High-Frequency Filters

(Part 1)

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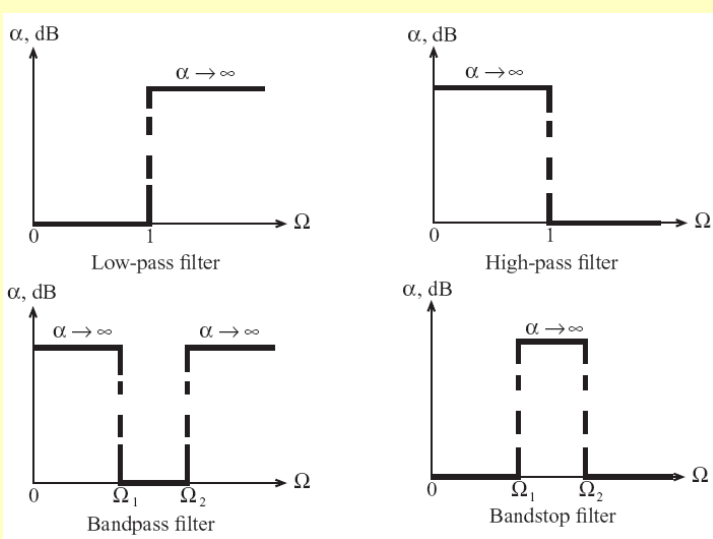
Outline

- Filter design at high frequencies
- General characteristics of filters
- Methods for filter design at high-frequencies
- The insertion loss method
- Example of a low-pass prototype filter design

Filter Design at High-Frequencies

- Lumped inductors and capacitors are unsuitable for frequencies above 500 MHz
- At high-frequencies, we use distributed elements
- An impedance-normalized low-pass filter is the basic building block
- We also use a normalized frequency Ω
- Transformations are used to convert lumped elements to distributed elements (e.g. Richards transformation, Kuroda identities, etc.)
- Transfer function is usually attenuation or insertion loss (instead of voltage gain)

Types of Filters

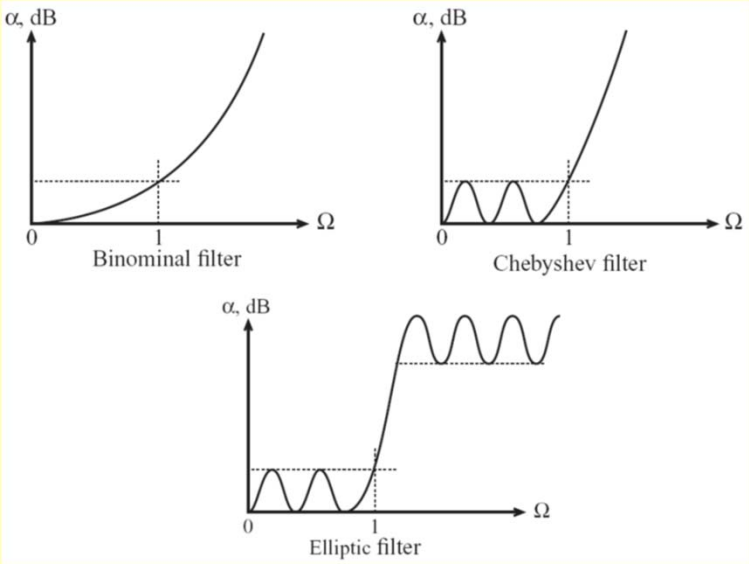


$$\gamma = \alpha + j\beta$$

$$\Omega = \omega / \omega_c$$

(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

Types of Filtering Profiles



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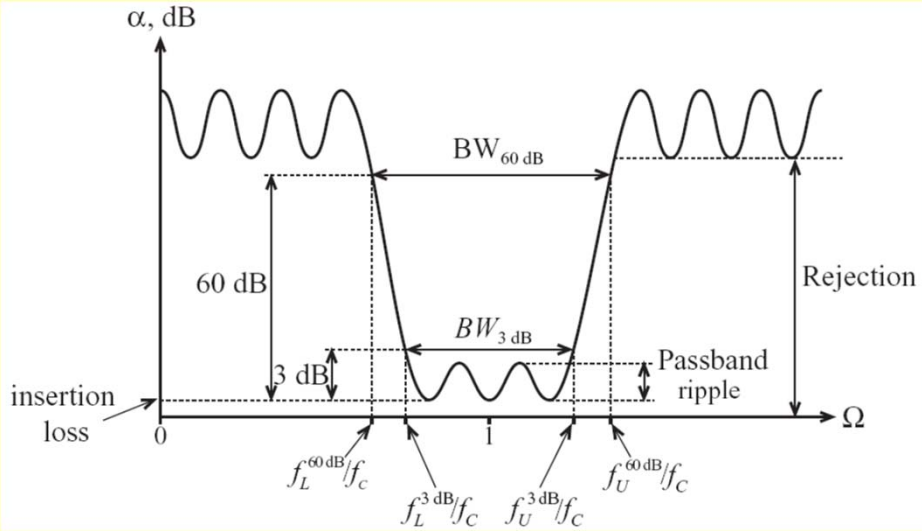
Filter Response Parameters



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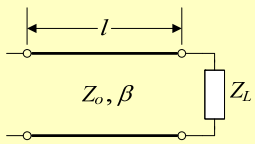
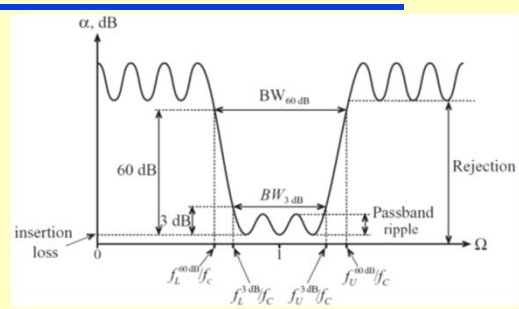
Filter Response Parameters (cont.)





$$P_{av} = \frac{1}{2}\frac{|V_o^+|^2}{Z_o}\left(1-|\Gamma|^2\right)$$

$$P_{\mathrm{LR}} = \frac{P_{inc}}{P_L} \quad \text{(power loss ratio)}$$

$$IL = 10\log\frac{P_{inc}}{P_L} = -10\log\left(1-|\Gamma|^2\right)$$

$BW_{3\mathrm{dB}}$: relative bandwidth

$$S_F = \frac{BW_{60\mathrm{dB}}}{BW_{3\mathrm{dB}}} \quad \text{(shape factor)}$$

$$Q_{LD} = \frac{1}{BW_{3\mathrm{dB}}} = \frac{f_C}{f_U^{3\mathrm{dB}} - f_L^{3\mathrm{dB}}} \quad \text{(loaded Q)}$$

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(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

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General Methods for Filter Design

- The Image Parameter method
- The Insertion Loss method
- CAD techniques

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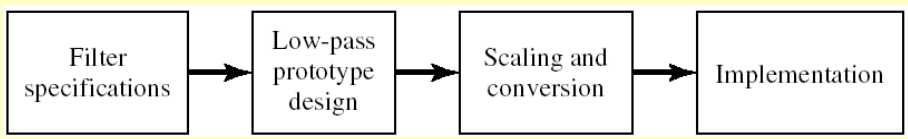
The Insertion Loss Method

- It uses network synthesis techniques from a completely specified frequency response
- The characterizing response is the power-loss ratio (or the insertion loss)
- General procedure:



(D. M. Pozar, Microwave Engineering, Wiley, 2005)

Power-Loss Ratio Characterization

$$P_{\mathrm{LR}} = \frac{P_{inc}}{P_L} = \frac{\text{power from the source}}{\text{power delivered to the load}} = \frac{P_{inc}}{P_{inc} - P_{ref}} = (1 - |\Gamma|^2)^{-1}$$

$$IL = 10 \log P_{\mathrm{LR}} = -10 \log\left(1 - |\Gamma(\omega)|^2\right)$$

$$P_{\mathrm{LR}} = \frac{1}{1 - |\Gamma(\omega)|^2}$$

It can be shown that $\Gamma(\omega)$ is an even function of ω ($\Gamma(\omega)$ can be represented by even series of the form $k_0 + k_2\omega^2 + k_4\omega^4 + \ldots$)

Since $|\Gamma(\omega)| \leq 1$, it can be expressed as

$$|\Gamma(\omega)|^2 = \frac{M(\omega^2)}{M(\omega^2) + N(\omega^2)} \qquad \text{then} \qquad P_{\mathrm{LR}} = 1 + \frac{M(\omega^2)}{N(\omega^2)}$$

Power-Loss Ratio Filtering Profiles

- Maximally Flat profile (or Binomial or Butterworth)

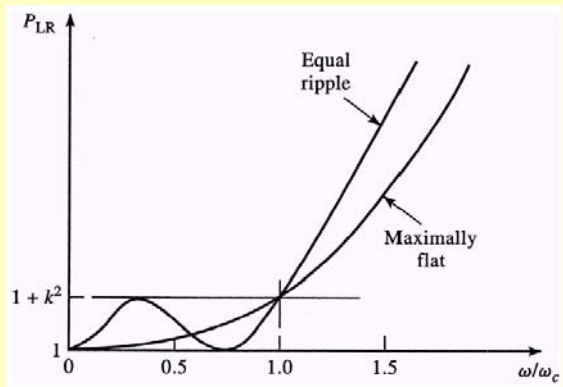
$$P_{\mathrm{LR}} = 1 + k^2 \left(\frac{\omega}{\omega_c} \right)^{2N}$$

N: filter order

- Chebyshev profile

$$P_{\mathrm{LR}} = 1 + k^2 T_N^2 \left(\frac{\omega}{\omega_c} \right)$$

$T_N(x)$ is the Chebyshev polynomial of order N



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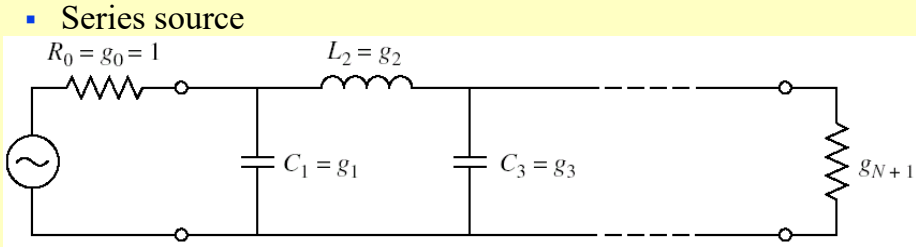
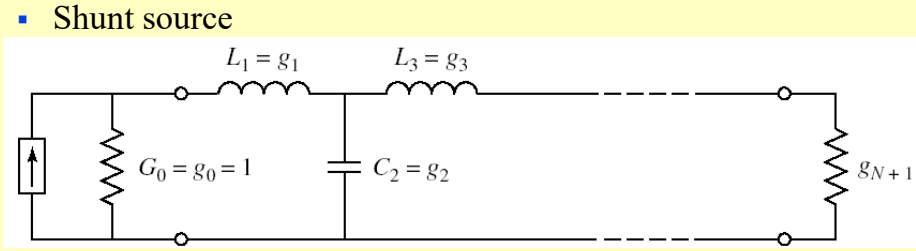
Normalized Low-Pass Prototypes

- Series source



- Shunt source



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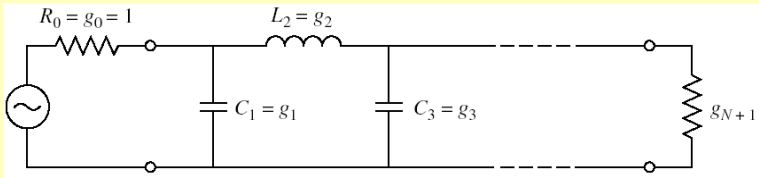
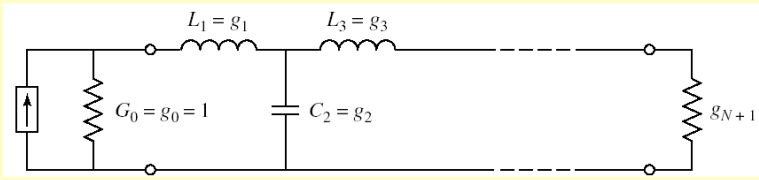
Normalized Low-Pass Prototypes (cont.)

- Series source



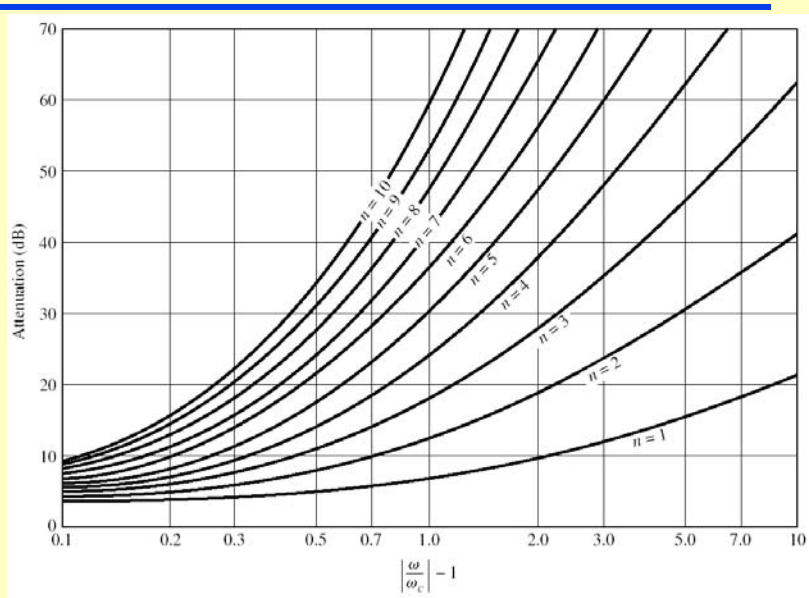
- Shunt source



$$g_{N+1} = \begin{cases} \text{Scaled load resistance if } g_N \text{ is a shunt capacitor} \\ \text{Scaled load conductance if } g_N \text{ is a series inductor} \end{cases}$$

(D. M. Pozar, Microwave Engineering, Wiley, 2005)

Attenuation for L-P Prototypes (Butterworth)



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Element Values L-P Prototypes (Butterworth)

(Assuming $g_0 = 1$ and $\omega_c = 1$)

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

Source: Reprinted from G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures* (Dedham, Mass.: Artech House, 1980) with permission.

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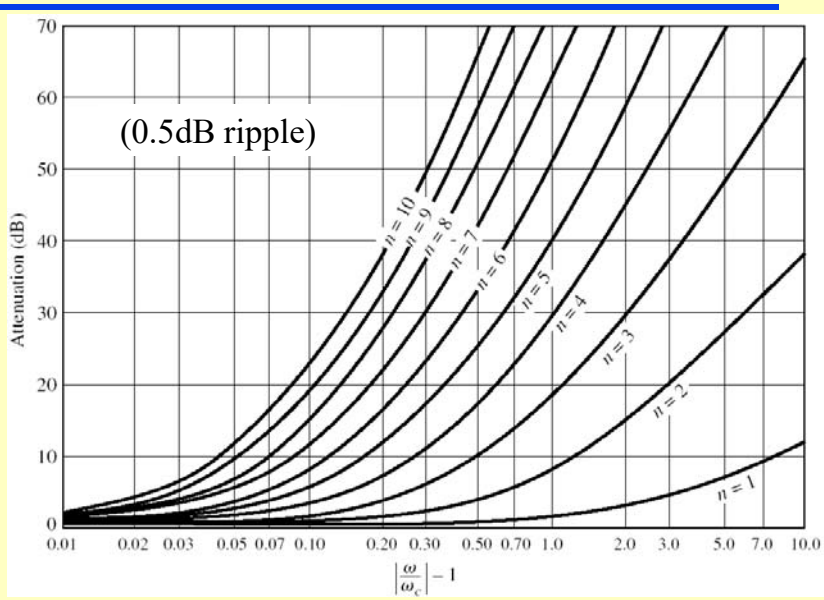
Attenuation for L-P Prototypes (Chebyshev)



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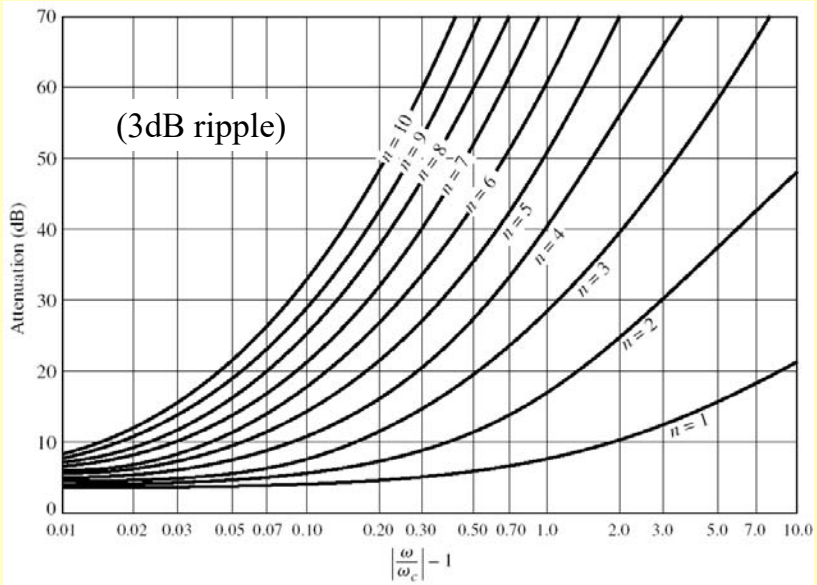
Attenuation for L-P Prototypes (Chebyshev)



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Element Values L-P Prototypes (Chebyshev)

(Assuming $g_0 = 1$ and $\omega_c = 1$)

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	1.000			
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

(In this case, ω_c is at –0.5dB)

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Element Values L-P Prototypes (Chebyshev)

(Assuming $g_0 = 1$ and $\omega_c = 1$)

3.0 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	1.9953	1.0000									
2	3.1013	0.5339	5.8095								
3	3.3487	0.7117	3.3487	1.0000							
4	3.4389	0.7483	4.3471	0.5920	5.8095						
5	3.4817	0.7618	4.5381	0.7618	3.4817	1.0000					
6	3.5045	0.7685	4.6061	0.7929	4.4641	0.6033	5.8095				
7	3.5182	0.7723	4.6386	0.8039	4.6386	0.7723	3.5182	1.0000			
8	3.5277	0.7745	4.6575	0.8089	4.6990	0.8018	4.4990	0.6073	5.8095		
9	3.5340	0.7760	4.6692	0.8118	4.7272	0.8118	4.6692	0.7760	3.5340	1.0000	
10	3.5384	0.7771	4.6768	0.8136	4.7425	0.8164	4.7260	0.8051	4.5142	0.6091	5.8095

Source: Reprinted from G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures* (Dedham, Mass.: Artech House, 1980) with permission.

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De-Normalized Element Values L-P Prototypes

The final element values for a low-pass prototype are obtained from:

$$L_k = \frac{R_0 g_k}{\omega_c} \qquad \leftarrow g_k = (\omega_c L_k)/R_0$$

$$C_k = \frac{g_k}{R_0 \omega_c} \qquad \leftarrow g_k = (\omega_c C_k) R_0$$

$$R_L = \begin{cases} R_0 / g_{N+1} & \text{if } g_{N+1} \text{ corresponds to a load conductance} \\ R_0 g_{N+1} & \text{if } g_{N+1} \text{ corresponds to a load resistance} \end{cases}$$

R_0 is the actual source resistance = reference impedance Z_0

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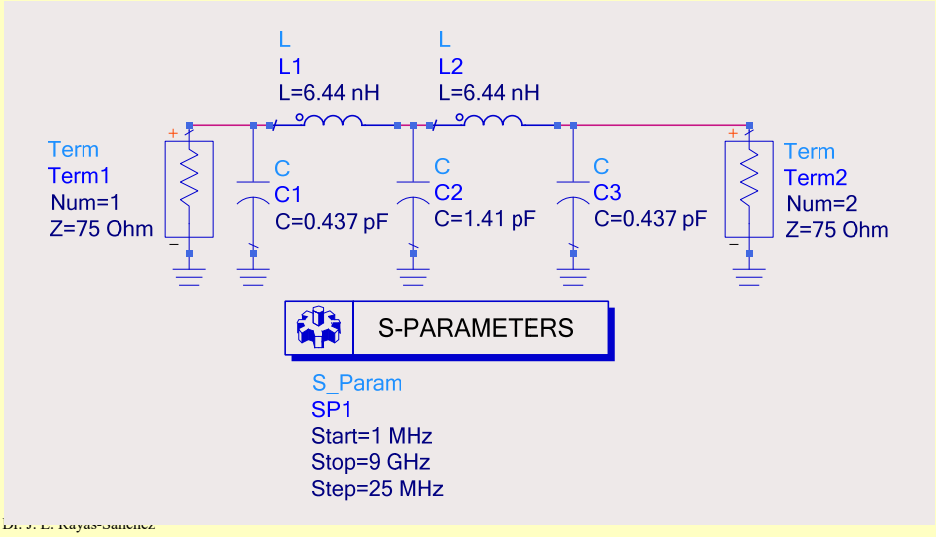
Example: Low-Pass Filter Prototype

Design a low-pass filter with the following specifications:

- Cut-off frequency at 3 GHz
- For a 75-Ω system
- Minimum attenuation of 20 dB at 5 GHz
- Butterworth filtering profile
- Use a series voltage source topology

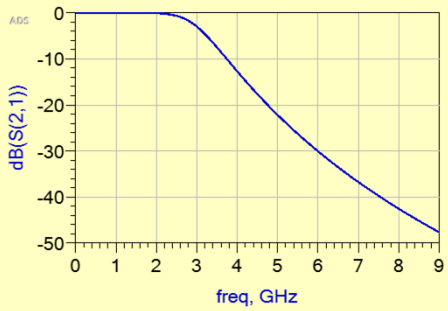
Example: Low-Pass Filter Prototype (cont.)

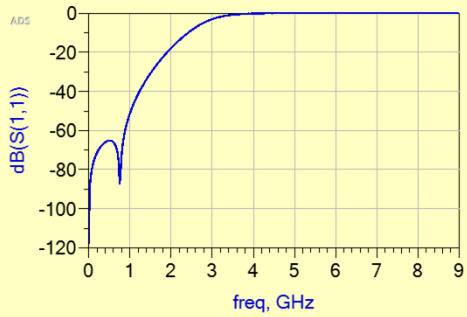
ADS simulation:



Example: Low-Pass Filter Prototype (cont.)

ADS simulation results:





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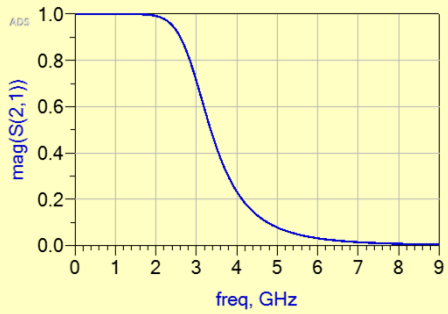
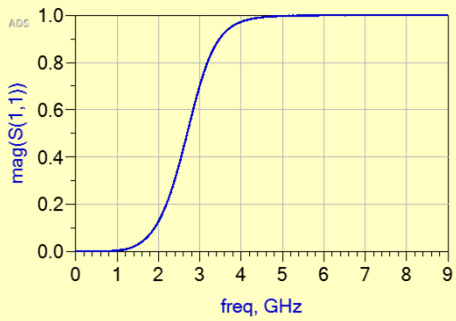
Example: Low-Pass Filter Prototype (cont.)

ADS simulation results (cont.):





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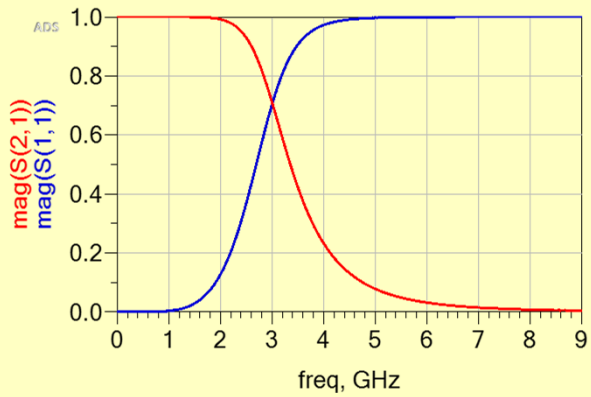
Example: Low-Pass Filter Prototype (cont.)

ADS simulation results (cont.):



$$|S_{11}|^2 + |S_{21}|^2 = 1$$