meets specification.

It can be observed that adding dielectric loss using non-zero loss tangent shifts the S11 magnitude and phase responses from the lossless case. The shifts are a result of the microstrip characteristic impedance becoming complex due to the addition of the loss component.

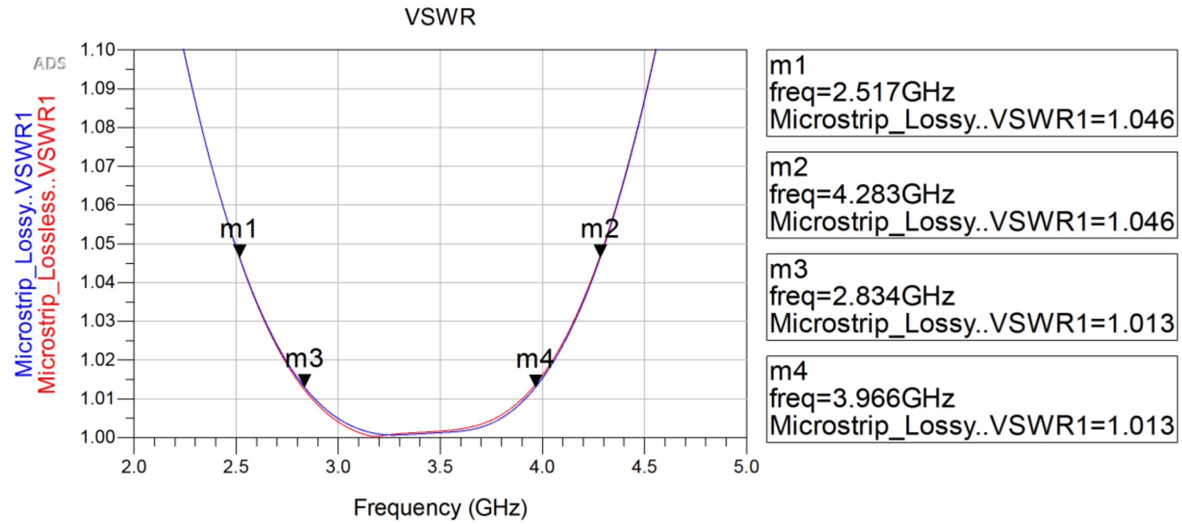


Fig D.6 Lossy and Lossless Microstrip VSWR 1 to 1.1 Scale showing markers at BWs

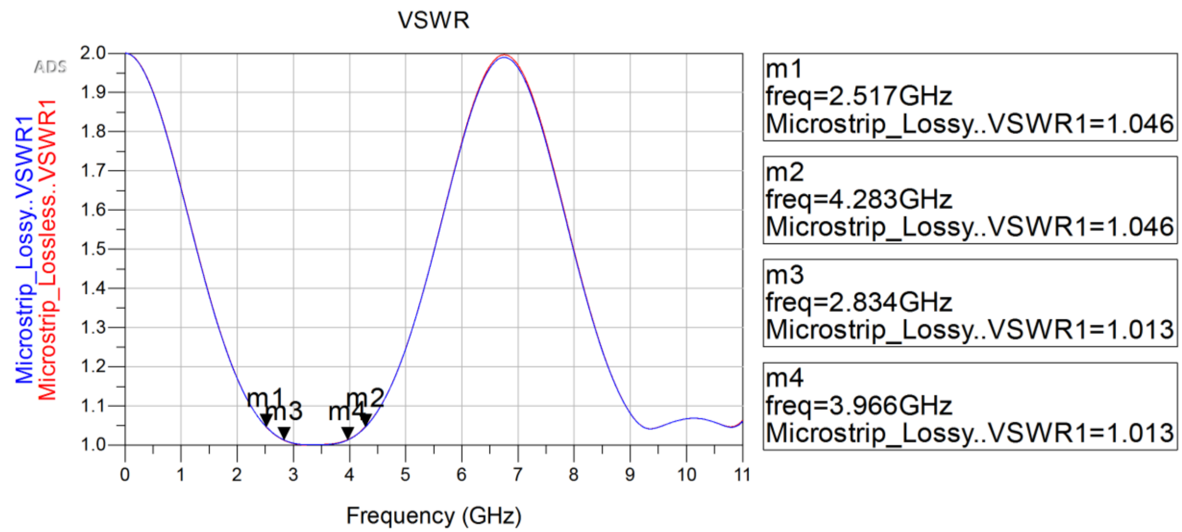


Fig D.7 Lossy and Lossless Microstrip VSWR 1 to 2 Scale showing markers at BWs

$$BW_{computed} = m2 - m1 = 4.283 - 2.517 = 1.766 \ GHz$$

The lossy and lossless VSWR curves are very similar in shape and value. One small difference is the computed bandwidth for the lossy microstrip being slightly larger than the computed bandwidth for the lossless microstrip by 0.03 GHz. The increased bandwidth may be attributed to a reduced Q factor from the addition of the dielectric loss.

E. Back-to-Back Microstrip Model

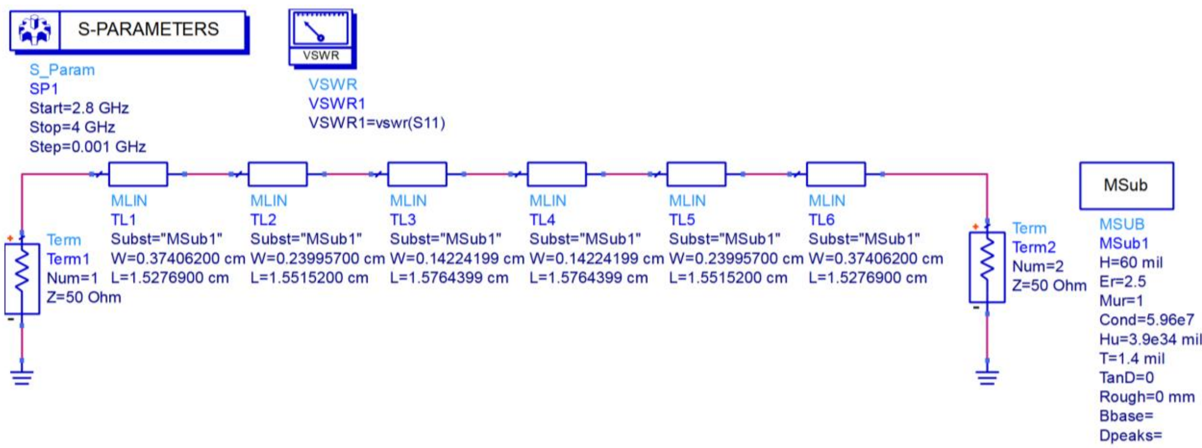


Fig E.1 Back-to-Back Microstrip ADS Schematic

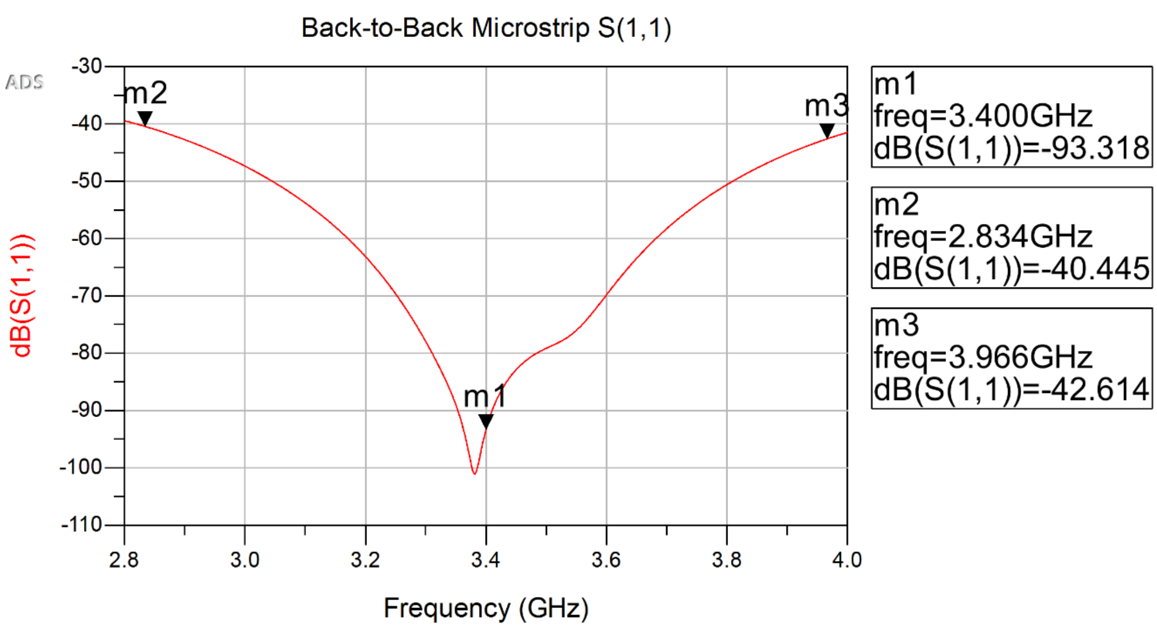


Fig E.2 Back-to-Back Microstrip S(1,1) showing markers at FBW edge and center frequency

$$f = f_0 = 3.4\ GHz$$

$$RL = 93.318\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{93.318}{-20}} = 2.1582413 * 10^{-5}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 2.1582413 * 10^{-5}}{1 - 2.1582413 * 10^{-5}} \approx 1$$

$$f = f_{FBW\ edge1} = 2.834\ GHz$$

$$RL = 40.445\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{40.445}{-20}} = 0.00950057$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 +\ 0.00950057}{1 -\ 0.00950057} = 1.0191833 \leq 1.046$$

$$f = f_{FBW\ edge2} = 3.966\ GHz$$

$$RL = 42.614\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{42.614}{-20}} = 0.00740116$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 +\ 0.00740116}{1 -\ 0.00740116} = 1.0149126 \leq 1.046$$

Matched back-to-back microstrip and band edge VSWR meets specification.

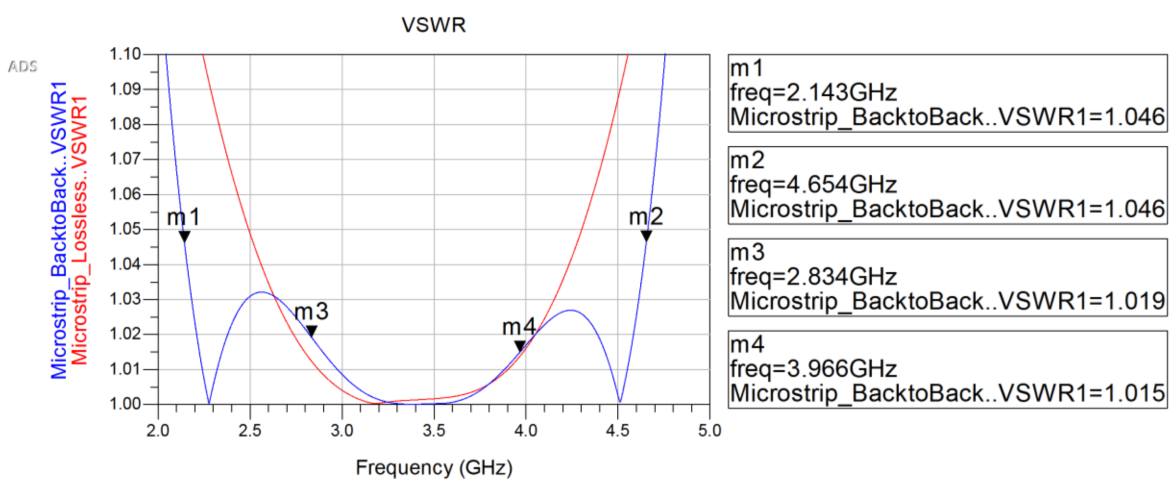


Fig E.3 Lossless and Back-to-Back Microstrip VSWR 1 to 1.1 Scale showing markers at BWs

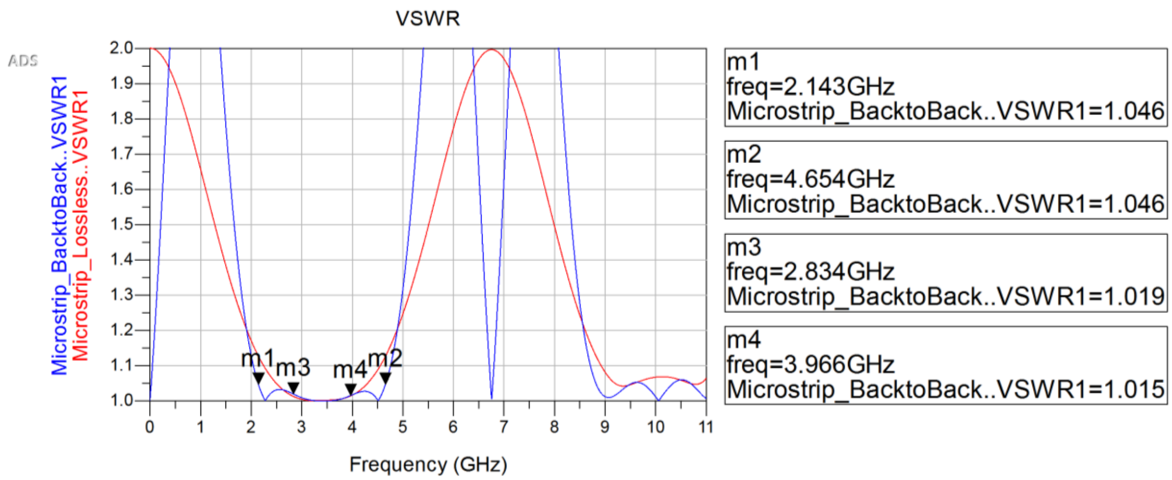


Fig E.4 Lossless and Back-to-Back Microstrip VSWR 1 to 2 Scale showing markers at BWs

$BW_{computed} = m2 - m1 = 4.654 - 2.143 = 2.511\ GHz$

The back-to-back microstrip has a wider bandwidth as well as an increased number of resonant frequencies that reflects the increased number of microstrip sections. The back-to-back construction provides equal 50 Ω terminations on both ends of the circuit which is helpful when characterizing the circuit with a network analyzer. Therefore, it is preferable to manufacture the back-to-back version for measurement purpose.

F. Single Section Microstrip Model

For $N = 1$

$n = 0$

$$\ln\left(\frac{Z_{o1}}{Z_o}\right) = \frac{1}{2} C_0{}^1 \ln\left(\frac{Z_L}{Z_o}\right) = \frac{1}{2}\ln\left(\frac{100}{50}\right)$$

$$\rightarrow Z_{o1} = Z_o e^{\frac{1}{2}\ln(2)} = 50 * e^{\frac{1}{2}\ln(2)} = 70.710678\ \Omega$$

N = 1

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
70.710678	2.018	0.23995700	1.5515200

Fig F.1 Single Section Microstrip Parameters from LineCalc

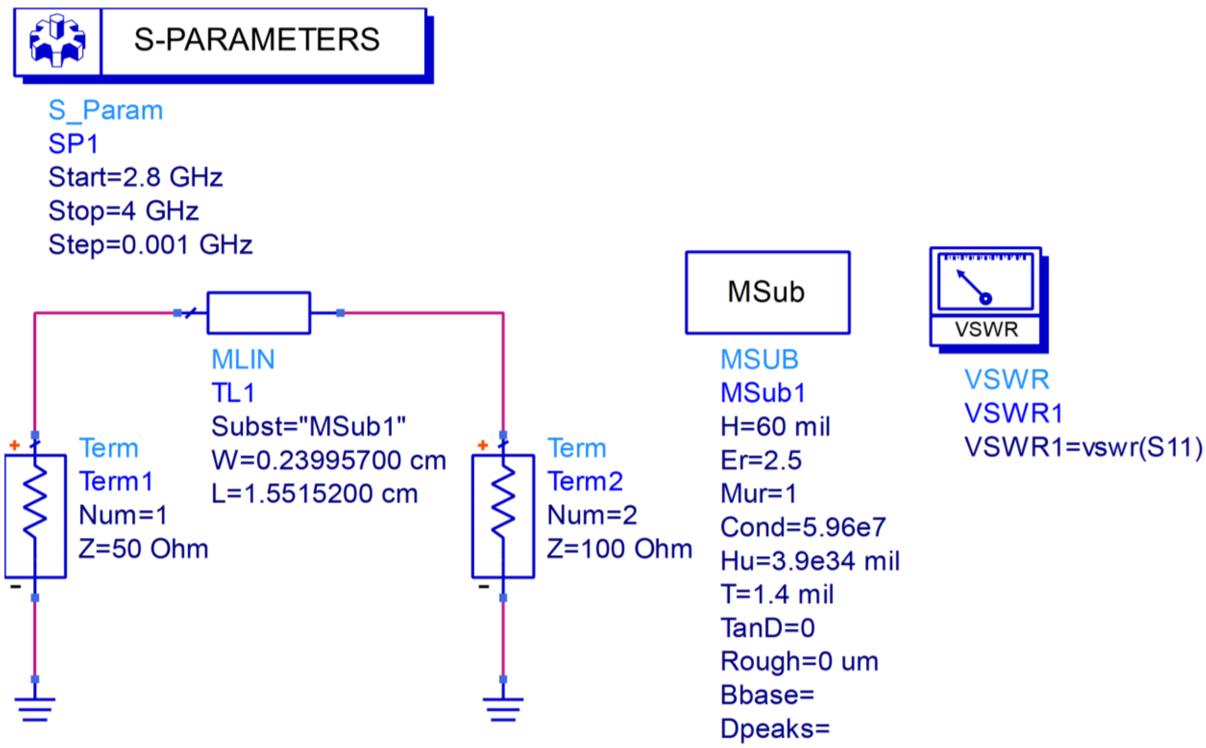


Fig F.2 Single Section Microstrip ADS Schematic

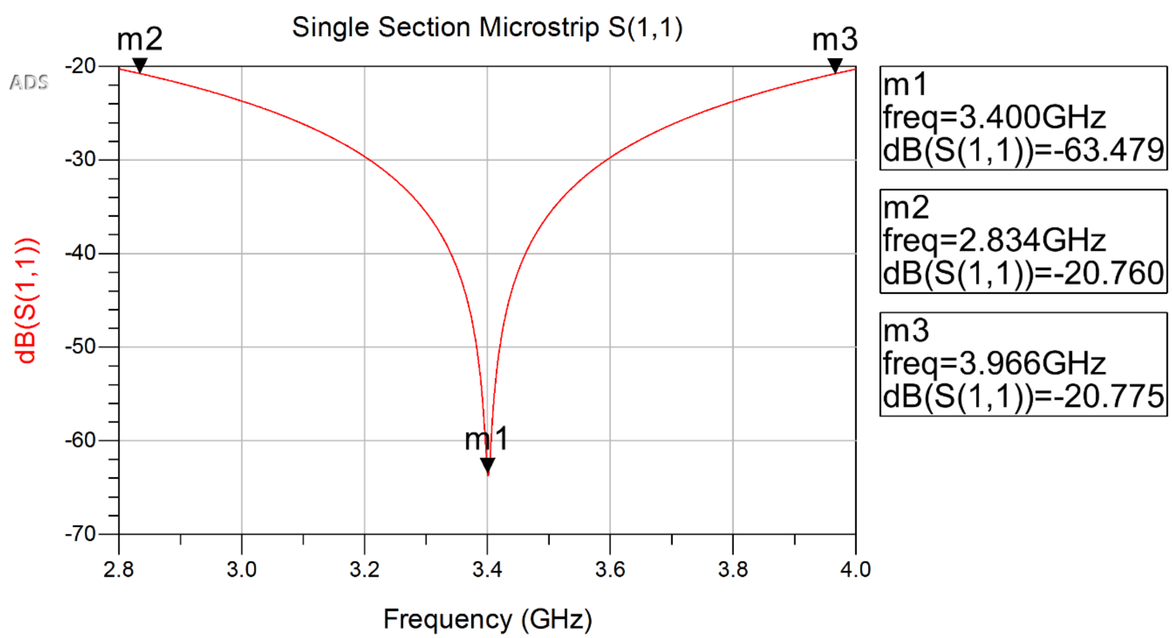


Fig F.4 Single Section Microstrip S(1,1) showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$$RL = 63.479\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{63.479}{-20}} = 6.6996173 * 10^{-4}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 6.6996173 * 10^{-4}}{1 - 6.6996173 * 10^{-4}} \approx 1$$

$$f = f_{FBW\ edge1} = 2.834\ GHz$$

$$RL = 20.760\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{20.760}{-20}} = 0.09162204$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 0.09162204}{1 - 0.09162204} = 1.2017266 \nleq 1.046$$

$$f = f_{FBW\ edge2} = 3.966\ GHz$$

$$RL = 20.775\ dB$$

$$RL = -20 \log_{10} \rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{20.775}{-20}} = 0.09146395$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 0.09146395}{1 - 0.09146395} = 1.2013435\ \nleq 1.046$$

Matched single section microstrip but band edge VSWR does not meet specification as expected.

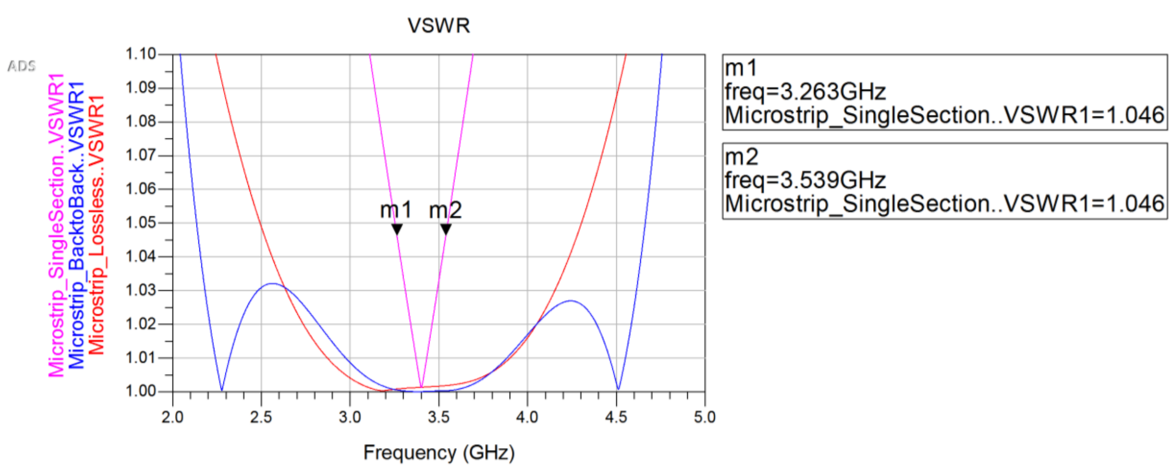


Fig F.5 Lossless, Single Section, and Back-to-Back Microstrip VSWR 1 to 1.1 Scale showing marker at Computed BW

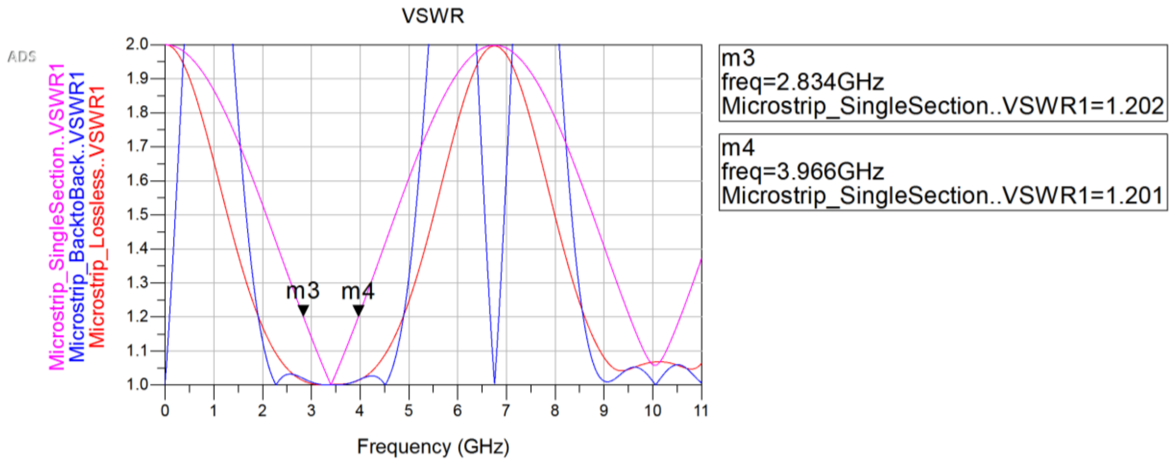


Fig F.6 Lossless, Single Section, and Back-to-Back Microstrip VSWR 1 to 2 Scale showing marker at Prescribed BW

$$BW_{computed} = m2 - m1 = 3.539 - 3.263 = 0.276\ GHz$$

The single section microstrip has a very narrow bandwidth as well as a decreased density of resonating frequencies.

G. Transformer Bandwidth, VSWR, and Return Loss

Transformer	$BW_{computed}\ (GHz)$	$FBW_{computed}\ (\%)$	VSWR	RL (dB)
Single Section	0.276	8. 1176470	1.2015350	20.767499
Lossless	1.763	51.852941	1.0130601	43.770499
Lossy	1.766	51.941176	1.0132043	43.793000
Back-to-Back	2.511	73.852941	1.0170479	41.529499

Fig G.1 Bandwidth, VSWR, and Return Loss at band edge of different transformers. VSWR and RL is averaged for each transformer's respective two band edges. From lowest to highest BW.

Recall,

$$\rho_m = \frac{VSWR_m - 1}{VSWR_m + 1} = \frac{1.046 - 1}{1.046 + 1} = 0.02248289$$

$$\theta_m = \cos^{-1}\left[\left|\frac{\rho_m}{\frac{Z_L - Z_o}{Z_L + Z_o}}\right|^{\frac{1}{N}}\right] = \cos^{-1}\left[\left|\frac{0.02248289}{\frac{100-50}{100+50}}\right|^{\frac{1}{N}}\right] = \cos^{-1}\left[|0.06744867|^{\frac{1}{N}}\right]$$

$$FBW = \frac{\Delta f}{f_0} = 2\left(1 - \frac{2}{\pi}\theta_m\right)$$

$$FBW_{N=3} = 2\left(1 - \frac{2}{\pi}\cos^{-1}\left[|0.06744867|^{\frac{1}{3}}\right]\right) = 53.378321\%$$

$$FBW_{N=3}\ \%\ Error = \frac{|51.852941 - 53.378321|}{53.378321} * 100\% = 2.8576769\%$$

$$FBW_{N=1} = 2\left(1 - \frac{2}{\pi}\cos^{-1}[|0.06744867|]\right) = 8.5943562\%$$

$$FBW_{N=1}\ \%\ Error = \frac{|8.1176470 - 8.5943562|}{8.5943562} * 100\% = 5.5467703\%$$

The simulated lossless and single section microstrips in ADS differ from the theoretical calculations by 2.8576769% and 5.5467703% respectively. The errors are respectable and verify the accuracy of the ADS simulations.

Appendix

[A.1] N=2 Lossless Microstrip Test Simulation

Er	2.500	N/A
Mur	1.000	N/A
H	60.000	mil
Hu	3.9e+34	mil
T	1.400	mil
Cond	5.96e7	N/A
TanD	0.000	N/A
Rough	0.000	mil
DielectricLossModel	1.000	N/A
FreqForEpsrTanD	1.0e9	N/A
LowFreqForTanD	1.0e3	N/A
HighFreqForTanD	1.0e12	N/A

Fig A.1.1 Lossless Microstrip LineCalc Parameters

N=2

Impedance (Ω)	ε_{eff}	Width (cm)	Length (cm)
59.460355	2.061	0.32478600	1.5354599
84.089640	1.976	0.17126100	1.5680900

Fig A.1.2 N=2 Lossless Microstrip Parameters from LineCalc

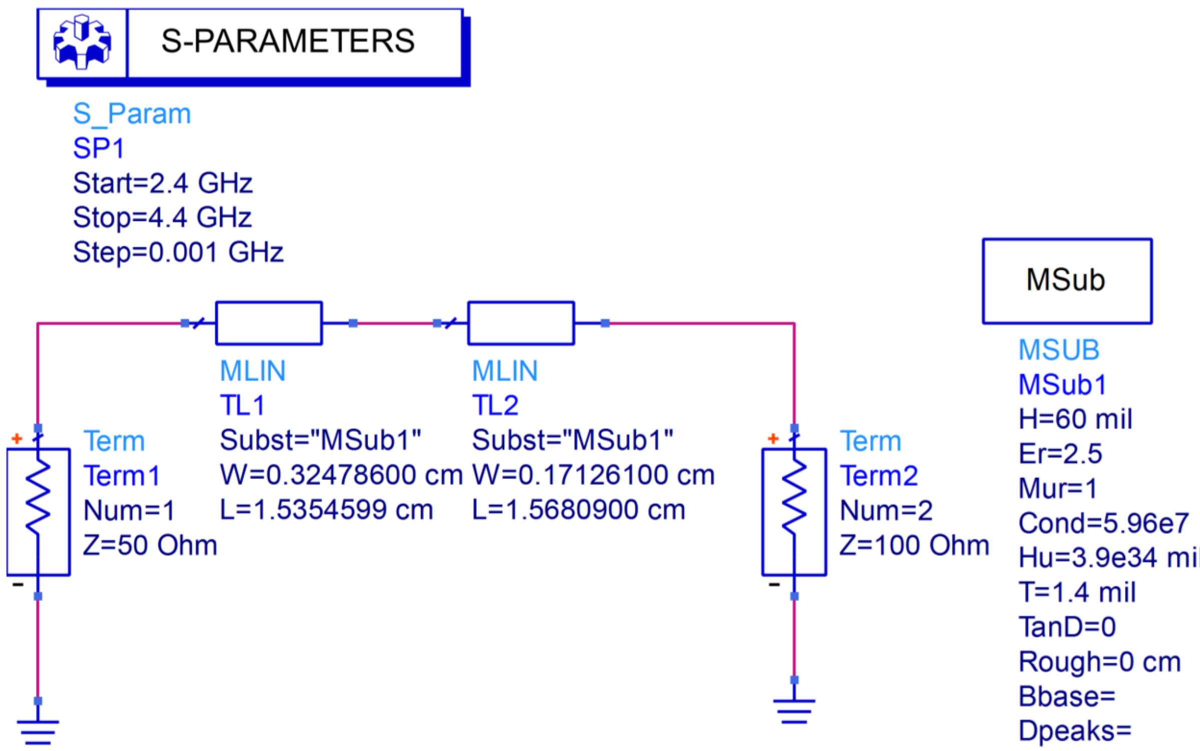


Fig A.1.3 N=2 Lossless Microstrip ADS Schematic

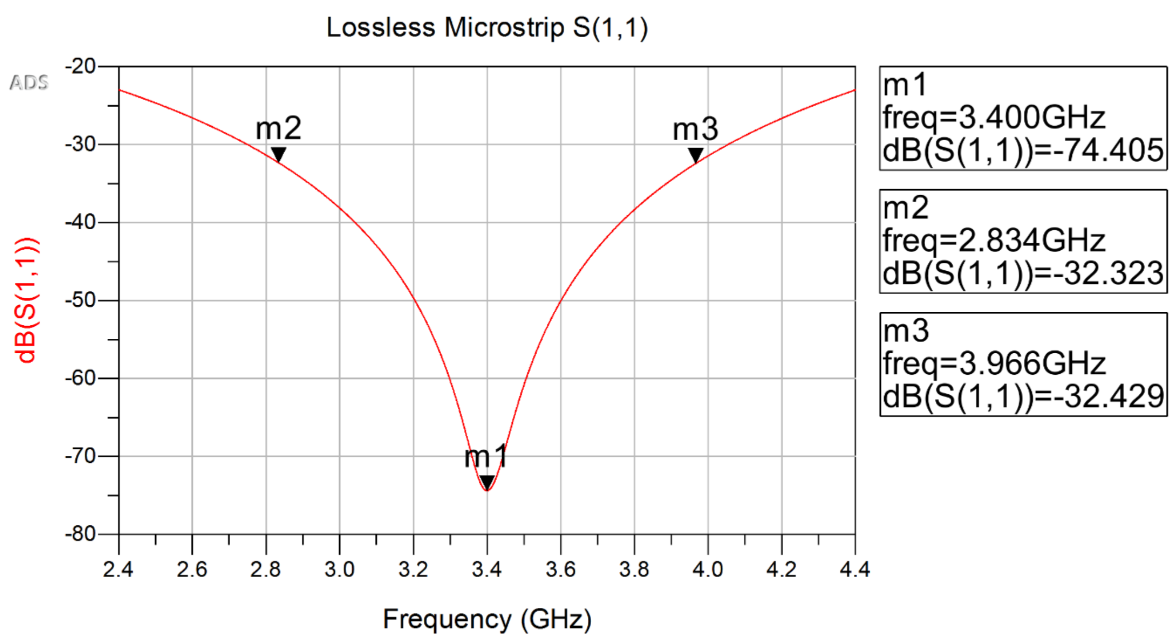


Fig A.1.4 N=2 Lossless Microstrip S(1,1) showing markers at FBW edge and center frequency

$f = f_0 = 3.4\ GHz$

$RL = 74.405\ dB$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{74.405}{-20}} = 1.9043641 * 10^{-4}$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1 + 1.9043641 * 10^{-4}}{1 - 1.9043641 * 10^{-4}} \approx 1$$

$$f = f_{FBW\ edge1} = 2.834\ GHz$$

$$RL = 32.323\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{32.323}{-20}} = 0.02420192$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+\ 0.02420192}{1-\ 0.02420192} = 1.0496043 \nleq 1.046$$

$$f = f_{FBW\ edge2} = 3.966\ GHz$$

$$RL = 32.429\ dB$$

$$RL = -20\log_{10}\rho$$

$$\rightarrow \rho = 10^{\frac{RL}{20}} = 10^{\frac{32.429}{-20}} = \ 0.02390837$$

$$VSWR = \frac{1+\rho}{1-\rho} = \frac{1+\ \ 0.02390837}{1-\ \ 0.02390837} = 1.0489879 \nleq 1.046$$

VSWR specifications not met.

References

[1] BSTJ 48: 5. May-June 1969: Microstrip Lines for Microwave Integrated Circuits "microstrip_lines.pdf" pg. 1430