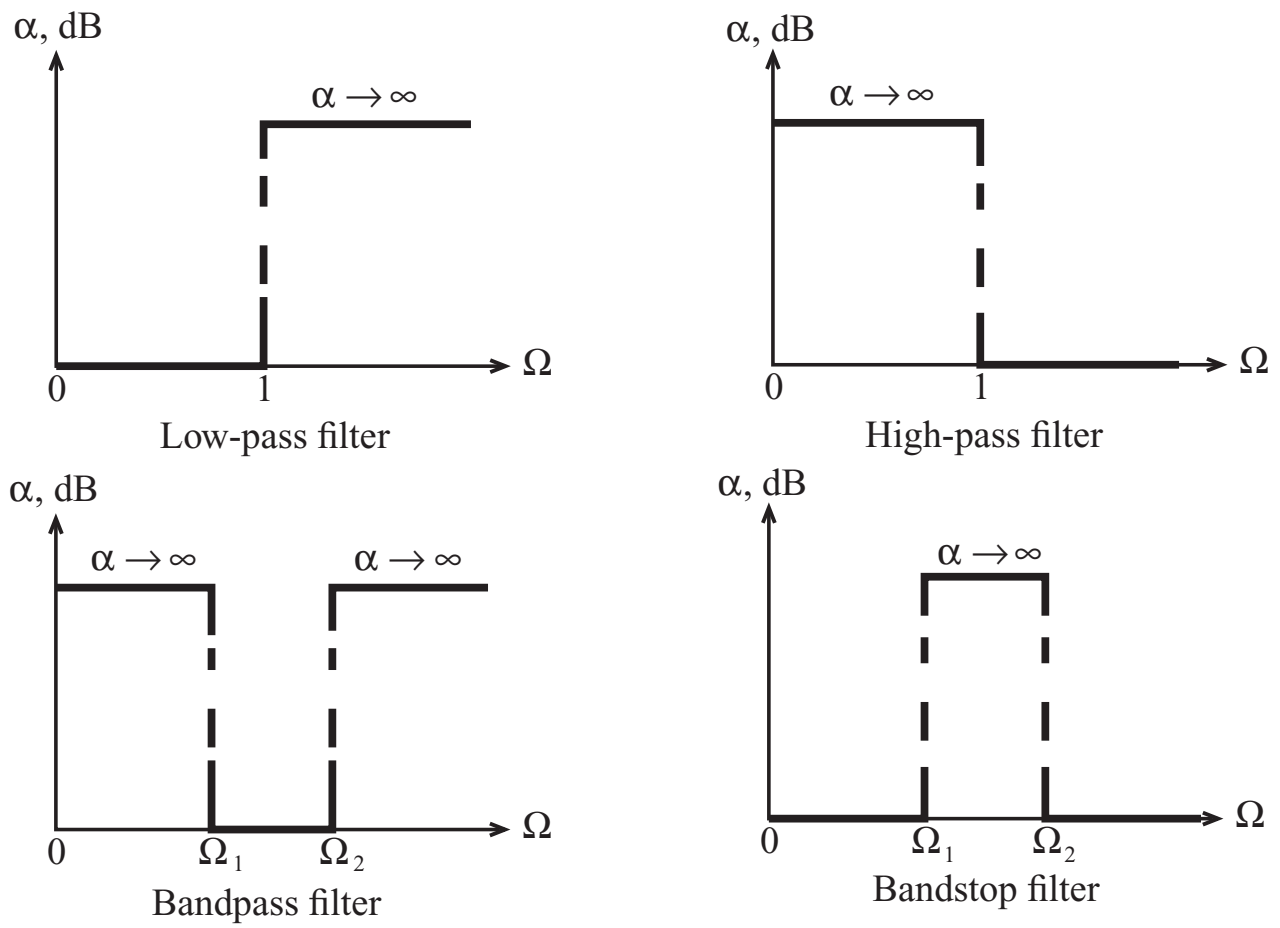
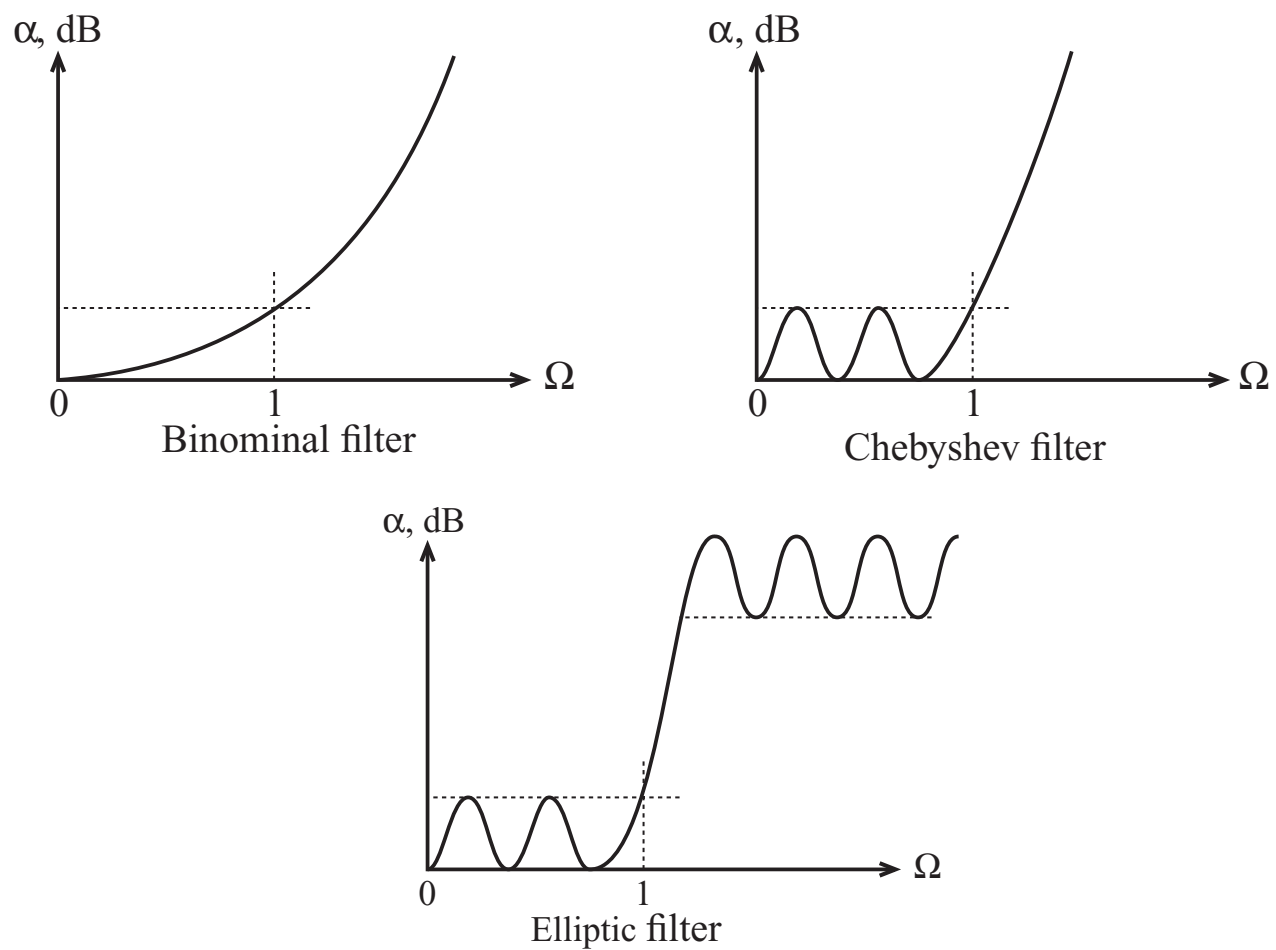


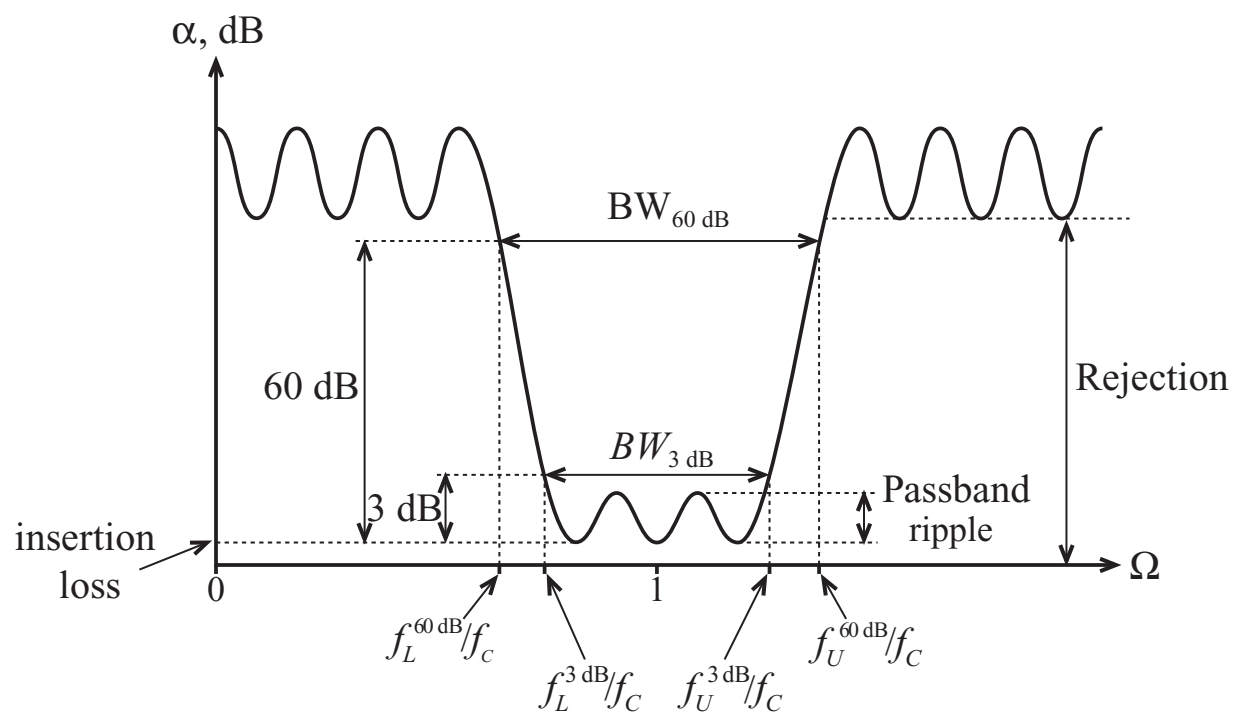
## FIGURES FOR CHAPTER 5



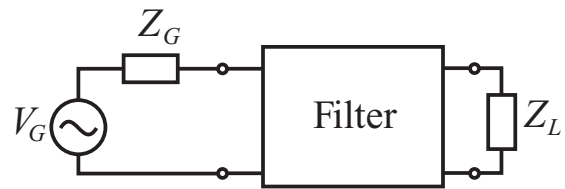
**Figure 5-1** Four basic filter types.



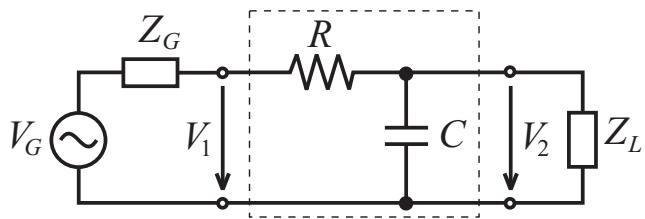
**Figure 5-2** Actual attenuation profile for three types of low-pass filters.



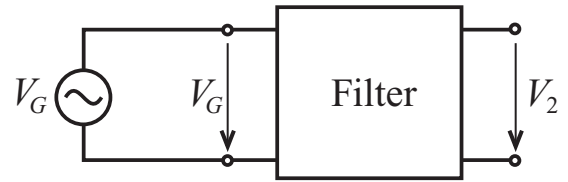
**Figure 5-3** Generic attenuation profile for a bandpass filter.



**Figure 5-4** Filter as a two-port network connected to an RF source and load.

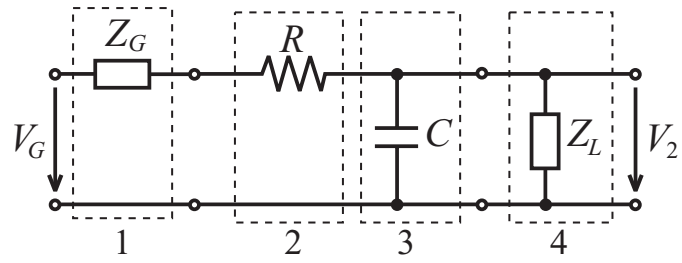


(a) Low-pass filter with load resistance.

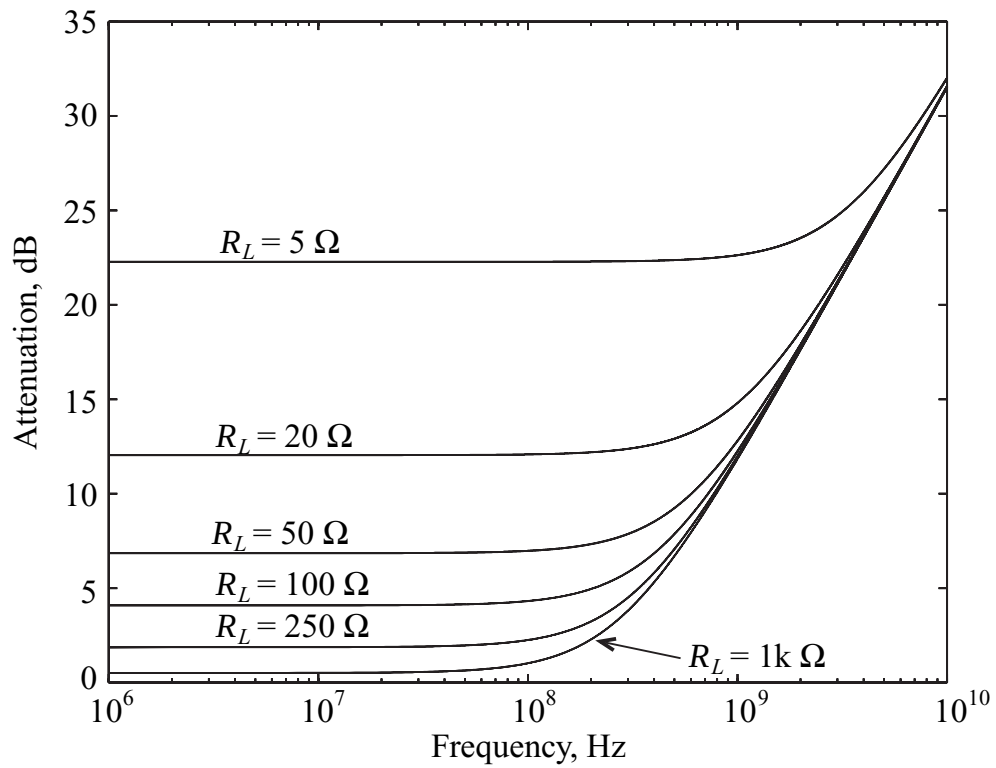


(b) Network with input/output voltages

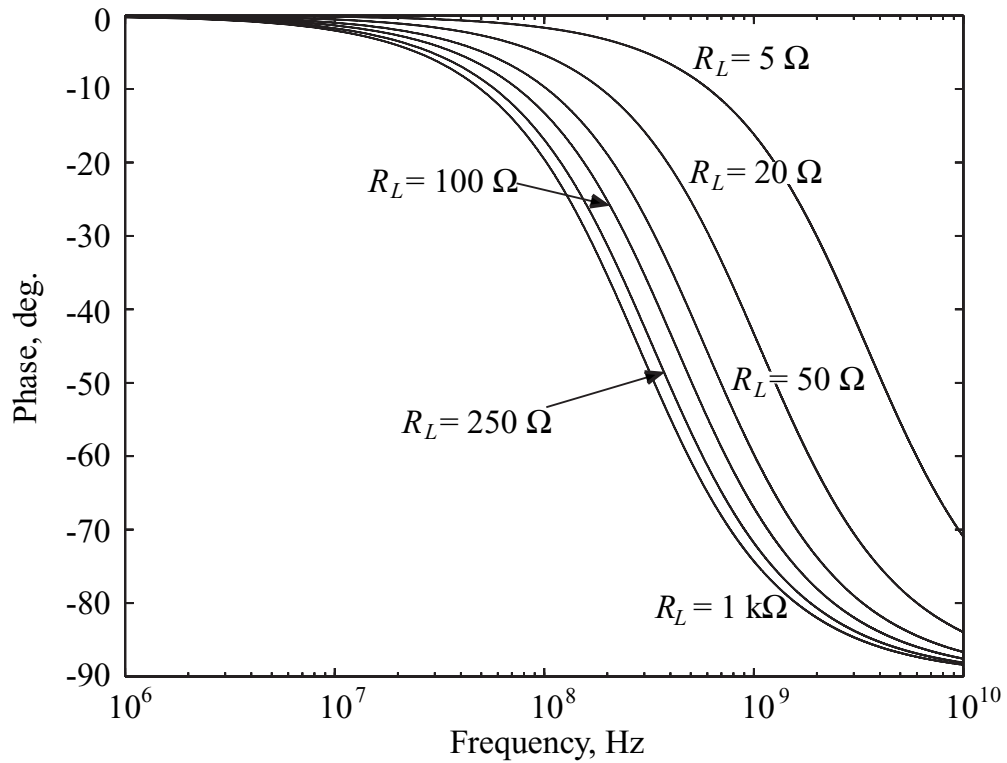
**Figure 5-5** Low-pass filter connected between source and load resistance.



**Figure 5-6** Cascading four *ABCD*-networks.

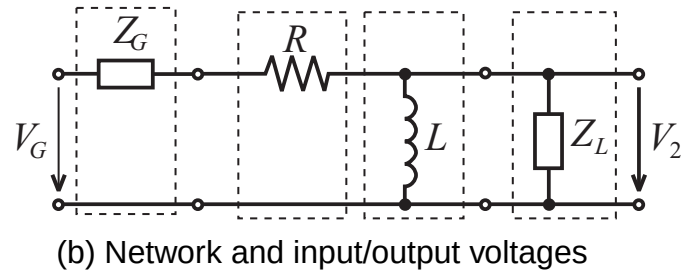
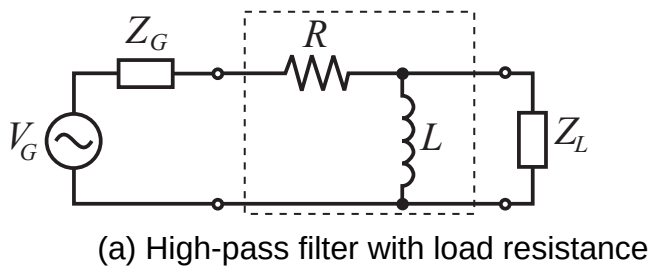


(a) Attenuation profile of the low-pass filter for various load resistances

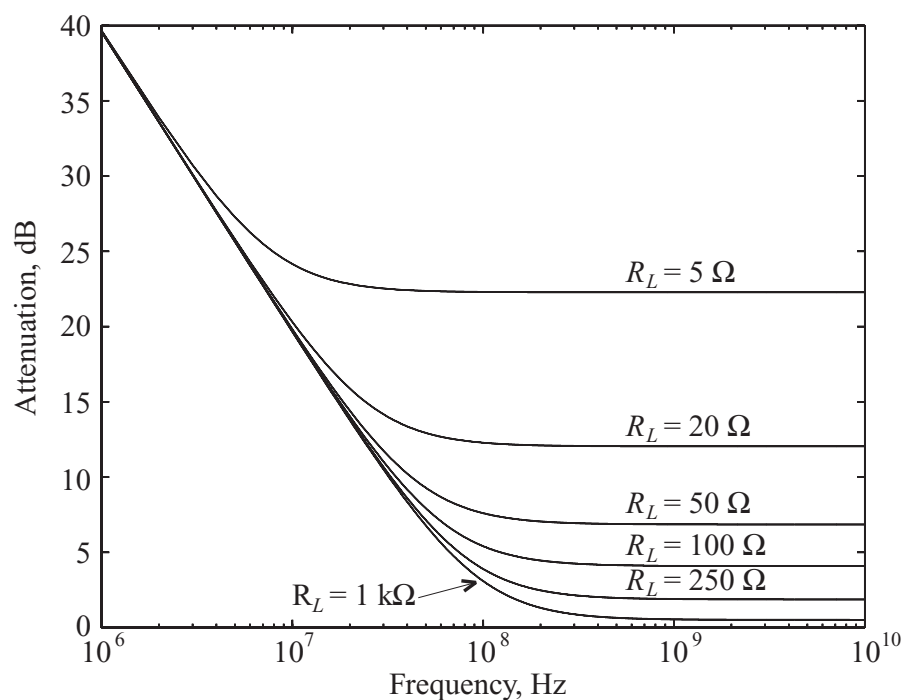


(b) Phase response of the low-pass filter for various load resistances

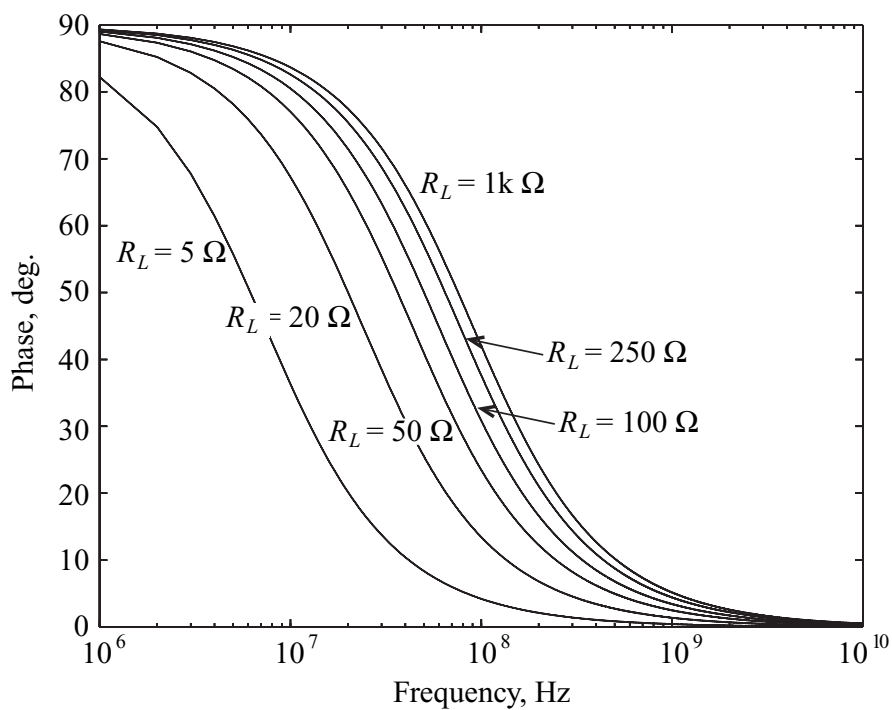
**Figure 5-7** First-order low-pass filter response as a function of various load resistances.



**Figure 5-8** First-order high-pass filter.

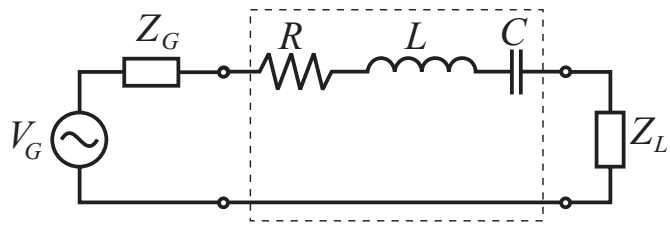


(a) Attenuation profile of the filter for various load resistances

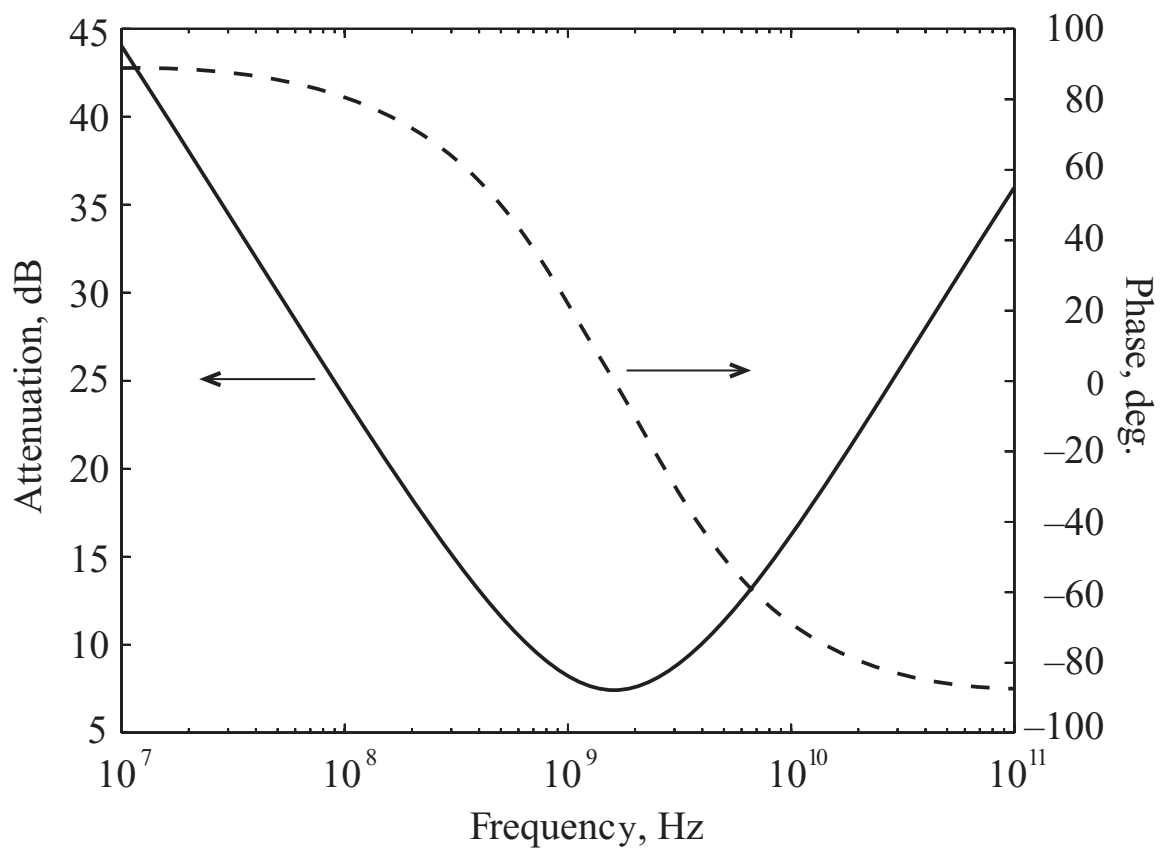


(b) Phase response of the filter for various load resistances

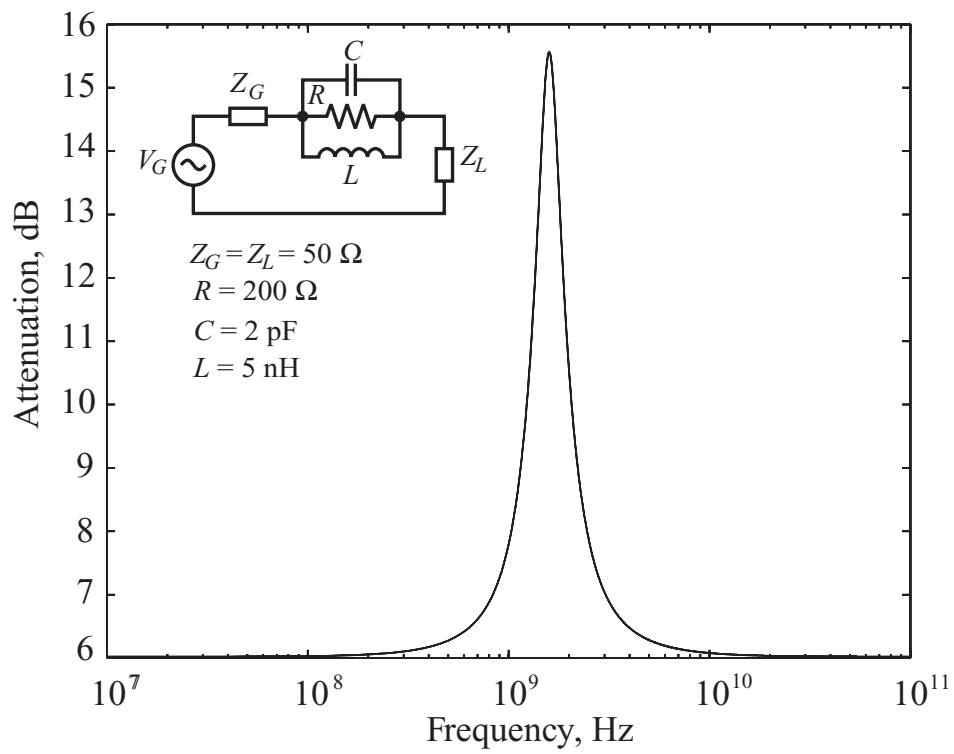
**Figure 5-9** Low-pass filter response as a function of various load resistances.



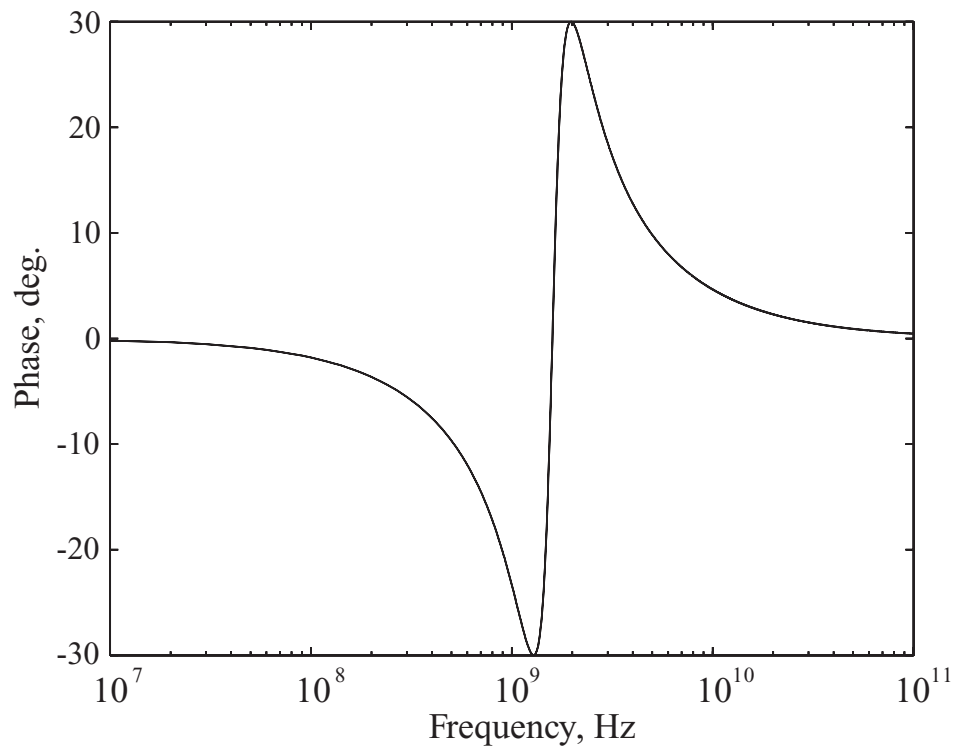
**Figure 5-10** Bandpass filter implemented in series configuration.



**Figure 5-11** Bandpass filter response.



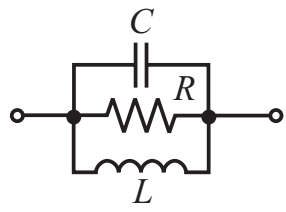
(a) Magnitude of transfer function

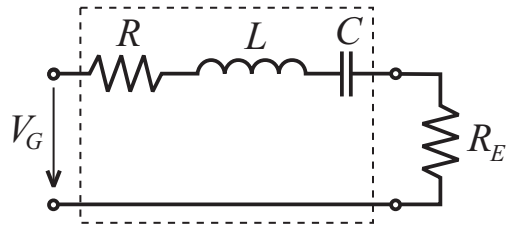


(b) Phase of transfer function

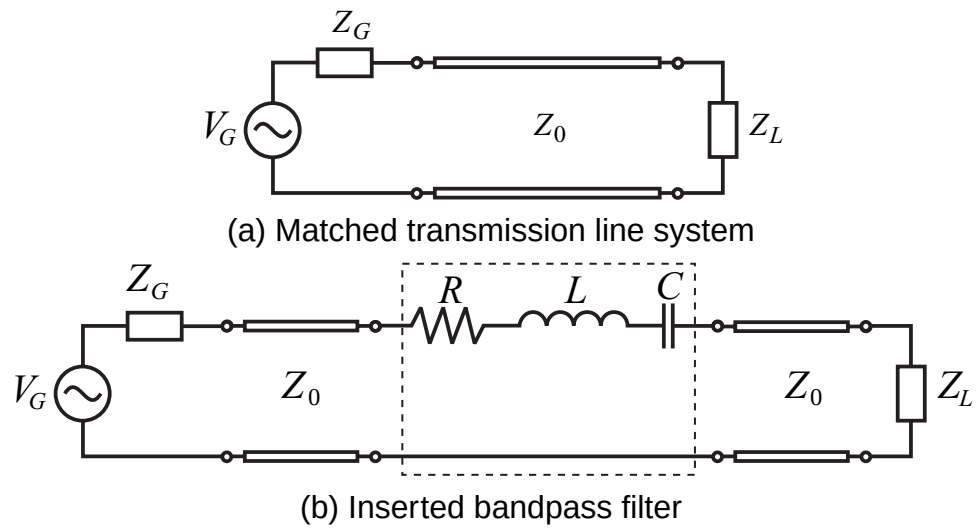
**Figure 5-12** Bandstop filter response.

**Table 5-1** Series and parallel resonators

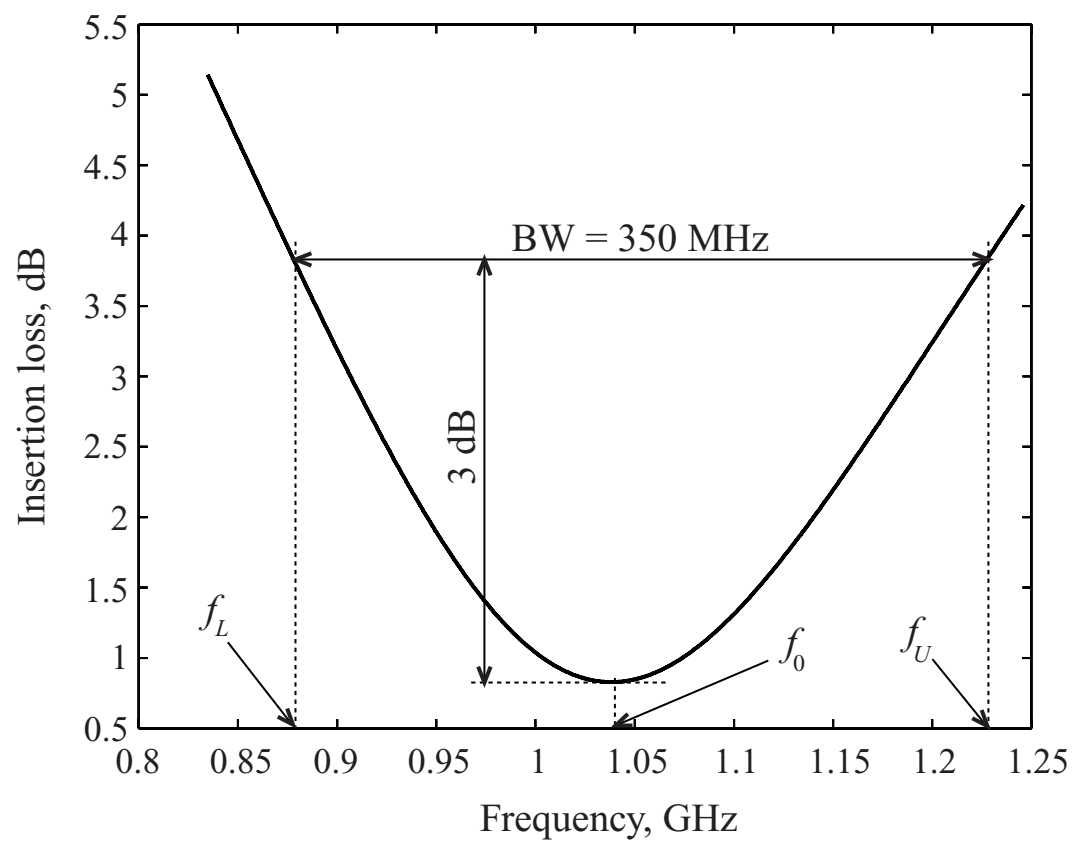
|                         |                                                                                   |                                                                                     |
|-------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Parameter               |  |  |
| Impedance or Admittance | $Z = R + j\omega L + \frac{1}{j\omega C}$                                         | $Y = G + j\omega C + \frac{1}{j\omega L}$                                           |
| Resonance Frequency     | $\omega_0 = \frac{1}{\sqrt{LC}}$                                                  | $\omega_0 = \frac{1}{\sqrt{LC}}$                                                    |
| Dissipation Factor      | $d = \frac{R}{\omega_0 L} = R\omega_0 C$                                          | $d = \frac{G}{\omega_0 C} = G\omega_0 L$                                            |
| Quality Factor          | $Q = \frac{\omega_0 L}{R} = \frac{1}{R\omega_0 C}$                                | $Q = \frac{\omega_0 C}{G} = \frac{1}{G\omega_0 L}$                                  |
| Bandwidth               | $BW = \frac{f_0}{Q} = \frac{1}{2\pi L} \frac{R}{\omega_0}$                        | $BW = \frac{f_0}{Q} = \frac{1}{2\pi C} \frac{G}{\omega_0}$                          |



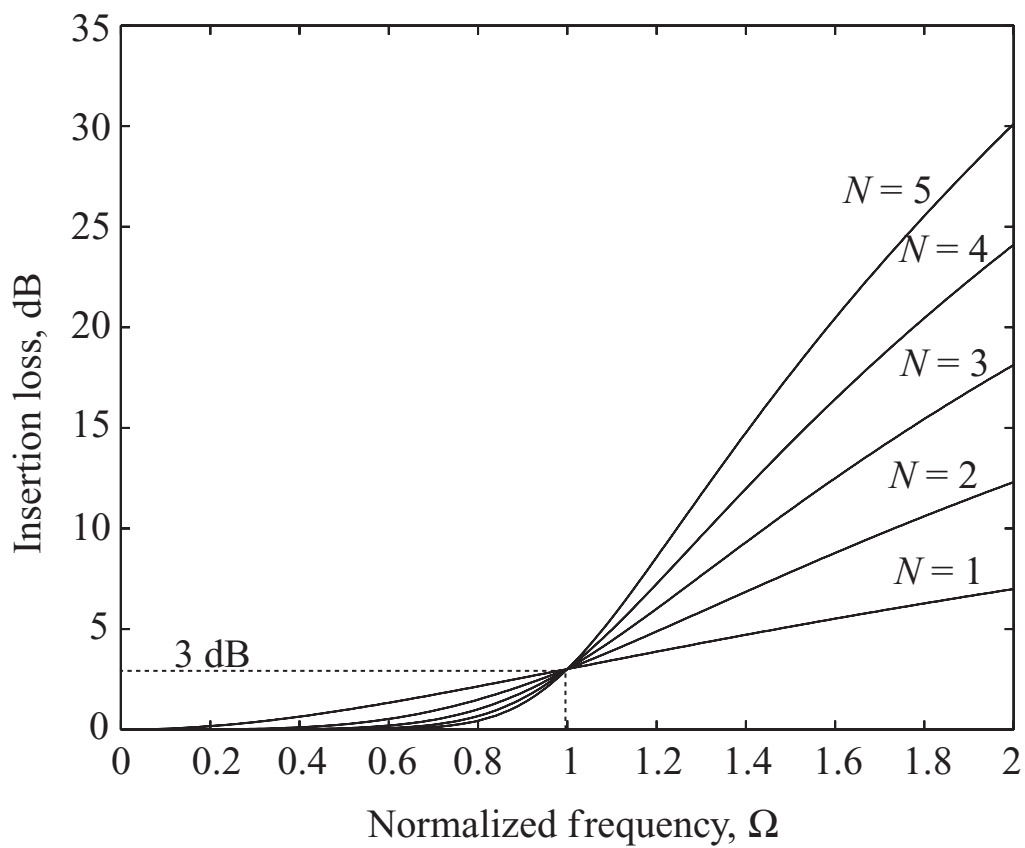
**Figure 5-13** Circuit used for the definitions of loaded and unloaded quality factors.



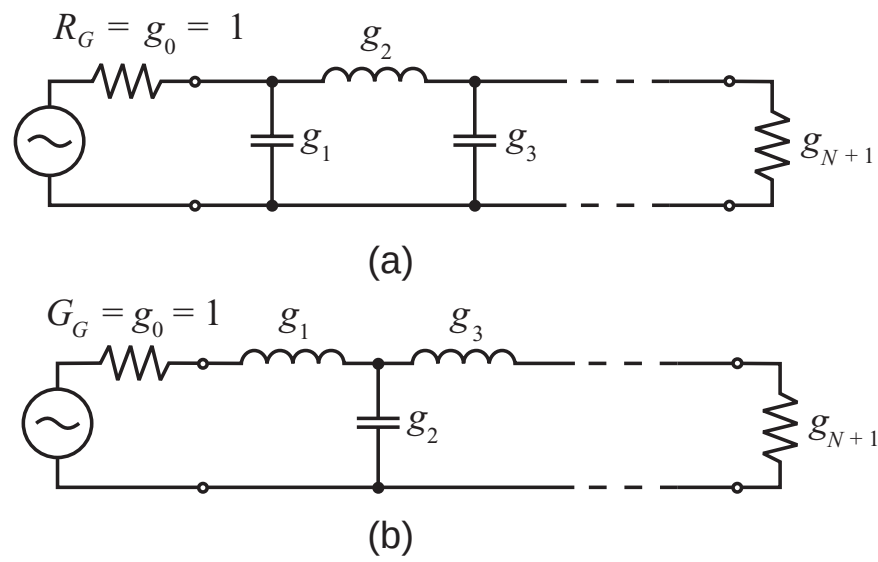
**Figure 5-14** Insertion loss considerations.



**Figure 5-15** Insertion loss versus frequency.



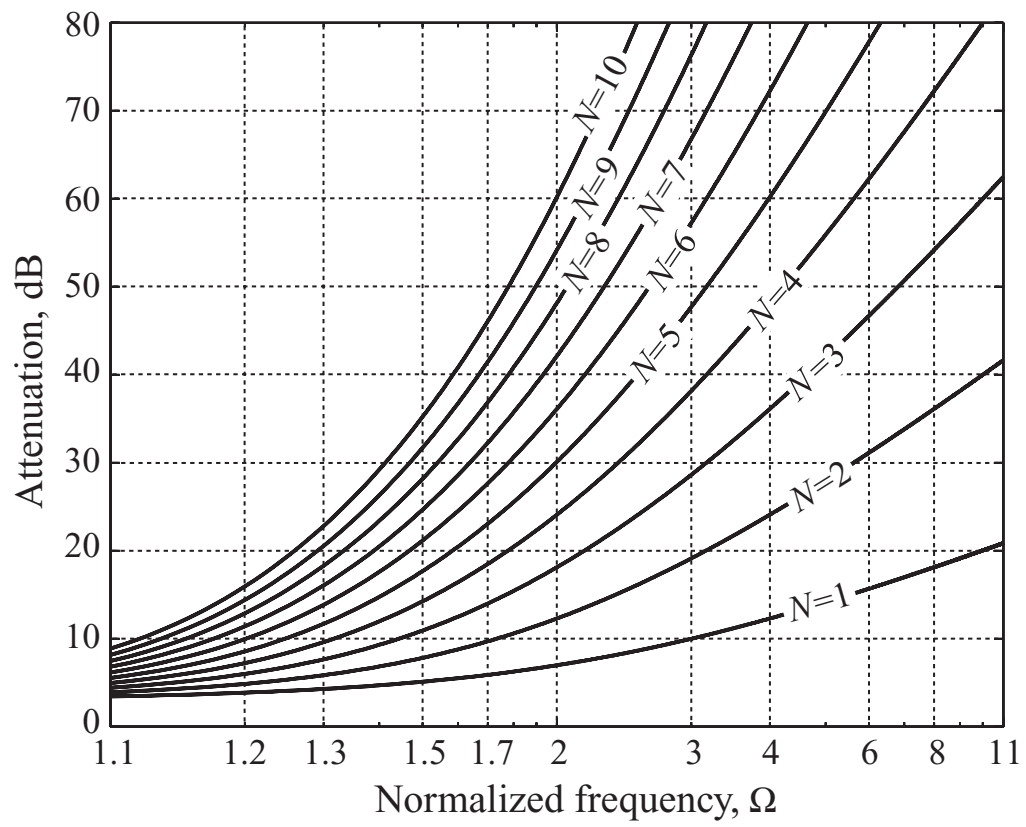
**Figure 5-16** Butterworth low-pass filter design.



**Figure 5-17** Two equivalent realizations of the generic multisection low-pass filter with normalized elements.

**Table 5-2** Coefficients for maximally flat low-pass filter ( $N = 1$  to 10)

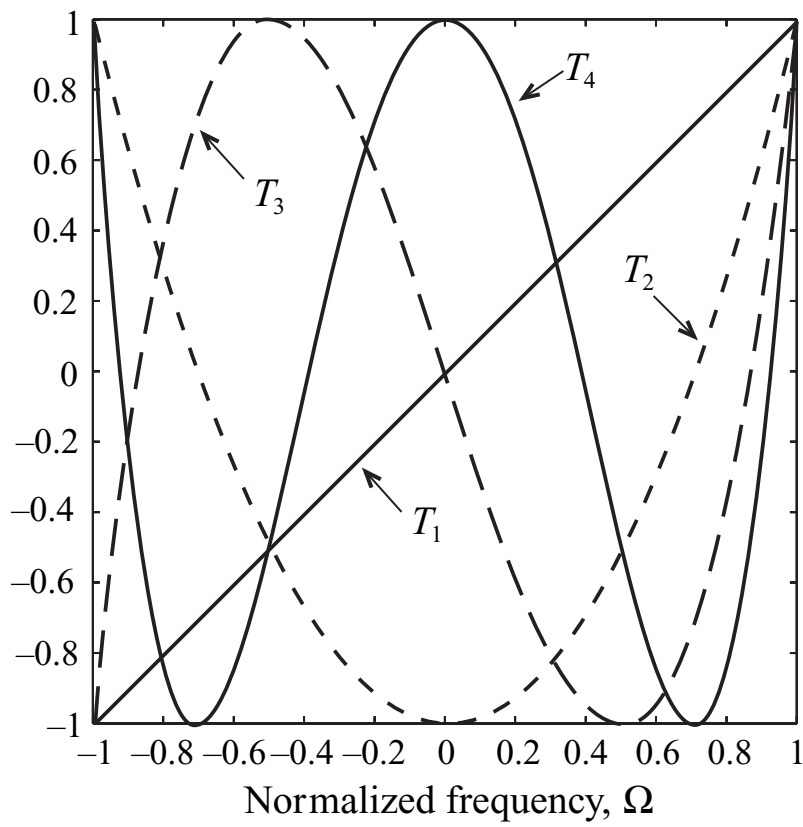
| $N$ | $g_1$  | $g_2$  | $g_3$  | $g_4$  | $g_5$  | $g_6$  | $g_7$  | $g_8$  | $g_9$  | $g_{10}$ | $g_{11}$ |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|
| 1   | 2.0000 | 1.0000 |        |        |        |        |        |        |        |          |          |
| 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   |



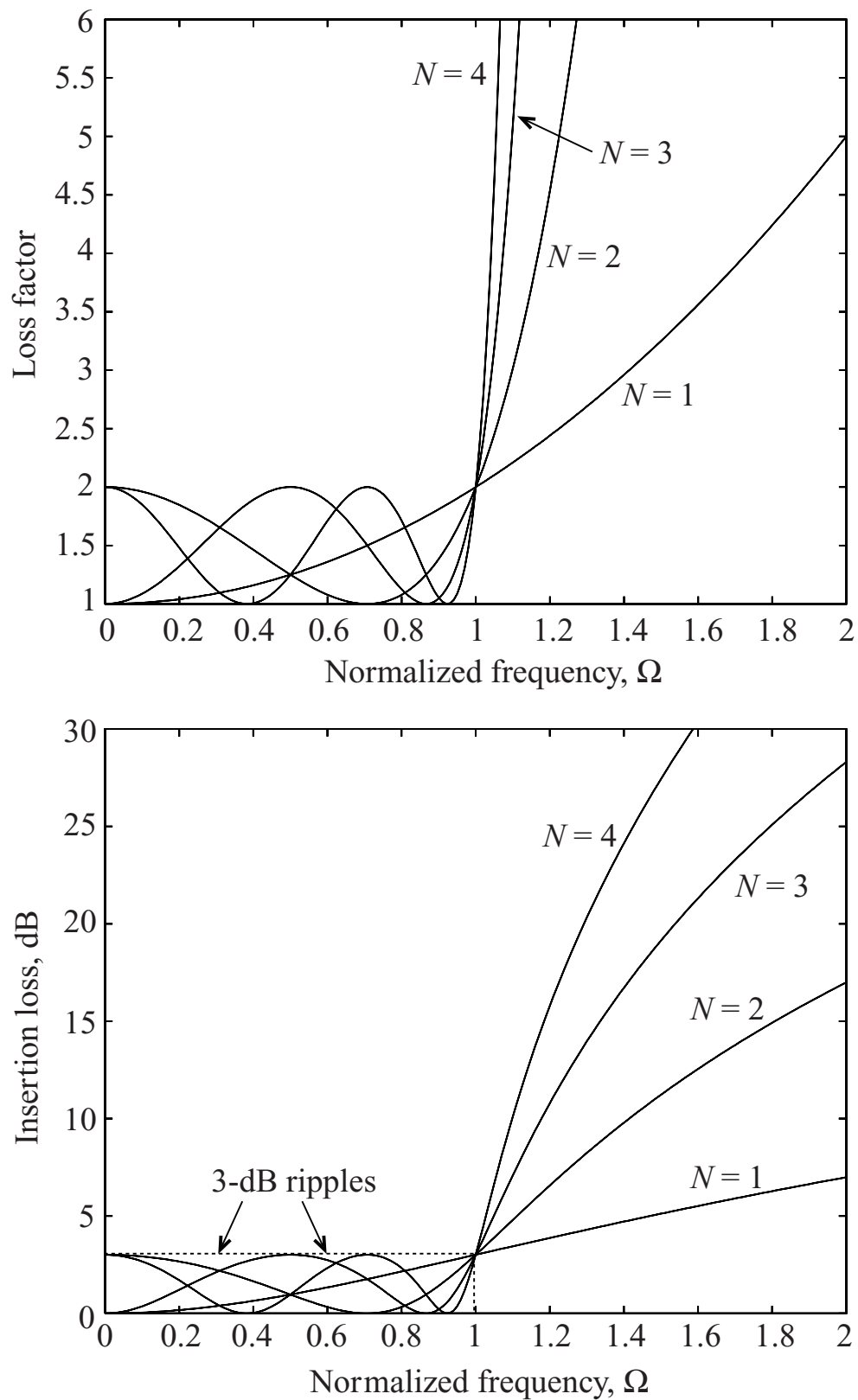
**Figure 5-18** Attenuation behavior of maximally flat low-pass filter versus normalized frequency.

**Table 5-3** Coefficients for linear phase low-pass filter ( $N = 1$  to 10).

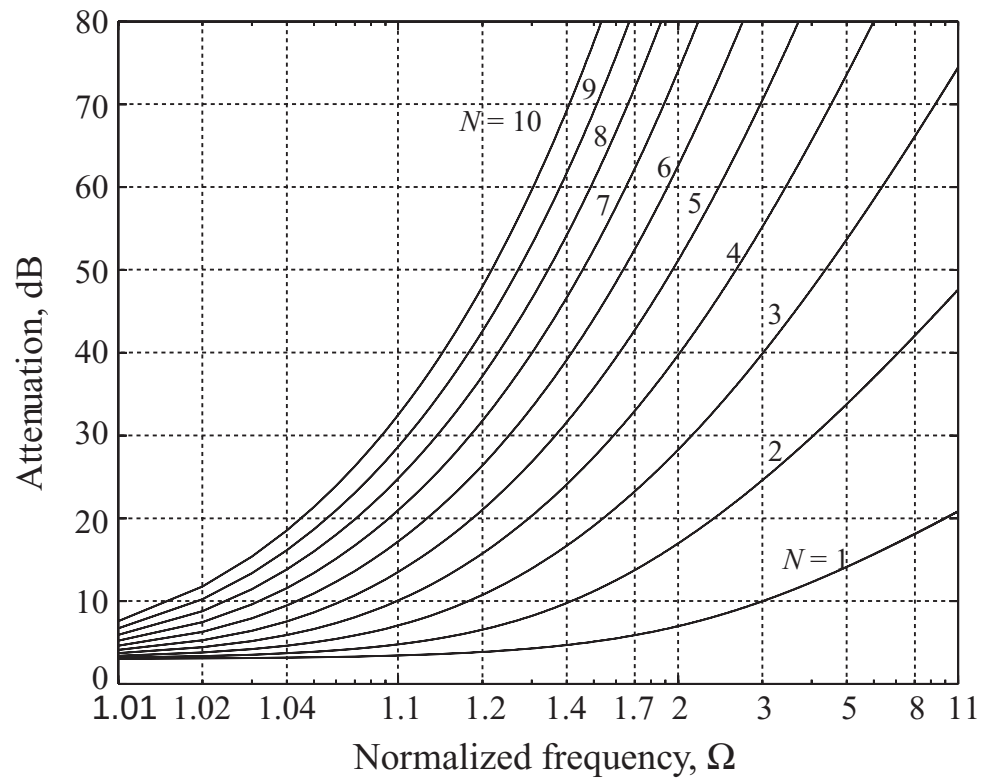
| $N$ | $g_1$  | $g_2$  | $g_3$  | $g_4$  | $g_5$  | $g_6$  | $g_7$  | $g_8$  | $g_9$  | $g_{10}$ | $g_{11}$ |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|
| 1   | 2.0000 | 1.0000 |        |        |        |        |        |        |        |          |          |
| 2   | 1.5774 | 0.4226 | 1.0000 |        |        |        |        |        |        |          |          |
| 3   | 1.2550 | 0.5528 | 0.1922 | 1.0000 |        |        |        |        |        |          |          |
| 4   | 1.0598 | 0.5116 | 0.3181 | 0.1104 | 1.0000 |        |        |        |        |          |          |
| 5   | 0.9303 | 0.4577 | 0.3312 | 0.2090 | 0.0718 | 1.0000 |        |        |        |          |          |
| 6   | 0.8377 | 0.4116 | 0.3158 | 0.2364 | 0.1480 | 0.0505 | 1.0000 |        |        |          |          |
| 7   | 0.7677 | 0.3744 | 0.2944 | 0.2378 | 0.1778 | 0.1104 | 0.0375 | 1.0000 |        |          |          |
| 8   | 0.7125 | 0.3446 | 0.2735 | 0.2297 | 0.1867 | 0.1387 | 0.0855 | 0.0289 | 1.0000 |          |          |
| 9   | 0.6678 | 0.3203 | 0.2547 | 0.2184 | 0.1859 | 0.1506 | 0.1111 | 0.0682 | 0.0230 | 1.0000   |          |
| 10  | 0.6305 | 0.3002 | 0.2384 | 0.2066 | 0.1808 | 0.1539 | 0.1240 | 0.0911 | 0.0557 | 0.0187   | 1.0000   |



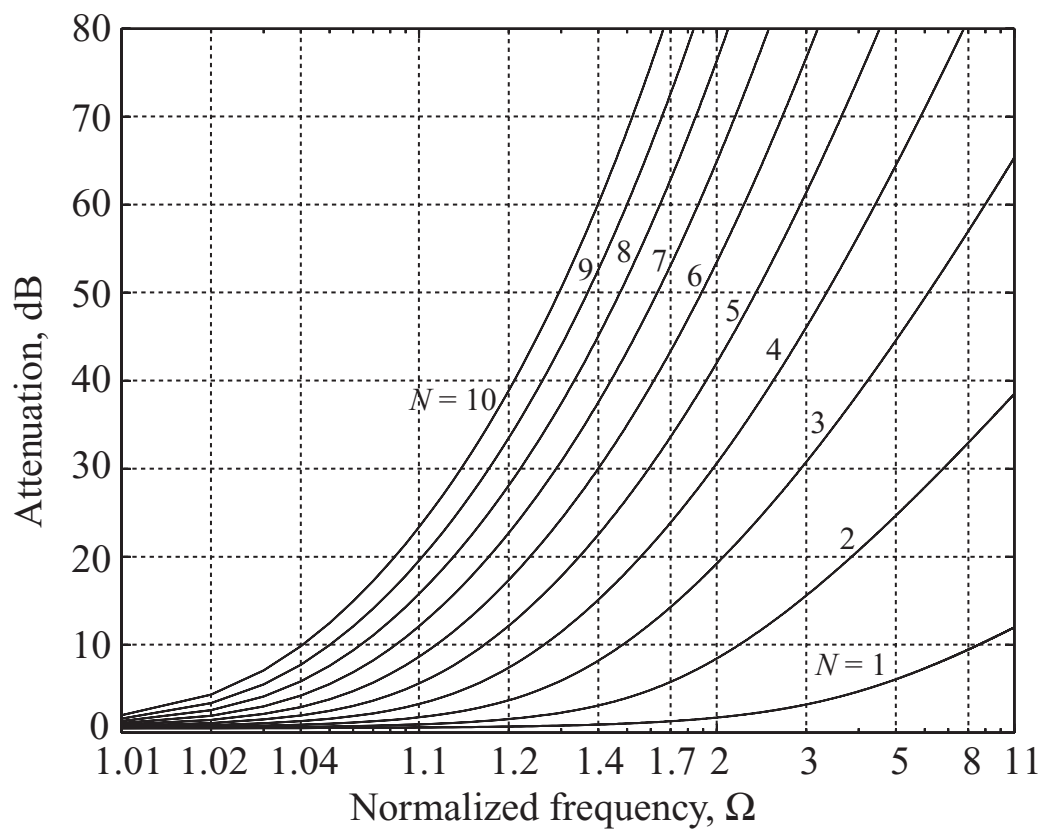
**Figure 5-19** Chebyshev polynomials  $T_1(\Omega)$  through  $T_4(\Omega)$  in the normalized frequency range  $-1 \leq \Omega \leq 1$ .



**Figure 5-20** Frequency dependence of the loss factor and insertion loss of the Chebyshev low-pass filter.



**Figure 5-21** Attenuation response for 3 dB Chebyshev design.



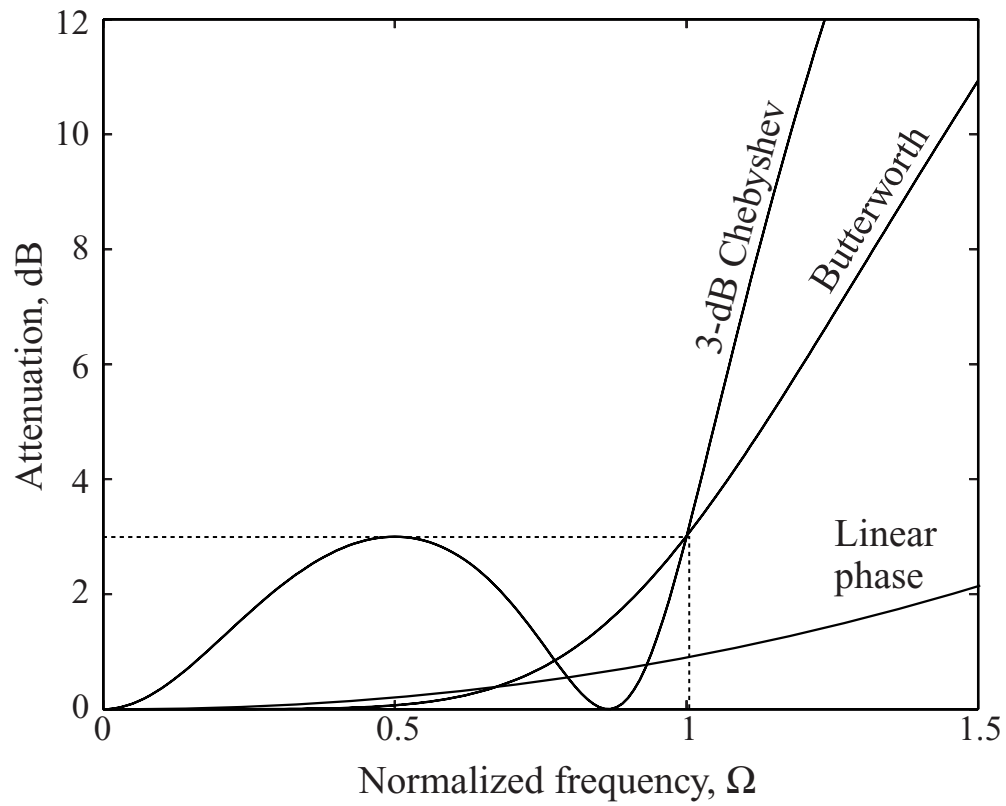
**Figure 5-22** Attenuation response for 0.5 dB Chebyshev design.

**Table 5-4 (a)** Chebyshev filter coefficients; 3 dB filter design ( $N = 1$  to 10)

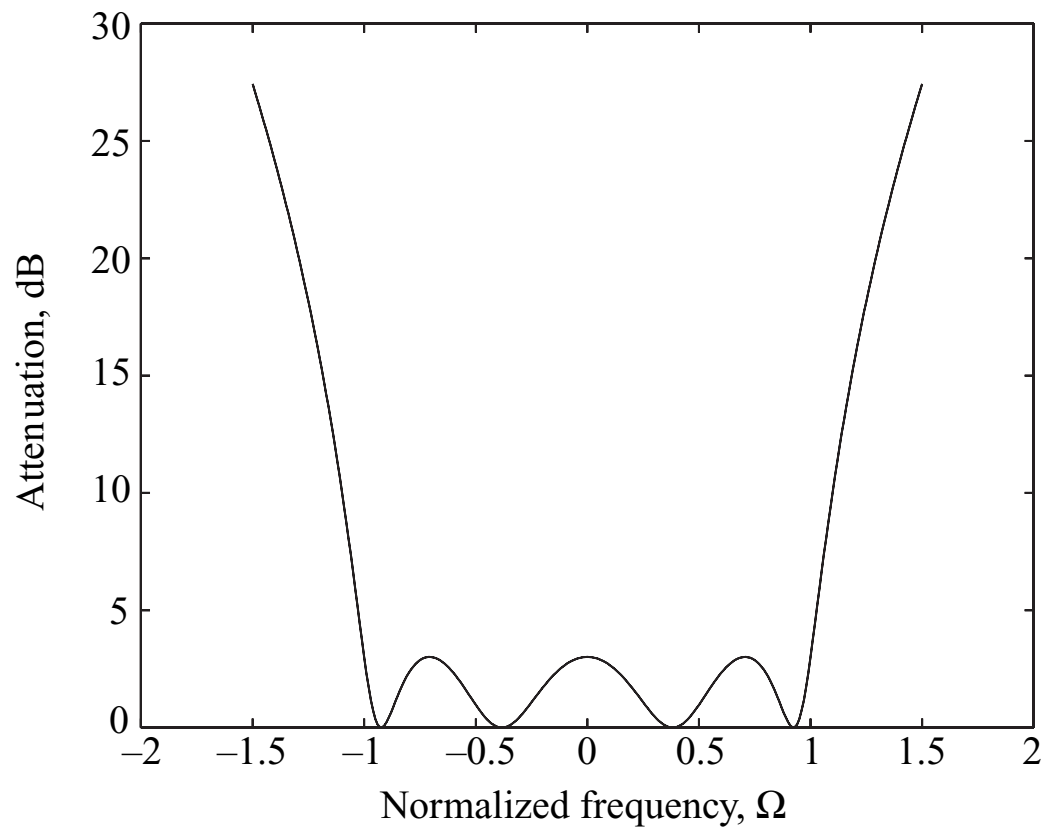
| $N$ | $g_1$  | $g_2$  | $g_3$  | $g_4$  | $g_5$  | $g_6$  | $g_7$  | $g_8$  | $g_9$  | $g_{10}$ | $g_{11}$ |
|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|
| 1   | 1.9953 | 1.0000 |        |        |        |        |        |        |        |          |          |
| 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   |

**Table 5-4 (b)** Chebyshev filter coefficients; 0.5 dB filter design ( $N = 1$  to 10)

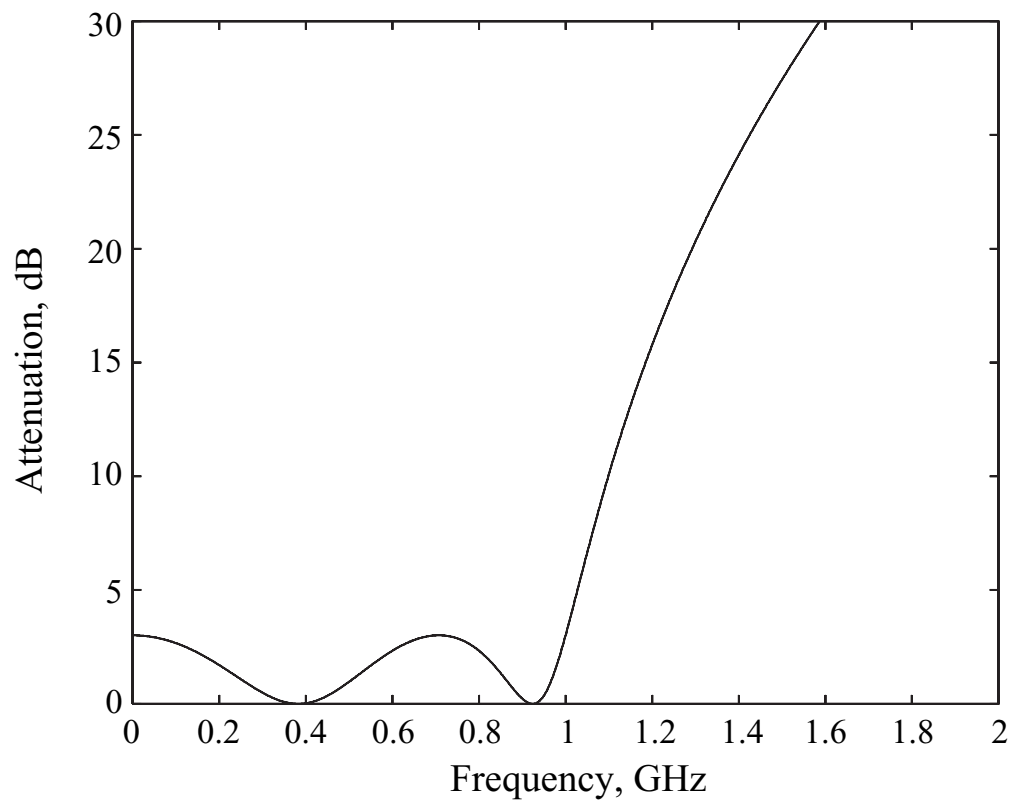
| N  | $g_1$  | $g_2$  | $g_3$  | $g_4$  | $g_5$  | $g_6$  | $g_7$  | $g_8$  | $g_9$  | $g_{10}$ | $g_{11}$ |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|
| 1  | 0.6986 | 1.0000 |        |        |        |        |        |        |        |          |          |
| 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 | 2.7939 | 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   |



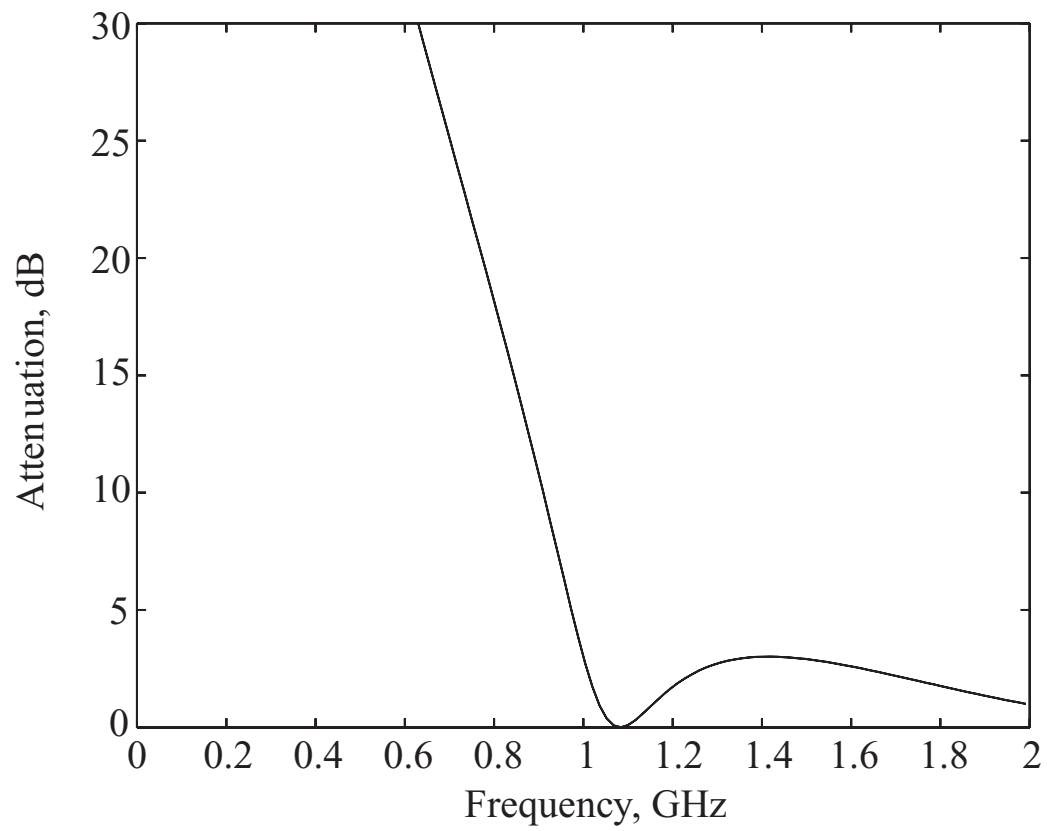
**Figure 5-23** Comparison of the frequency response of the Butterworth, linear phase, and 3-dB Chebyshev third-order filters.



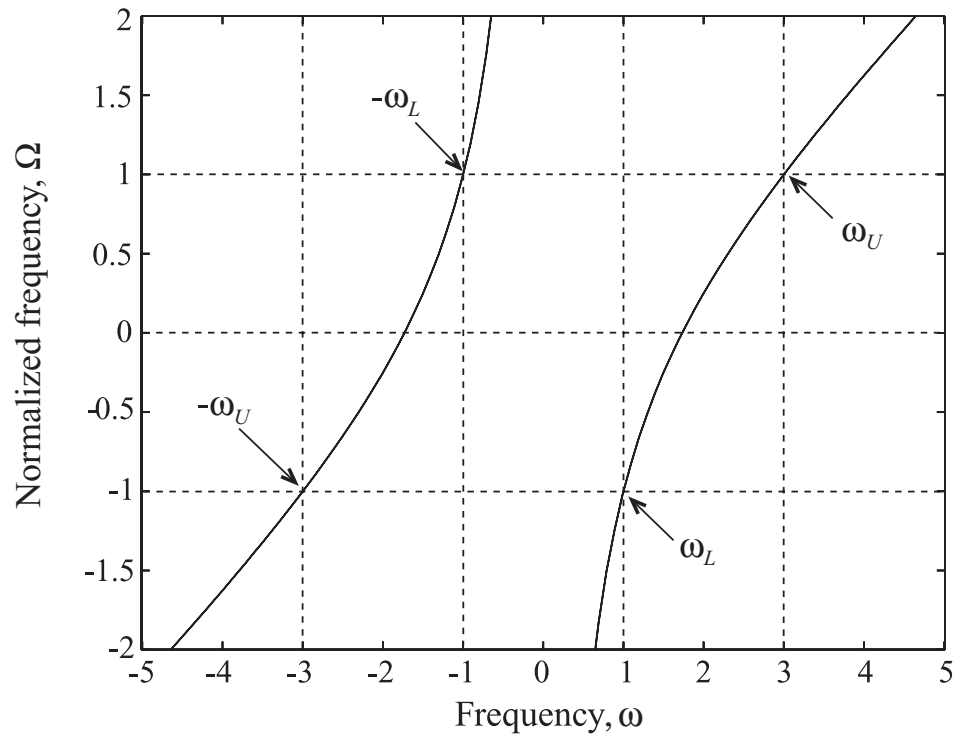
**Figure 5-24** Fourth-order low-pass Chebyshev filter with 3 dB ripples in the passband.



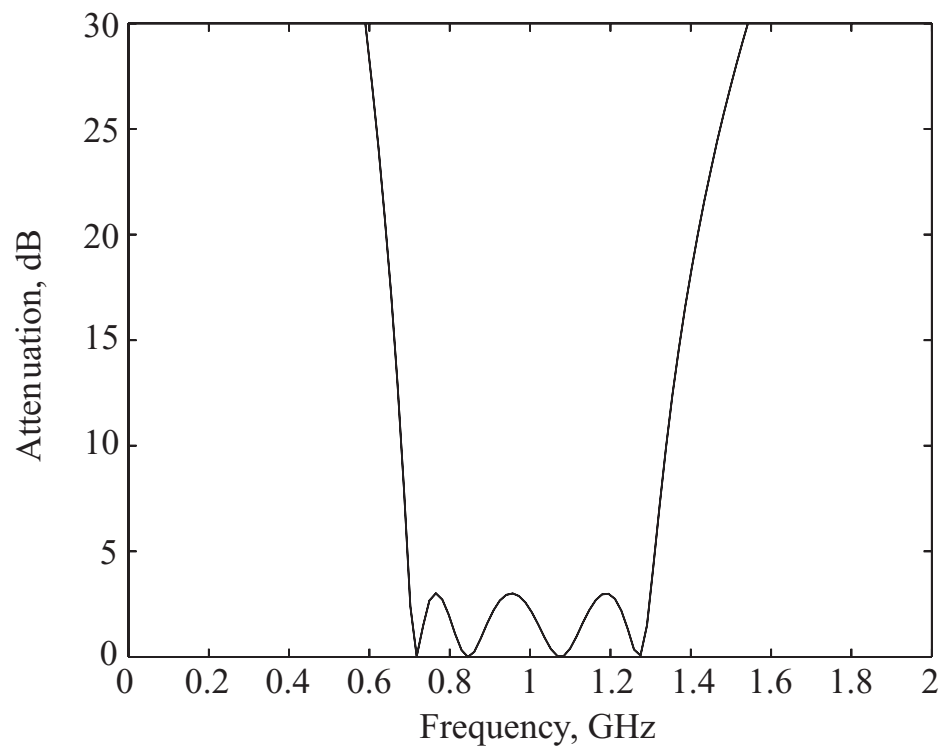
**Figure 5-25** Conversion of standard low-pass filter prototype into low-pass realization. Cut-off frequency is  $f_c = 1$  GHz.



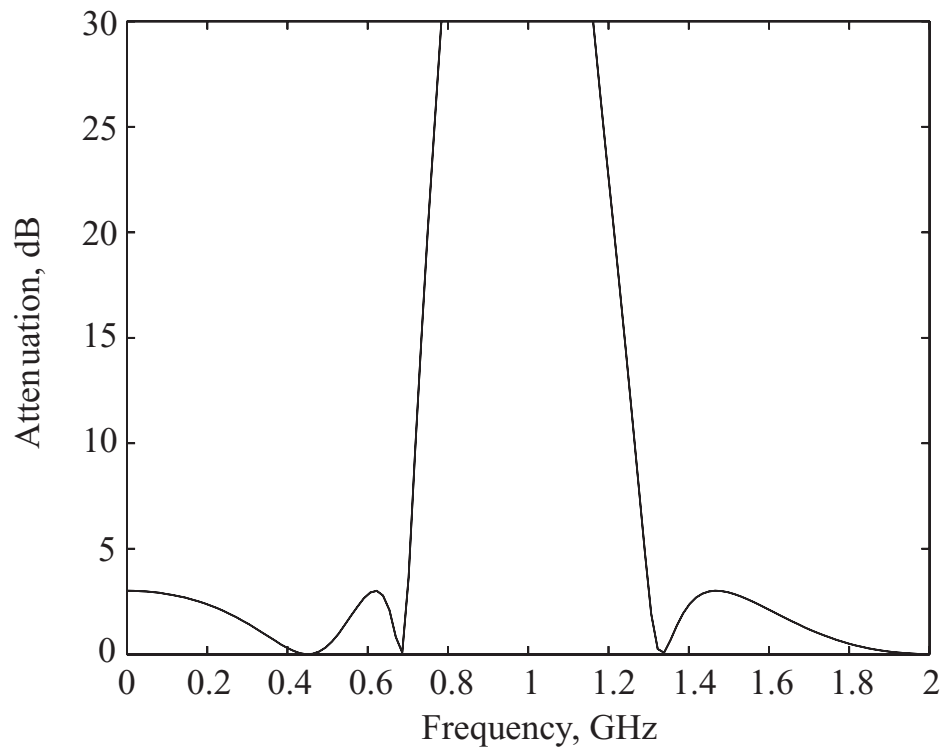
**Figure 5-26** Conversion of standard low-pass filter prototype into high-pass realization. Cut-off frequency is  $f_c = 1$  GHz.



**Figure 5-27** Mapping from standard frequency  $\Omega$  into actual frequency  $\omega$ . Lower cut-off frequency is  $\omega_L = 1$  and upper cut-off frequency is  $\omega_U = 3$ .

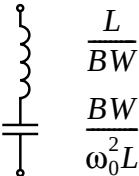
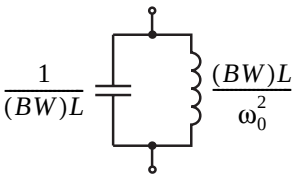
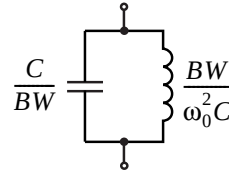
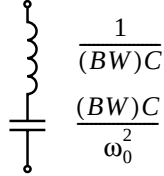


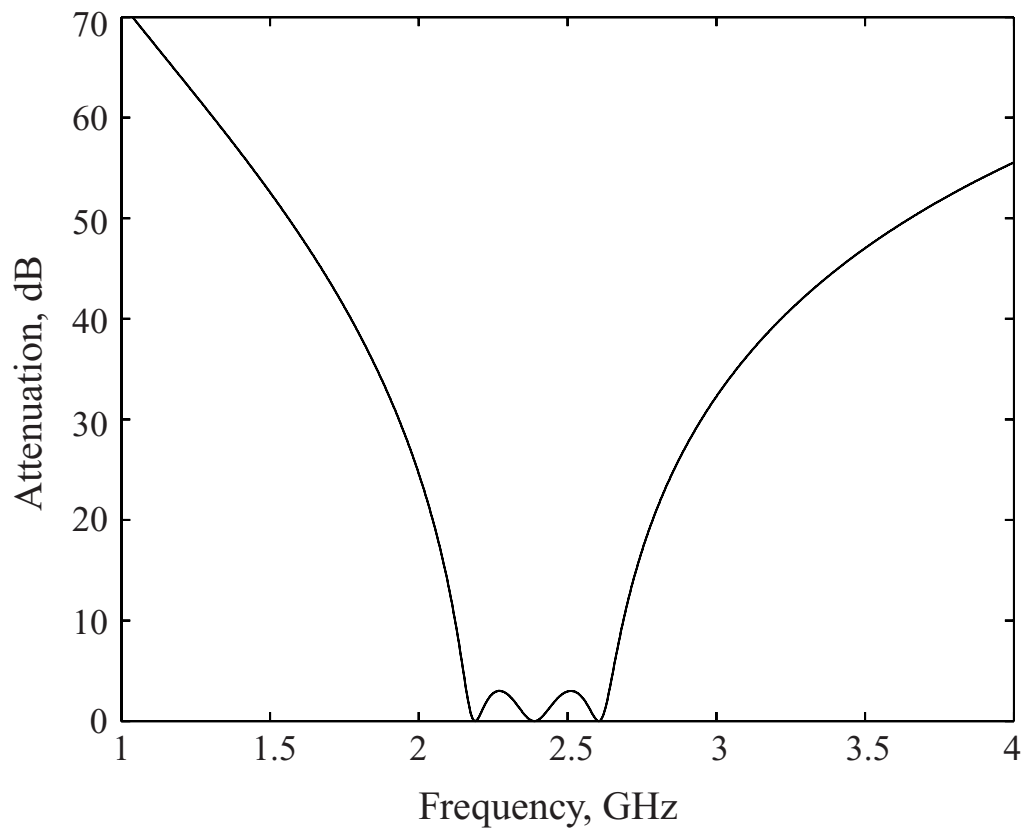
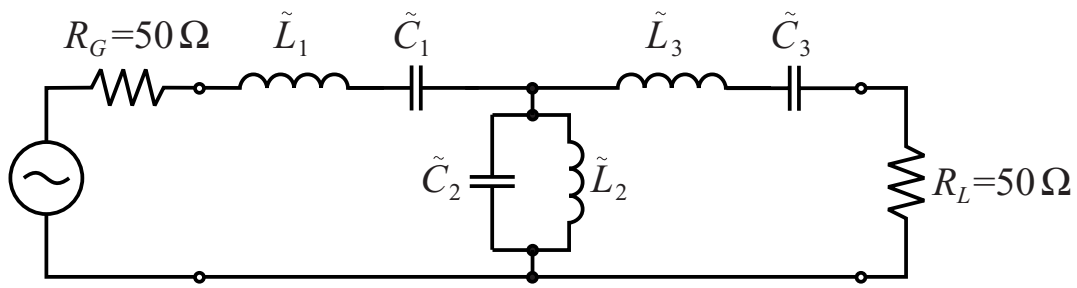
**Figure 5-28** Conversion of standard low-pass filter prototype into bandpass realization with lower cut-off frequency  $f_L = 0.7$  GHz, upper cut-off frequency  $f_U = 1.3$  GHz, and center frequency of  $f_0 = 1$  GHz.



**Figure 5-29** Conversion of standard low-pass filter prototype into band-stop realization with center frequency of  $f_0 = 1$  GHz. Lower cut-off frequency is  $f_L = 0.7$  GHz and upper cut-off frequency is  $f_U = 1.3$  GHz.

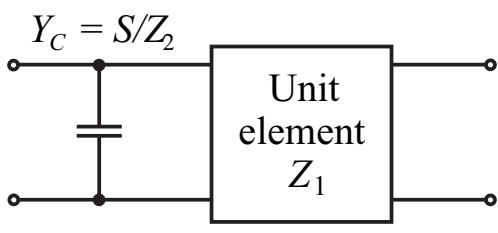
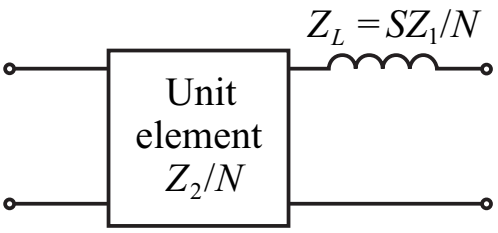
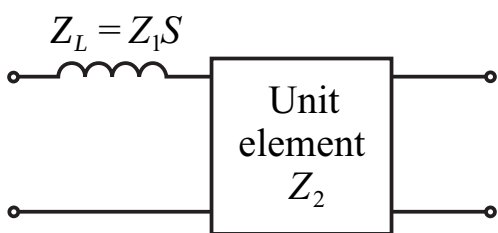
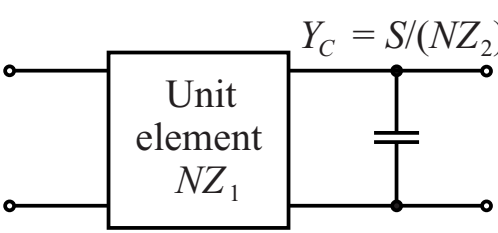
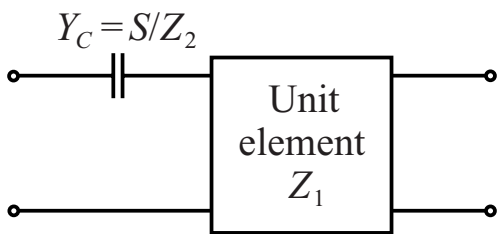
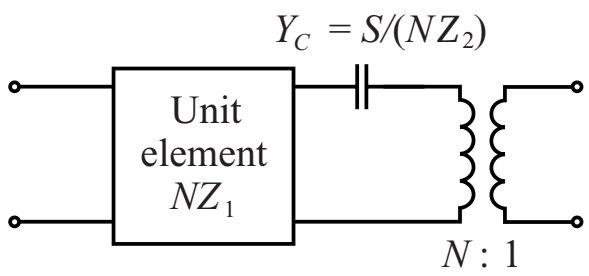
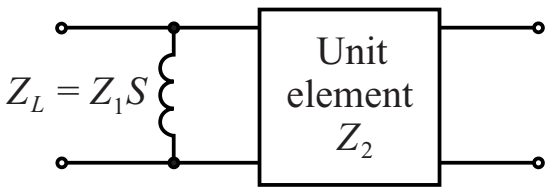
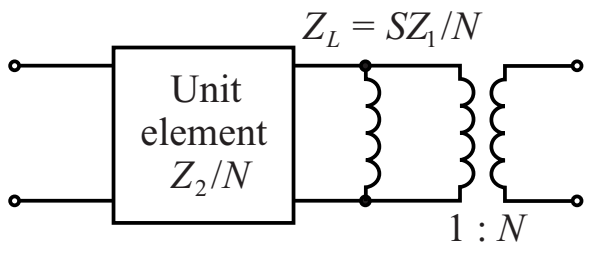
**Table 5-5** Transformation between normalized low-pass filter and actual bandpass and bandstop filter  
 $(BW = \omega_U - \omega_L)$

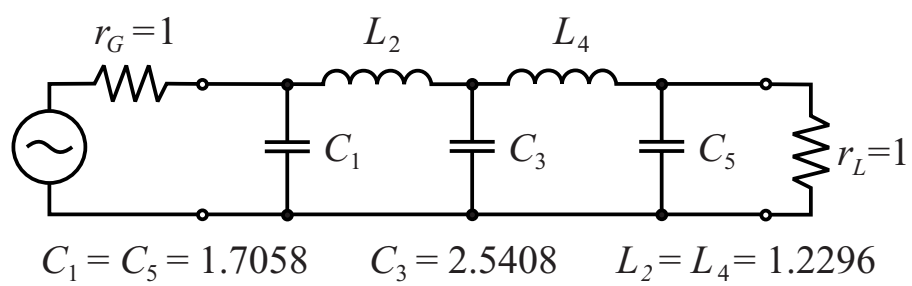
| Low-pass prototype                                                                          | Low-pass                                                                                               | High-pass                                                                                                | Bandpass                                                                                                                      | Bandstop                                                                                                                            |
|---------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
|  $L = g_k$ |  $\frac{L}{\omega_c}$ |  $\frac{1}{\omega_c L}$ |  $\frac{L}{BW}$<br>$\frac{BW}{\omega_0^2 L}$ |  $\frac{1}{(BW)L}$ $\frac{(BW)L}{\omega_0^2}$    |
|  $C = g_k$ |  $\frac{C}{\omega_c}$ |  $\frac{1}{\omega_c C}$ |  $\frac{C}{BW}$ $\frac{BW}{\omega_0^2 C}$    |  $\frac{1}{(BW)C}$<br>$\frac{(BW)C}{\omega_0^2}$ |



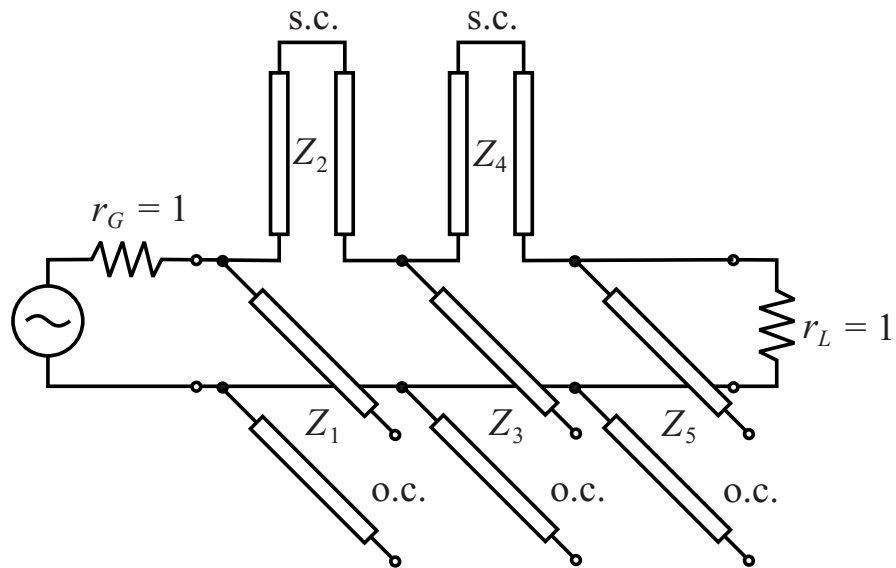
**Figure 5-30** Attenuation response of a third-order 3-dB ripple bandpass Chebyshev filter centered at 2.4 GHz. The lower cut-off frequency is  $f_L = 2.16$  GHz and the upper cut-off frequency is  $f_U = 2.64$  GHz.

**Table 5-6** Kuroda's Identities

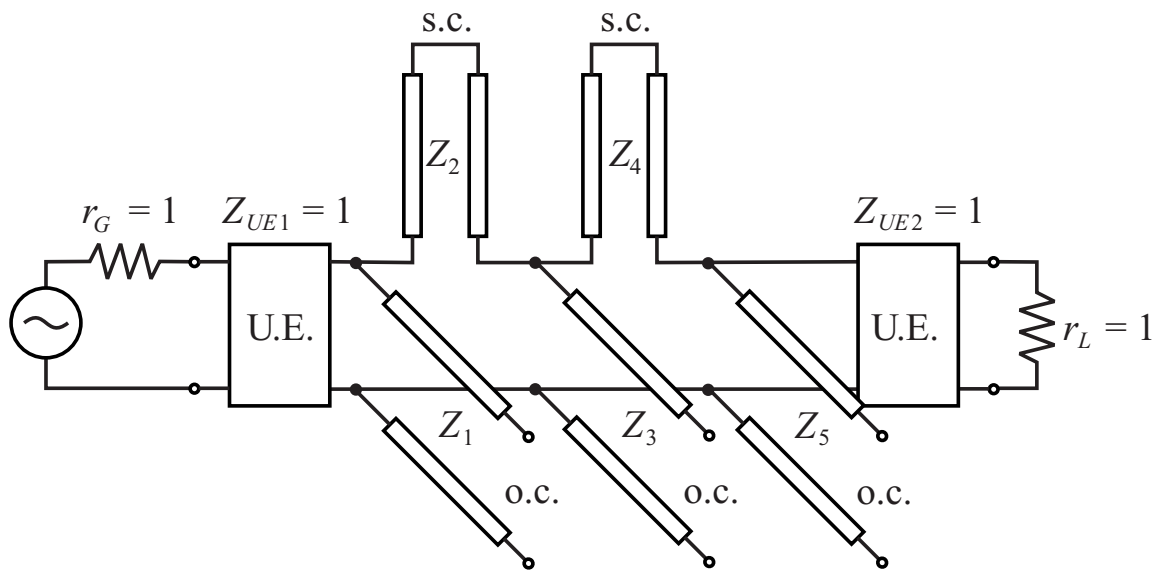
| Initial Circuit                                                                                                                                                                                                                                    | Kuroda's Identity                                                                                                                                                                                                                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>Initial circuit: A shunt capacitor with admittance <math>Y_C = S/Z_2</math> is connected to the input of a unit element with impedance <math>Z_1</math>.</p>  |  <p>Kuroda's Identity: A unit element with impedance <math>Z_2/N</math> is connected to the input, followed by a series inductor with impedance <math>Z_L = SZ_1/N</math>.</p>                                   |
|  <p>Initial circuit: A series inductor with impedance <math>Z_L = Z_1S</math> is connected to the input of a unit element with impedance <math>Z_2</math>.</p>    |  <p>Kuroda's Identity: A unit element with impedance <math>NZ_1</math> is connected to the input, followed by a shunt capacitor with admittance <math>Y_C = S/(NZ_2)</math>.</p>                                 |
|  <p>Initial circuit: A shunt capacitor with admittance <math>Y_C = S/Z_2</math> is connected to the input of a unit element with impedance <math>Z_1</math>.</p> |  <p>Kuroda's Identity: A unit element with impedance <math>NZ_1</math> is connected to the input, followed by a series combination of a capacitor and an inductor forming an <math>N:1</math> transformer.</p>  |
|  <p>Initial circuit: A series inductor with impedance <math>Z_L = Z_1S</math> is connected to the input of a unit element with impedance <math>Z_2</math>.</p>  |  <p>Kuroda's Identity: A unit element with impedance <math>Z_2/N</math> is connected to the input, followed by a series combination of an inductor and a capacitor forming a <math>1:N</math> transformer.</p> |
| $V = 1 + Z_2/Z_1$                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                    |



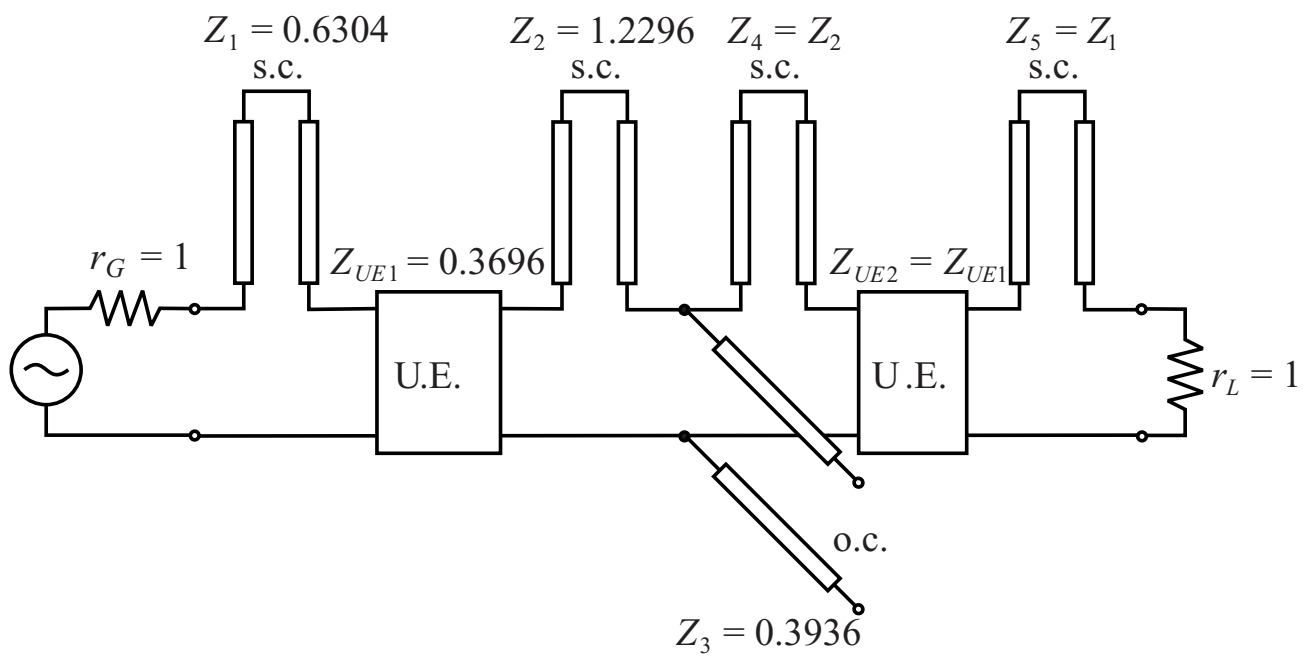
**Figure 5-31** Normalized low-pass filter of order  $N = 5$ .



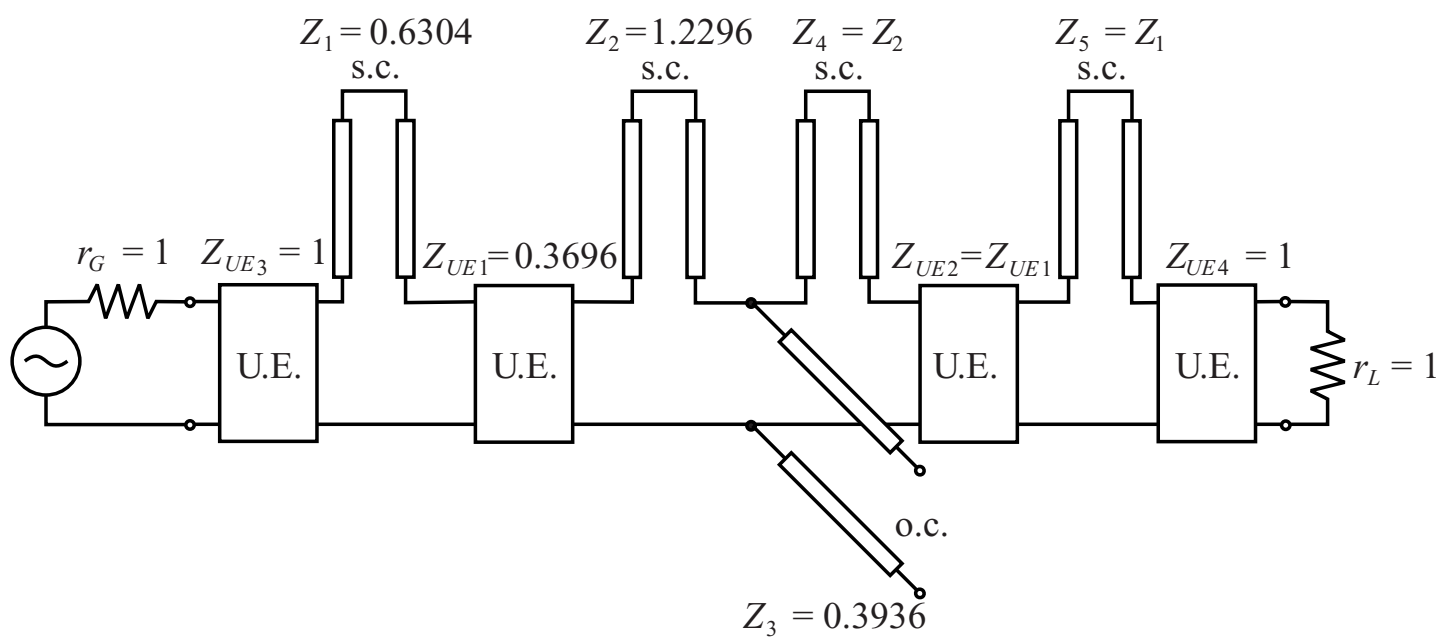
**Figure 5-32** Replacing inductors and capacitors by series and shunt stubs (o.c. = open circuit line, s.c. = short circuit line).



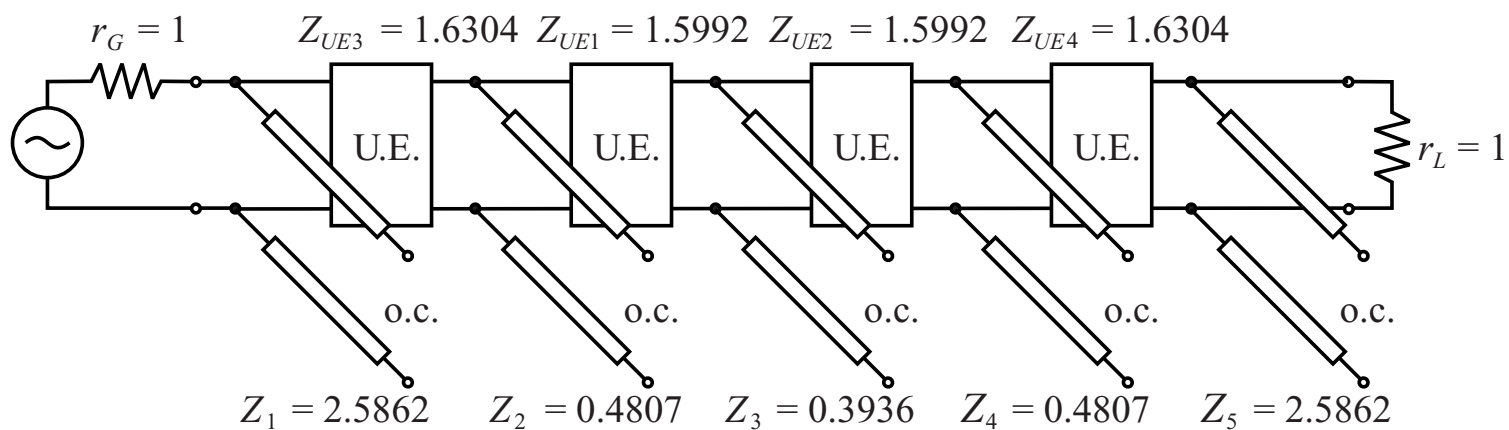
**Figure 5-33** Deployment of the first set of unit elements (U.E. = unit element).



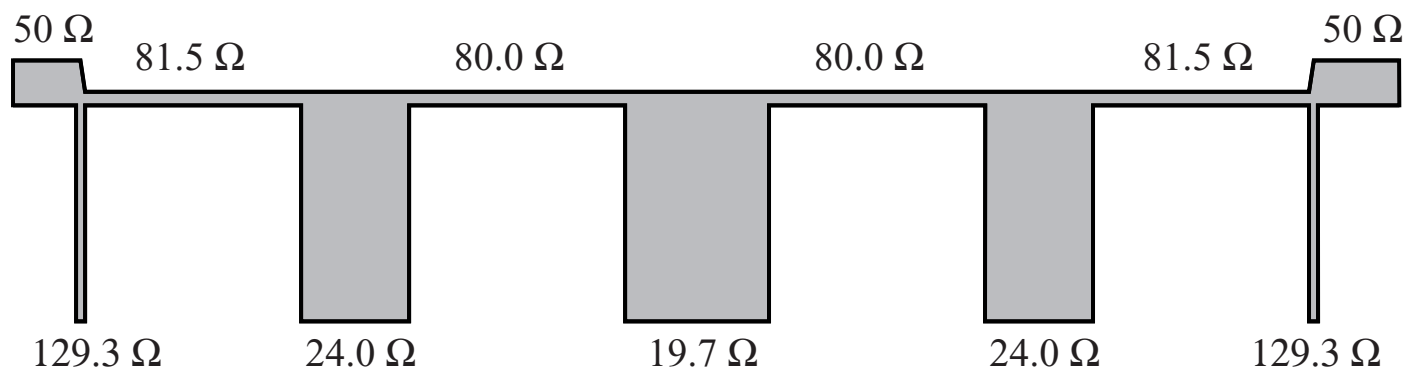
**Figure 5-34** Converting shunt stubs to series stubs.



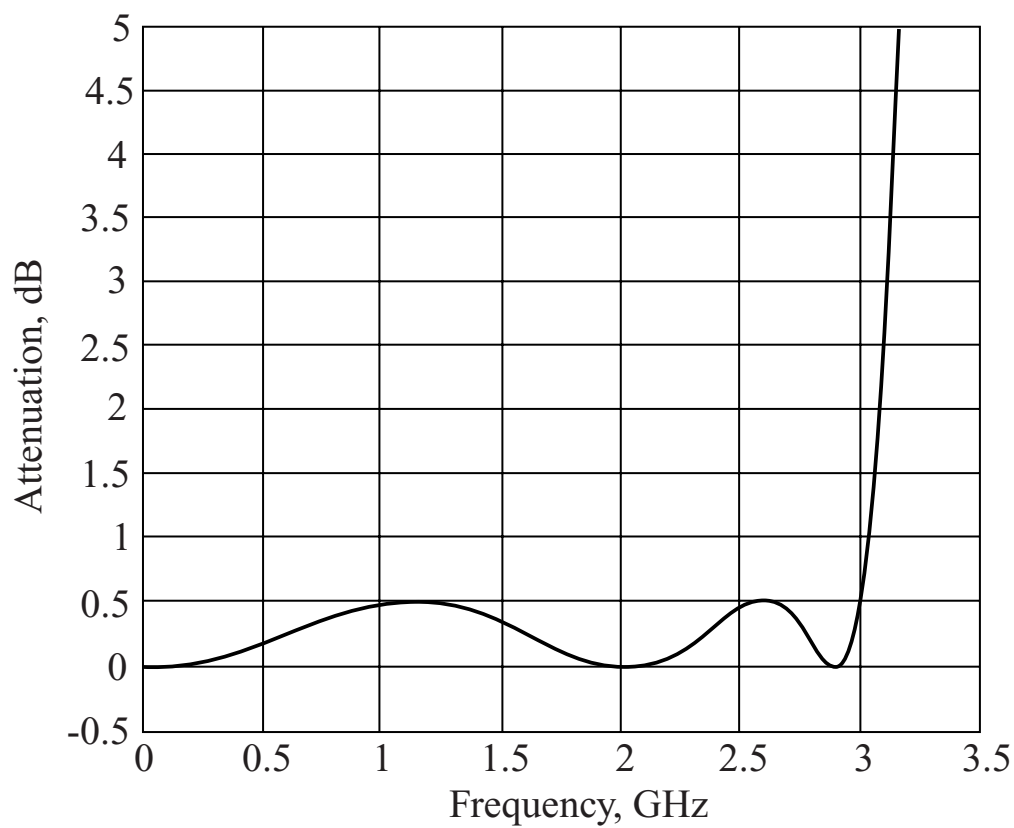
**Figure 5-35** Deployment of the second set of unit elements to the fifth-order filter.



**Figure 5-36** Realizable filter circuit obtained by converting series and shunt stubs using Kuroda's identities.

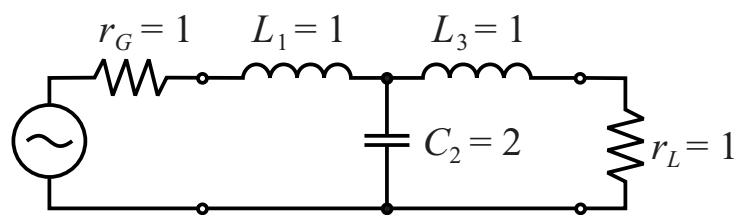


(a) Microstrip line low-pass filter implementation

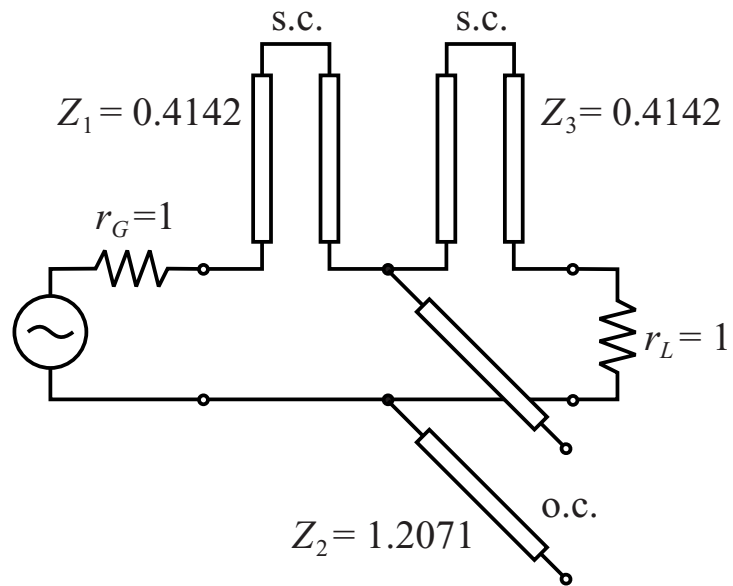


(b) Attenuation versus frequency response

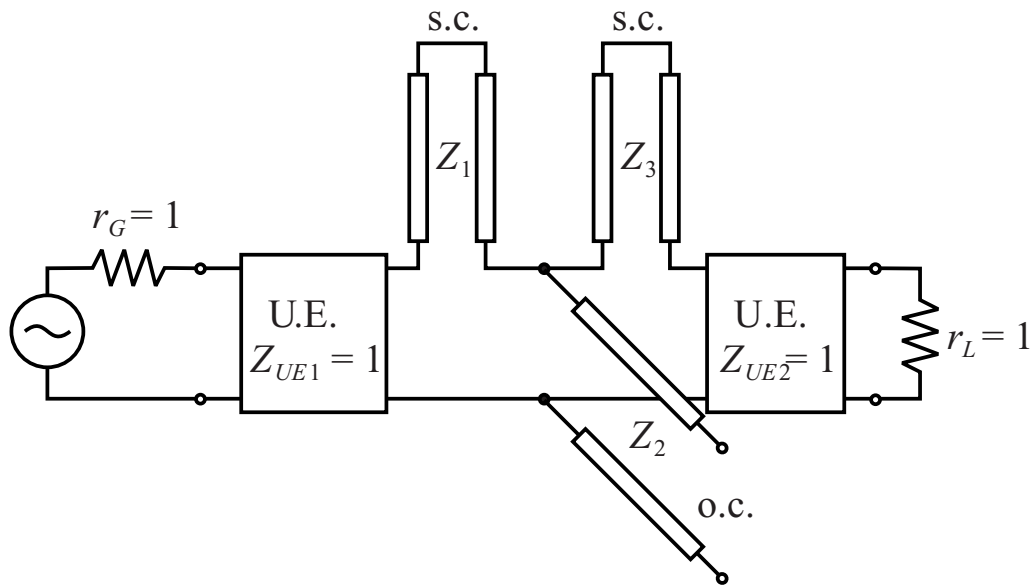
**Figure 5-37** Final microstrip line low-pass filter.



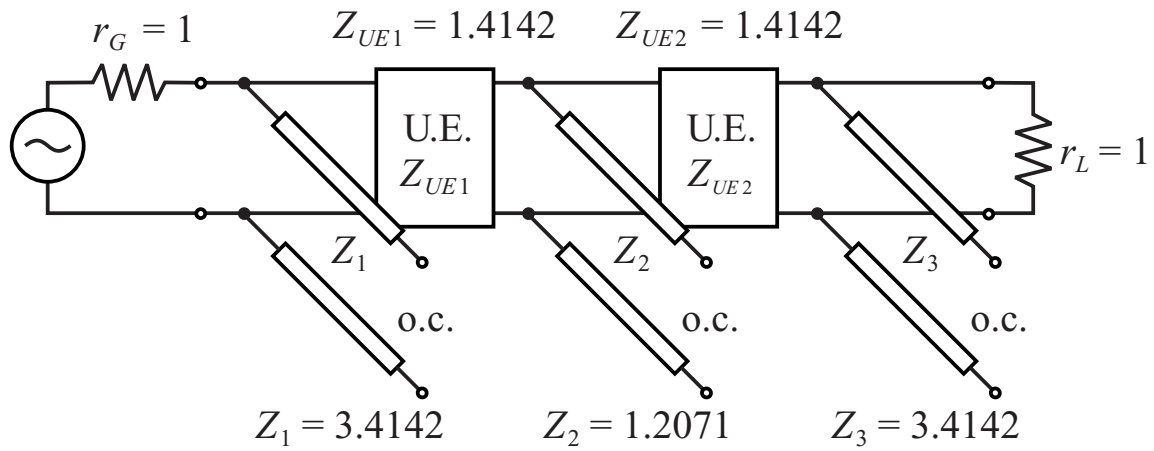
**Figure 5-38** Normalized third-order low-pass filter.



**Figure 5-39** Replacing inductors and capacitors by series and shunt stubs.

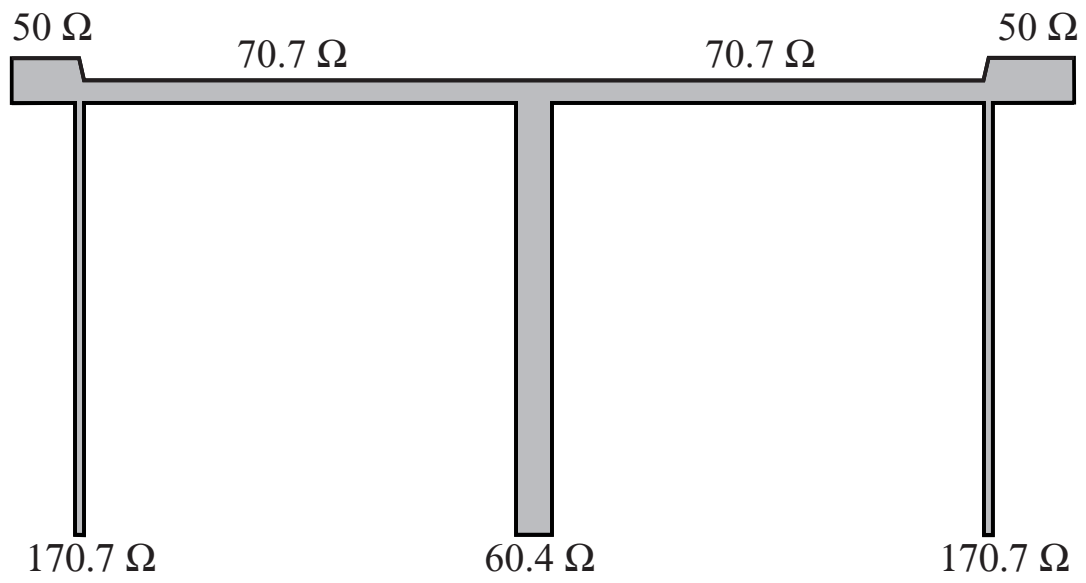


(a) Unit elements at source and load sides

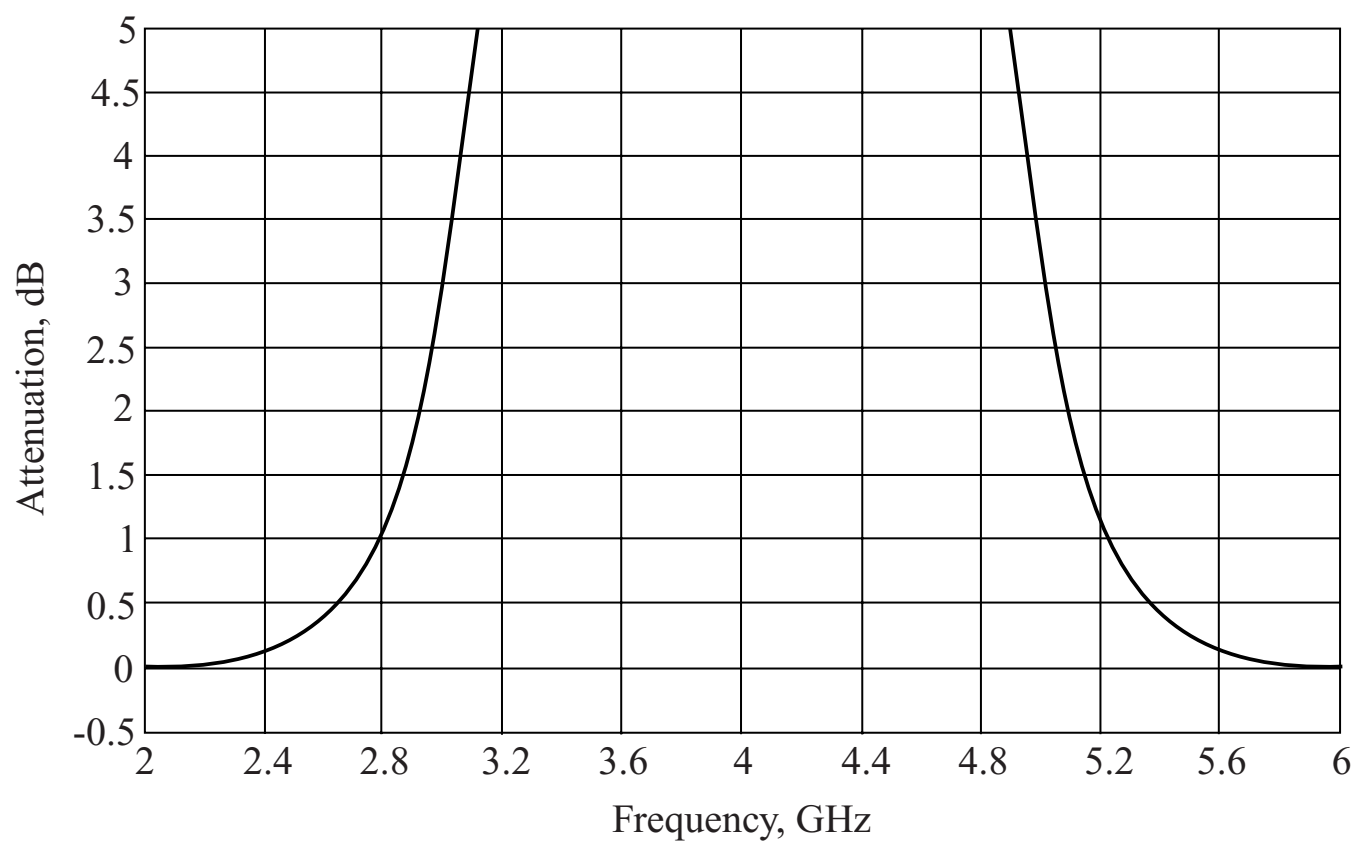


(b) Conversion from series to shunt stubs

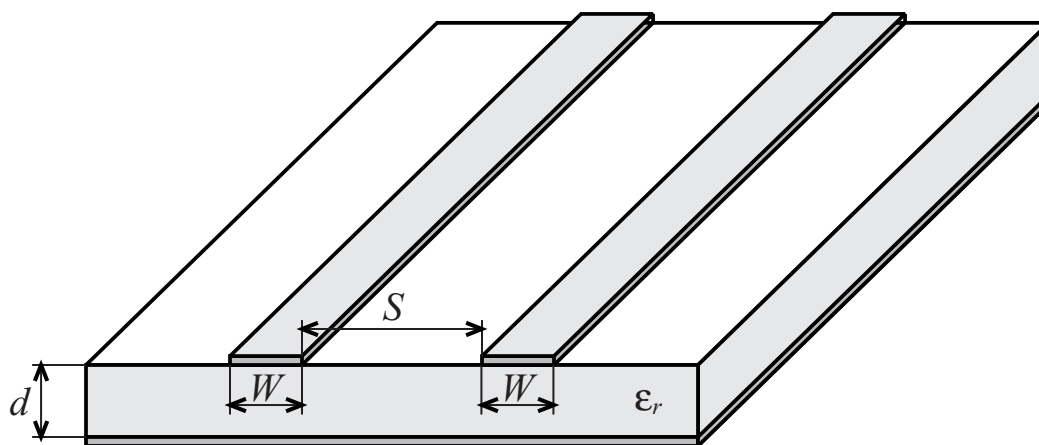
**Figure 5-40** Introducing unit elements and converting series stubs to shunt stubs.



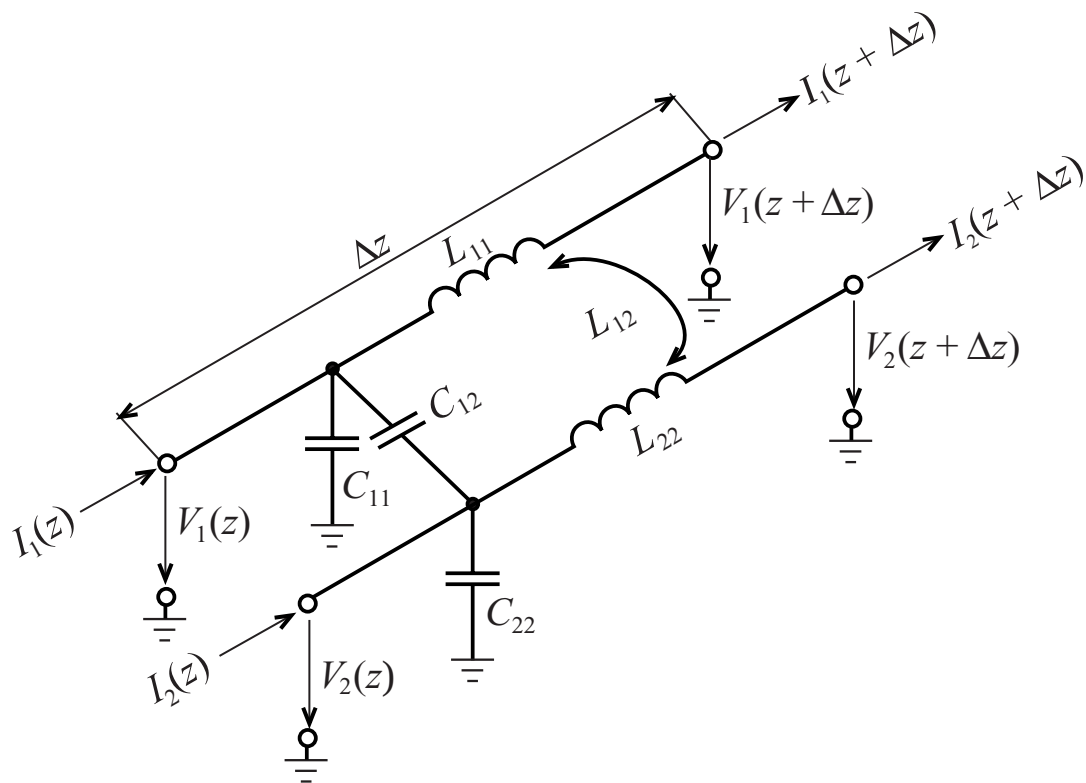
**Figure 5-41** Characteristic impedances of final microstrip line implementation of bandstop filter design.



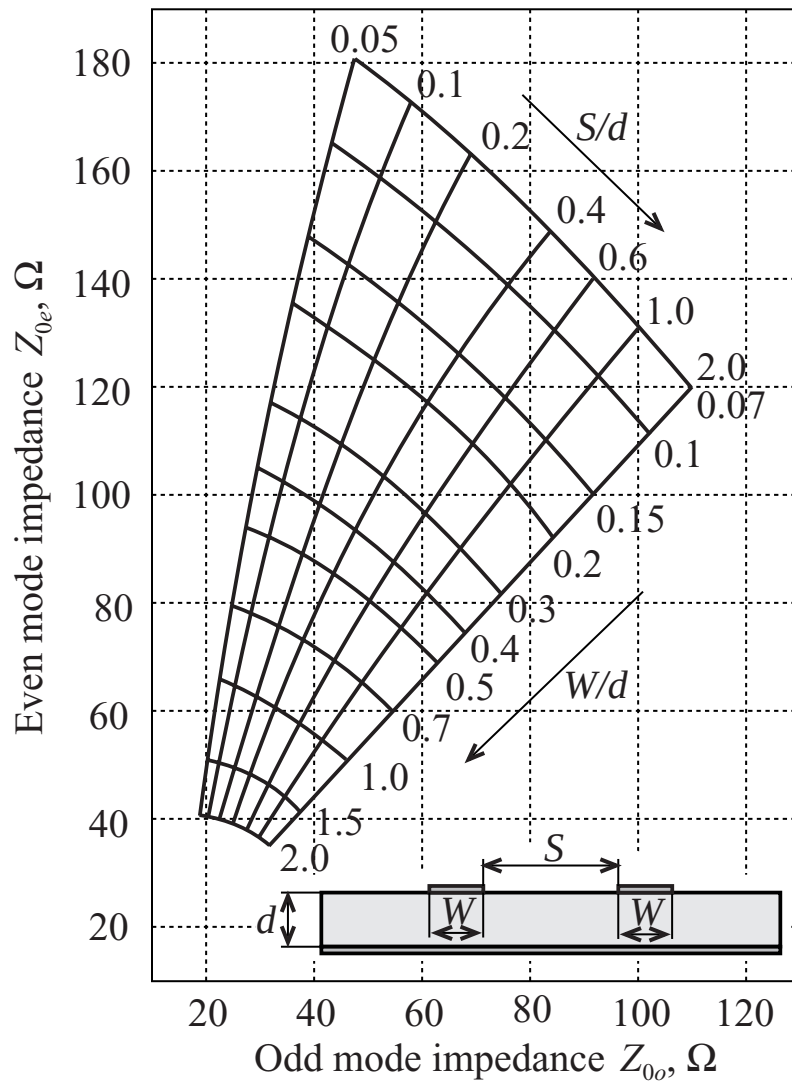
**Figure 5-42** Attenuation versus frequency response for third-order bandstop filter.



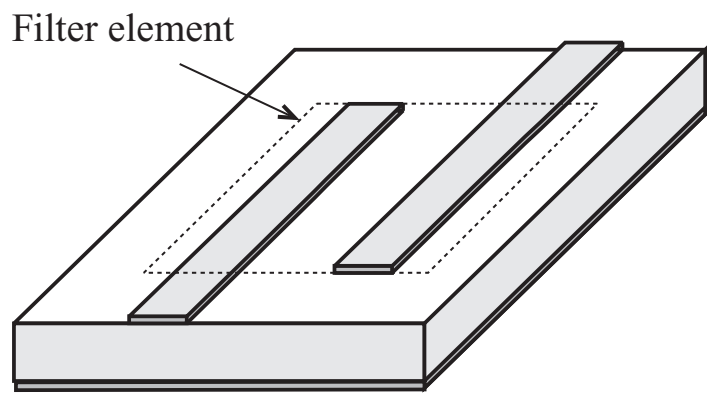
**Figure 5-43** Coupled microstrip lines.



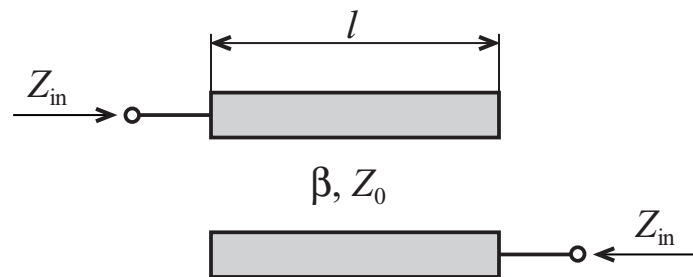
**Figure 5-44** Equivalent circuit diagram and appropriate voltage and current definitions for a system of two lossless coupled transmission lines.



**Figure 5-45** Even and odd characteristic impedance for microstrip lines.

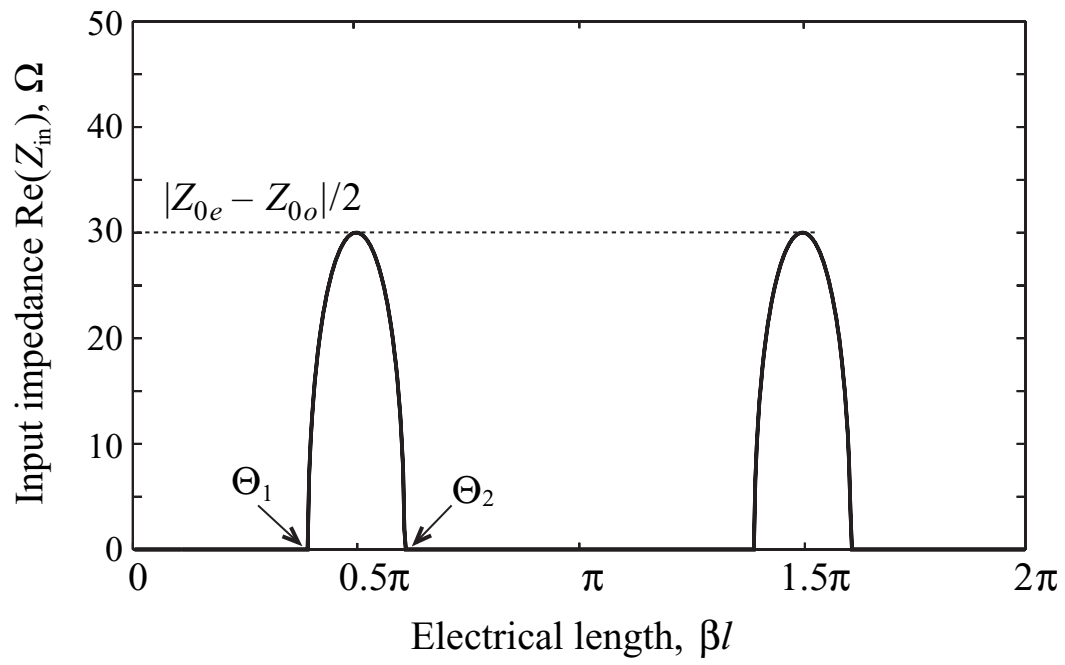


(a) Arrangement of two microstrip lines

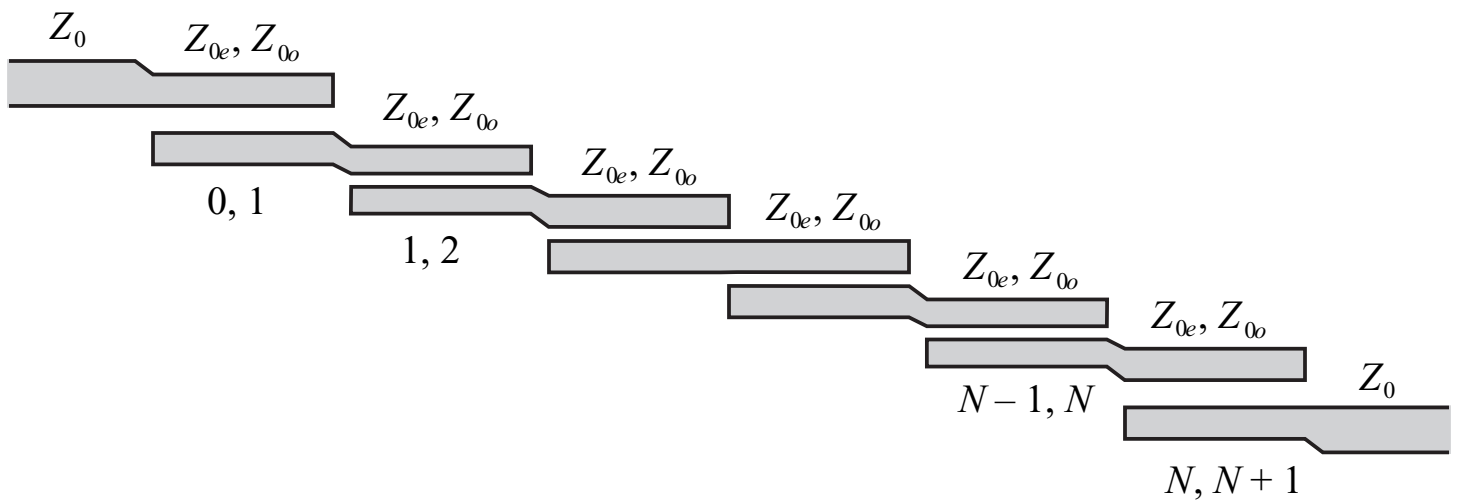


(b) Transmission line representation

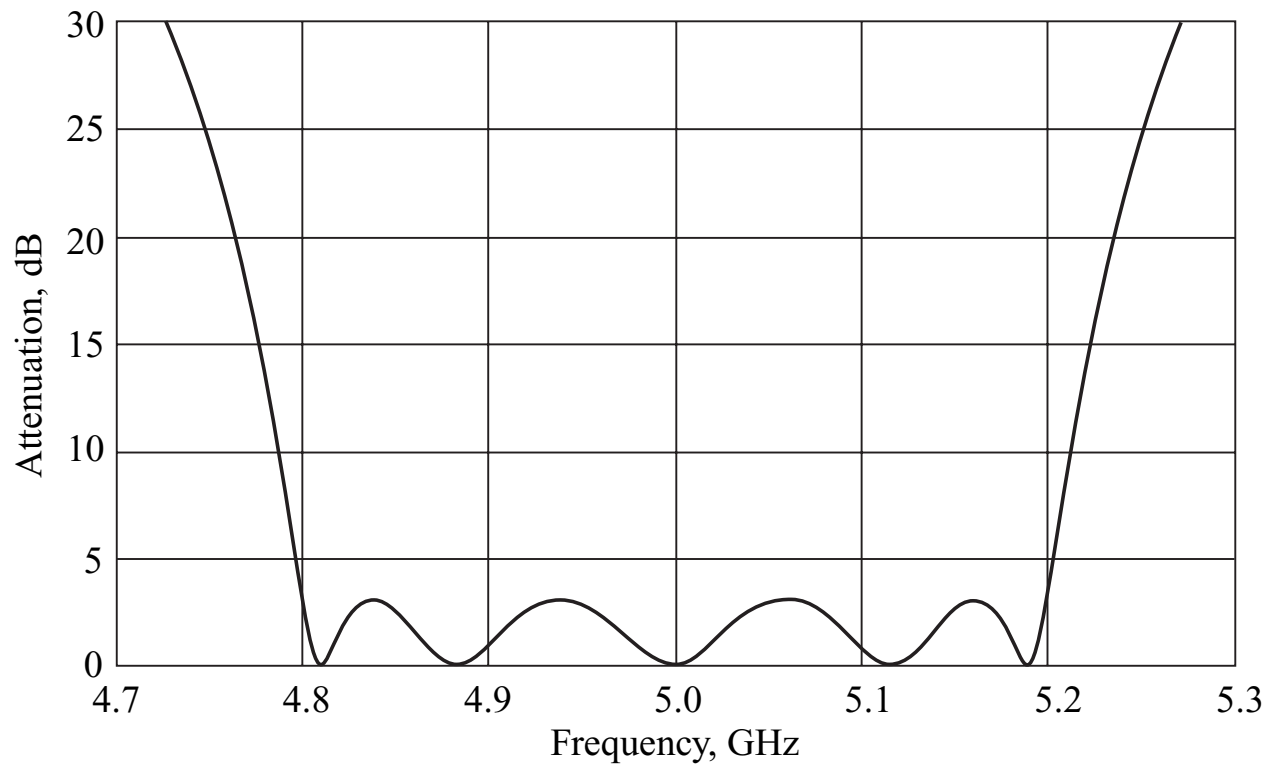
**Figure 5-46** Bandpass filter element.



**Figure 5-47** Input impedance behavior of equation (5.70).  $Z_{0e}$  and  $Z_{0o}$  are arbitrarily set to  $120 \Omega$  and  $60 \Omega$ , respectively.



**Figure 5-48** Multielement configuration of a fifth-order coupled-line bandpass filter ( $N = 5$ ).



**Figure 5-49** MMICAD simulations of the fifth-order coupled-line Chebyshev bandpass filter with 3 dB ripple in the passband. The lower cut-off frequency is 4.8 GHz and the upper cut-off frequency is 5.2 GHz.