ECEN 452-500: Ultra High Frequency Techniques
Spring 2016 – Prof. Huff
Lab 6

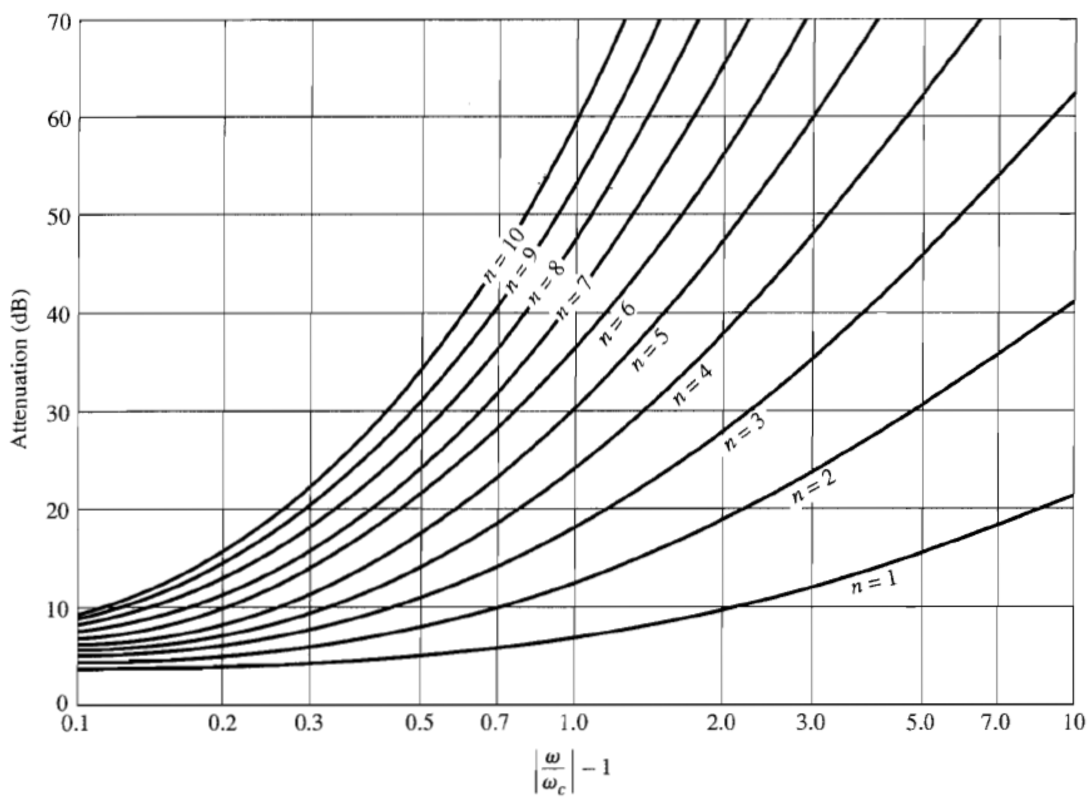
Pull the *Lab 6* subdirectory in the ECEN 452 GitHub directory *Labs* and locate the HFSS project files "*ECEN452_Lab6_Filters.hfss*". Open each project file (File-Open…), then save them to the local drive of the computer you are running your simulations on and rename it by appending your team number to each file (e.g., "ECEN452_LabX_TopicY_TeamZ").

In this lab you will be completing two designs of a low pass filter and the design of a band stop. These are found in your "*ECEN452_Lab6_Filters_GroupX.hfss*" project file. These design files are named "*N5_MaxFlat_LPF_T-Line*", "*N5_MaxFlat_LPF_T-Line_Tapped*", and "*N5_MaxFlat_BSF_T-Line*". You will be designing these for a Z_0 = 50 Ω reference impedance on the 62 mil thick FR4 (ε_r = 4.1, $\tan\delta$ = 0.01) substrate.

Task 1: Synthesis and implementation of a maximally-flat low-pass filter.

In this exercise you will synthesize a maximally-flat low-pass filter with a cut-off frequency f_c = 2.5 GHz and a minimum attenuation of 10 dB at 3.25 GHz.

Step 1: First, calculate the order *N* of the filter required to meet the specifications of providing 10 dB isolation at 3.25 GHz using $\left|\omega/\omega_c\right| - 1 = \left|f_{10dB}/f_c\right| - 1$ and the figure below.

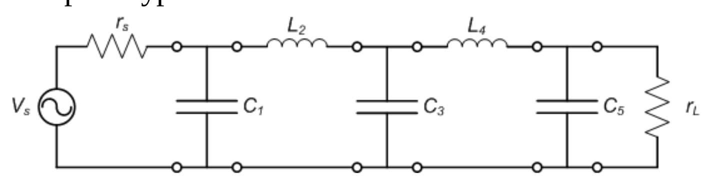


Step 2: Next, use the table on the following page to determine the filter coefficients for the (hint: five-element) low-pass prototype.

Element Values for Butterworth (Maximally Flat) Low-Pass Filter Prototypes
(g_o=1,w_c=1,N=1 to 10)

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0000	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	1.0000

Step 3: Assemble the prototype LC ladder network.



To simplify the analysis (visually), we will replace this ladder network will the table shown below.

Shunt	Series	Shunt	Series	Shunt
C	L	C	L	C
g1	g2	g3	g4	g5
0.61803	1.61803	2.00000	1.61803	0.61803

Step 4: Use Richard's Transformation to convert the capacitors into open circuit stubs and the inductors into short circuit stubs.

Shunt	Series	Shunt	Series	Shunt
OC	SC	OC	SC	OC
z1=1/g1	z2=g2	z3=1/g3	z4=g4	z5=1/g5
1.61804	1.61803	0.50000	1.61803	1.61804

Step 5: Use Kuroda's identities to convert series stubs to shunt stubs. This is a multi-step process, but the filter coefficients are symmetric in so we only need to transform one side of the filter and then capitalize on the symmetry. This will begin at the load and/or source side and work to the center of the filter (note: the center element is a shunt open-circuit stub, so it will remain untouched in this process).

Step 5.1 Insert unit elements source and load sides of the circuit to separate z1 from z2 and z5 from z4.

Unit	Shunt	Series	Shunt	Series	Shunt	Unit
Element	OC	SC	OC	SC	OC	Element
ue1	z1	z2	z3	z4	z5	ue2
1.00000	1.61804	1.61803	0.50000	1.61803	1.61804	1.00000

N1=1+ue1/z1	N2=1+ue2/Z5
N1=2.61304	N2=2.61304

Series	Unit	Series	Shunt	Series	Unit	Series
SC	Element	SC	OC	SC	Element	SC
z1'	ue1'	z2	z3	z4	ue2'	z5'
ue1/N1	z1/N1	1.61803	0.50000	1.61803	z5/N1	ue2/N1

Step 5.2 Insert two more unit element source and load sides of the circuit. This will separate z2 from z3 and z4 from z3, then separate z4 from z5 and z1 from z2. This process will also convert z1, z2, z4, and z5 into shunt OC stubs.

Unit Element ue3 1.00000	Series SC z1' 0.38194	Unit Element ue1' 0.61803	Series SC z2 1.61803	Shunt OC z3 0.50000	Series SC z4 1.61803	Unit Element ue2' 0.61803	Series SC z5' 0.38194	Unit Element ue4 1.00000
N3=1+z1'/ue3 N3=3.61804		N5=1+z2/ue1' N5=1.38197			N6=1+z4/ue2' N6=1.38197		N4=1+z5'/ue4 N4=3.61804	
Shunt OC z1'' ue3*N3	Unit Element ue3' z1'*N3	Shunt OC z2' ue1'*N5	Unit Element ue1'' z2*N5	Shunt OC z3 0.50000	Unit Element ue2'' z4*N5	Shunt OC z4' ue2'*N6	Unit Element ue4' z5'*N3	Shunt OC z5'' ue4*N4

Step 5.3 Perform impedance scaling for the transmission line.

Shunt OC z1'' 3.61804	Unit Element ue3' 1.38196	Shunt OC z2' 0.85410	Unit Element ue1'' 2.23607	Shunt OC z3 0.50000	Unit Element ue2'' 2.23607	Shunt OC z4' 0.85410	Unit Element ue4' 1.38196	Shunt OC z5'' 3.61804
Shunt OC 181 0.125λ	Unit Element 69 0.125λ	Shunt OC 43 0.125λ	Unit Element 112 0.125λ	Shunt OC 25 0.125λ	Unit Element 112 0.125λ	Shunt OC 43 0.125λ	Unit Element 69 0.125λ	Shunt OC 181 0.125λ

Step 6: Calculate the widths of the transmission lines and enter these into the design *"N5_MaxFlat_LPF_T-Line"* within the HFSS project *"ECEN452_Lab6_Filters.hfss"*. You will also need to enter this information into the "*N5_MaxFlat_LPF_T-Line.zov"* Z0lver assignment.

Step 7: Perform impedance and frequency scaling for the lumped element prototype you found in **Step 2** and enter these into the "*N5_MaxFlat_LPF_LC.zov"* Z0lver assignment.

Step 8: Calculate the values x1, x2, x3, x4, and x5 (e.g., the electrical length of the stubs) for the modified low pass filter design *"N5_MaxFlat_LPF_T-Line_Tapped_Stubs"* that uses tapped stubs with a 1 mm width (Z_0 = 89 W).

Shunt OC 89 x1*λ		Shunt OC 89 x2*λ		Shunt OC 89 x3*λ		Shunt OC 89 x4*λ		Shunt OC 89 x5*λ
	Unit Element 69 0.125λ		Unit Element 112		Unit Element 112		Unit Element 69	
Shunt OC 89 x1*λ		Shunt OC 89 x2*λ		Shunt OC 89 x3*λ		Shunt OC 89 x4*λ		Shunt OC 89 x5*λ

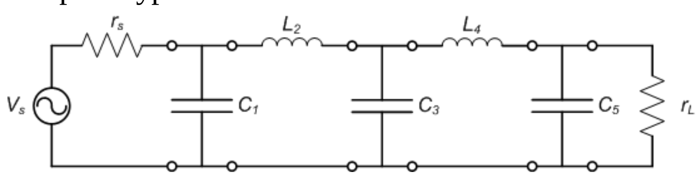
Task 2: Synthesis and implementation of an equi-ripple band-stop filter.

In this exercise you will synthesize a fifth-order 0.5 dB equi-ripple band-pass filter with a center frequency f_c = 3.0 GHz and a bandwidth of 2.25 GHz to 3.75 GHz (e.g., Δ = 0.5), and then implement your design using microstrip transmission lines for a Z_0 = 50 Ω reference impedance on a 62 mil thick FR4 (ε_r = 4.1, *tan* δ = 0.01).

Step 1: First, use the table on the following page to determine the element values of the low pass prototype.

					0.5 dB Ripple						
N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}
1	0.6986	1.0000									
2	1.4029	0.7071	1.9841								
3	1.5963	1.0967	1.5963	1.0000							
4	1.6703	1.1926	2.3661	0.8419	1.9841						
5	1.7058	1.2296	2.5408	1.2296	1.7058	1.0000					
6	1.7254	1.2479	2.6064	1.3137	2.4758	0.8696	1.9841				
7	1.7372	1.2583	2.6381	1.3444	2.6381	1.2583	1.7372	1.0000			
8	1.7451	1.2647	2.6564	1.3590	2.6964	1.3389	2.5093	0.8796	1.9841		
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000	
10	1.7543	1.2721	2.6754	1.3725	2.7392	1.3806	2.7231	1.3485	2.5239	0.8842	1.9841

Step 2: Assemble the prototype LC ladder network.



To simplify the analysis (visually), we will replace this ladder network will the table shown below.

Shunt C g1 1.7058	Series L g2 1.2296	Shunt C g3 2.5408	Series L g4 1.2296	Shunt C g5 1.7058

Step 3: Convert this to a band-stop filter topology by replacing shunt elements with shunted LC series networks, and series LC parallel networks.

Shunt Series LC L1', C1'	Series Parallel LC L2', C2'	Shunt Series LC L3', C3'	Series Parallel LC L4', C4'	Shunt Series LC L5', C5'

Step 4: Use inverters (e.g., quarter-wave transformers) to provide separation between the series elements and convert series stubs into shunt stubs.

Shunt Series LC L1', C1'	Inverter J1 1	Shunt Series LC L2', C2'	Inverter J2 1	Shunt Series LC L3', C3'	Inverter J3 1	Shunt Series LC L4', C4'	Inverter J4 1	Shunt Series LC L5', C5'

Shunt OC z1 0.25λ	Inverter J1 1 0.25λ	Shunt OC z2 0.25λ	Inverter J2 1 0.25λ	Shunt OC z3 0.25λ	Inverter J3 1 0.25λ	Shunt OC z4 0.25λ	Inverter J4 1 0.25λ	Shunt OC z5 0.25λ

Step 5: Calculate the scaled impedance values of the equivalent open-circuit stubs using

$$Z_s = \frac{4Z_0}{\pi \times \Delta \times g_n}$$

Shunt	Inverter	Shunt	Inverter	Shunt	Inverter	Shunt	Inverter	Shunt
OC	J1	OC	J2	OC	J3	OC	J4	OC
75	50	104	50	50	50	104	50	75
0.25λ	0.25λ	0.25λ	0.25λ	0.25λ	0.25λ	0.25λ	0.25λ	0.25λ