Manual Filter Design

Each topology of filter has its own mathematical techniques to determine the filter components, given the frequencies and attenuations that define the filter behavior. These techniques are very precise, involving the use of tables and scaling techniques as discussed in the following sections. With the availability of filter design software, such as *Elsie* and *SVC Filter Designer* (both available with the online supplemental content) filters using different topologies can be designed easily, however. (Additional programs and design resources are listed in the References section at the end of the **Analog and Digital Filtering** chapter of the *ARRL Handbook*.)

Whether designing a filter manually or through the use of software, the design process begins with developing a set of filter *performance requirements* for:

- Type of response — low-pass, high-pass, band-pass, band-stop, or all-pass.
- Passband ripple — none or some maximum amount.
- Cutoff frequency (or frequencies) or bandwidth.
- Steepness of rolloff in transition region.
- Minimum stop-band attenuation and stop-band depth (optional).
- Group delay (optional).

The requirements shown as optional may not be important for simple filters. The next step is to identify the filter families that can meet those requirements. For example, if no ripple is allowed in the passband, the Butterworth or Bessel filter families would be suitable. If a very steep rolloff is required, try the Chebyshev or Cauer family.

After entering the basic requirements into the filter design software and observing the results of the calculation, the design is likely to require some adjustment. Component values can be unrealistic or the required order may be too high for practical implementation. At this point, your experience with filter design helps guide the choices of what changes to make — a different filter family, raising or lowering some of your requirements and so forth. The key is to experiment and observe to build understanding of filters.

Filter design and analysis programs show the responses of the resulting network in graphic form. This makes it easy to compare your filter to your requirements, making design adjustments quickly. Many design packages also allow the selection of nearest-5% values, tuning and other useful features. For example, the program *SVC Filter Designer* (SVC is *standard value component*) automatically selects the nearest 5% capacitor values. It selects the nearest 5% inductor values as an option. It also shows the resulting response degradations (which may be minor).

Although filter-design software has greatly simplified the design of lumped-element filters, going through the manual design process, which is based on the use of tables of component values, will give some insight into how to make better use the software to develop and refine a filter.

1 Transforming Filter Types

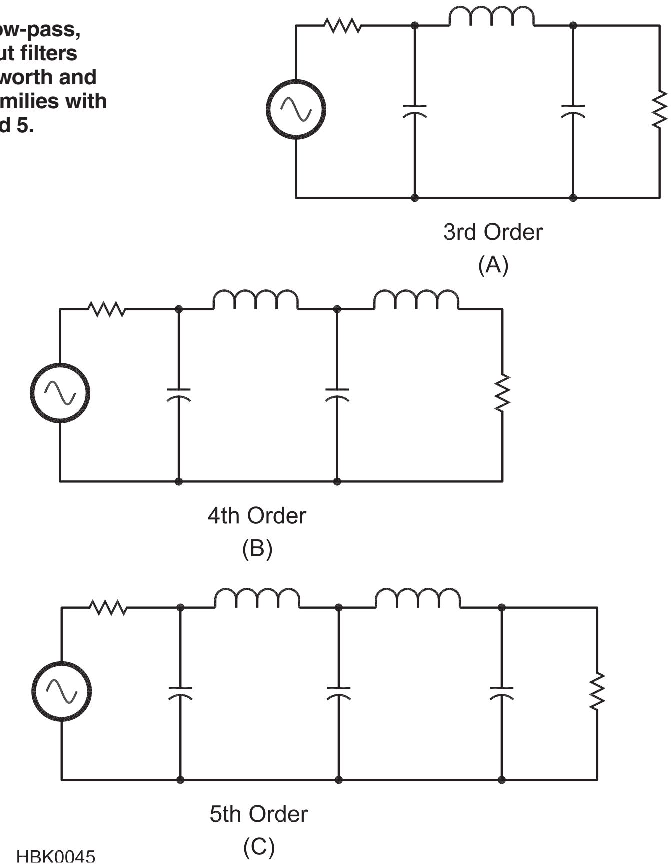
1.1 Low-Pass to Band-Pass Transformation

A band-pass filter is defined in part by a *bandwidth* and a *center frequency*. (An alternative method is to specify a lower and an upper cutoff frequency.) A low-pass design such as the one shown in **Figure 1A** can be converted to a band-pass filter by resonating each of the elements at the center frequency. **Figure 2** shows a third-order low-pass filter with a design bandwidth of 2 MHz for use in a 50-Ω system. It should be mentioned that the next several designs and the various manipulations were done using a computer.

If the shunt elements are now resonated with a parallel component, and if the series elements are resonated with a series component, the result is a band-pass filter as shown in **Figure 3**. The series inductor value and the shunt capacitor values are the same as those for the original low-pass design. Those components have been resonated at the center frequency for the filter (2.828 MHz in this case).

Now we can compare the magnitude response of the original low-pass filter with the band-pass design; the two responses are shown in **Figure 4**. The magnitude response of the low-pass version of this filter is down 3 dB at 2 MHz. The band-pass response is down 3 dB at 2 MHz and 4 MHz (the difference from the high side to the low side is 2 MHz). The response of the low-pass design is down 33 dB at 7 MHz while the response of the band-pass version is down 33 dB at 1 and 8 MHz (the difference from high side to low side is 7 MHz).

Figure 1 — Low-pass, capacitor-input filters for the Butterworth and Chebyshev families with orders 3, 4 and 5.



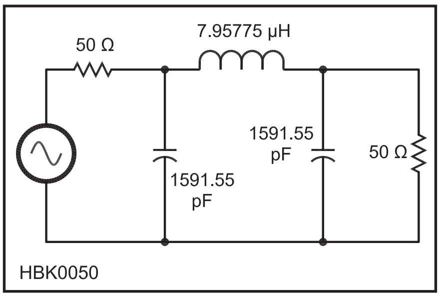


Figure 2 — Third-order low-pass filter with a bandwidth of 2 MHz in a 50 Ω system.

1.2 High-Pass to Band-Stop Transformation

Just as a low-pass filter can be transformed to a band-pass type, a high-pass filter can be transformed into a band-stop (also called a *band-reject*) filter. The procedures for doing this are similar in nature to those of the transformation from low-pass to band-pass. As with the band-pass filter example, to transform a high-pass to a band-stop we need to specify a center frequency. The bandwidth of a band-stop filter is measured between the frequencies at which the magnitude response drops 3 dB in the transition region into the stop band.

Figure 5 shows how to convert the 2 MHz capacitor-input high-pass filter of **Figure 6** to a band-stop filter centered at 2.828 MHz. The original high-pass components are resonated at the chosen center frequency to form a band-stop filter. Either a capacitor-input high-pass or an inductor-input high-pass may be transformed in this manner. In this case the series capacitor values and the shunt inductor values for the band-stop are the same as those for the high-pass. The series elements are resonated with an element in parallel with them. Similarly, the shunt elements are also resonated with an element in series with them. In each case the pair resonate at the center frequency of the band-stop. **Figure 7** shows the responses of both the original high-pass and the resulting band-stop filter.

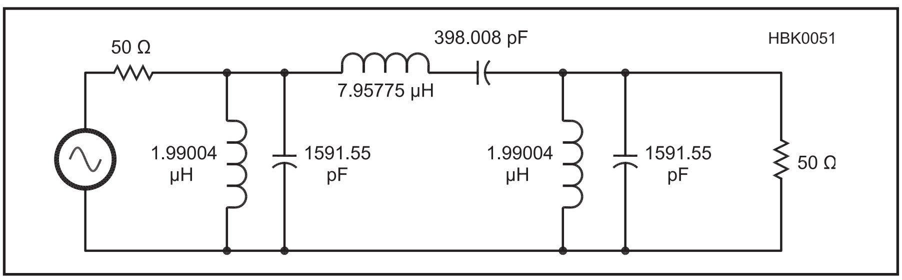


Figure 3 — The low-pass filter of Figure 2 can be transformed to a band-pass filter by resonating the shunt capacitors with a parallel inductor and resonating the series inductor with a series capacitor. Bandwidth is 2 MHz and the center frequency is 2.828 MHz.

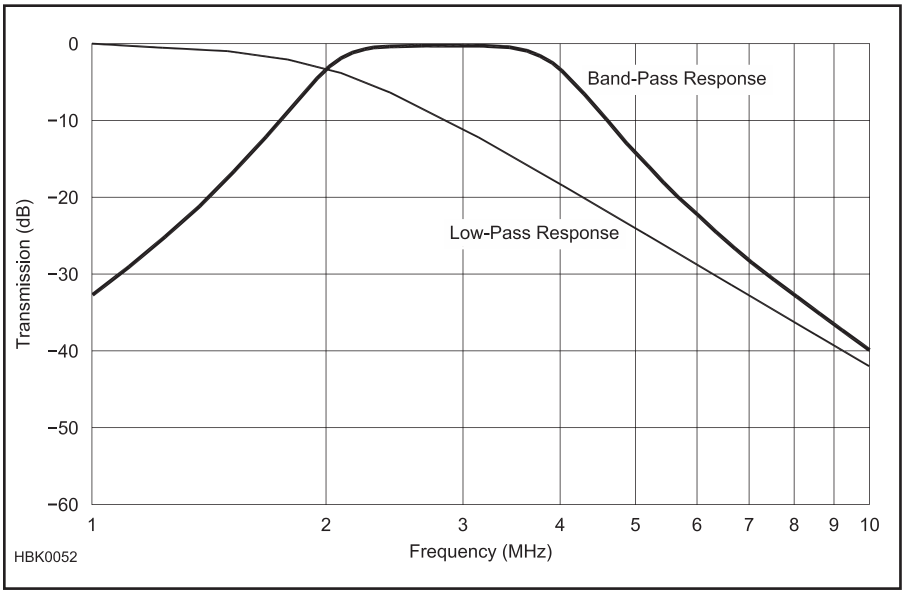


Figure 4 — Comparison of the response of the low-pass filter of Figure 2 with the band-pass design of Figure 3.

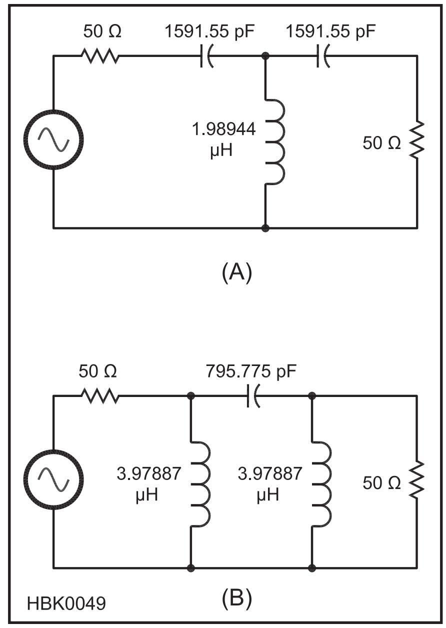


Figure 6 — Capacitor-input (A) and inductor-input (B) high-pass filters. Both designs have a 2 MHz cutoff.

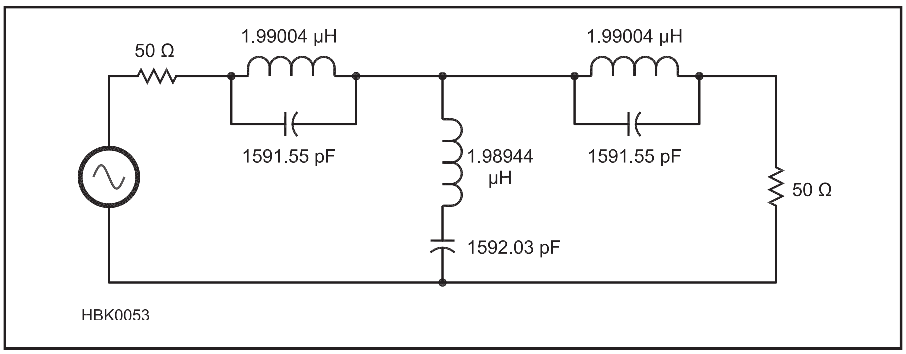


Figure 5 — The high-pass filter of Figure 6 can be converted to a band-stop filter with a bandwidth of 2 MHz, centered at 2.828 MHz.

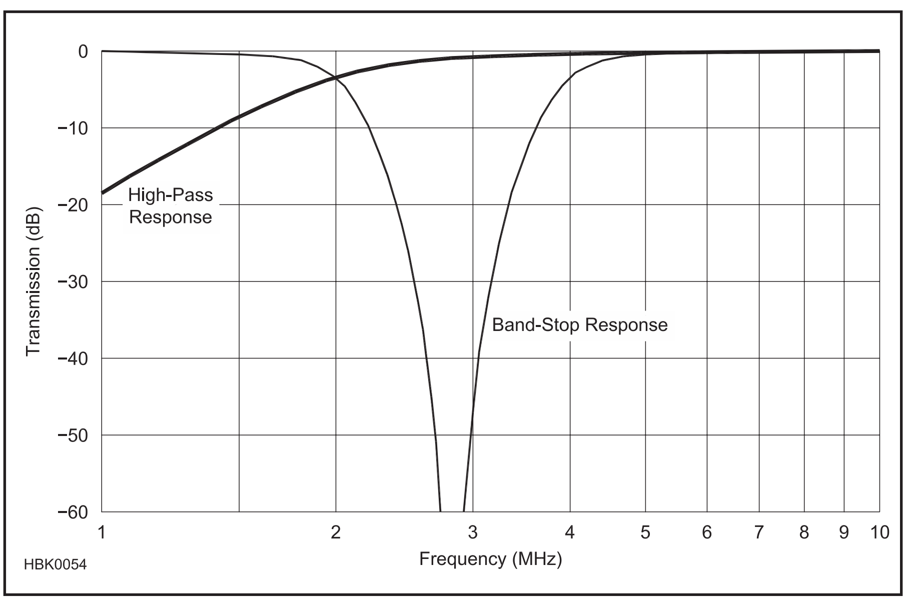


Figure 7 — Comparison of the response of the high-pass filter of Figure 6A with the band-stop design of Figure 5.

1.3 Refinements in Band-Pass Design

The method of transforming a low-pass filter to a band-pass filter described previously is simple, but it has a major drawback. The resulting component values are often awkward for building a narrowband band-pass filter or inappropriate for the frequencies involved. This can be addressed through additional transformation techniques or by changing the filter to a different *topology* (the general organization of the filter circuit elements and how they are connected).

The following discussion shows an example of band-pass filter design, starting with a low-pass filter and then applying various techniques to create a filter with appropriate component values and improved response characteristics. These transformations are tedious and are best done using filter design software. Some manual design methods are presented later in this chapter.

Figure 8 shows a band-pass filter centered at 3 MHz with a width of 100 kHz that was designed by resonating the elements of a 3-MHz low-pass ladder-type filter as previously described. This filter is impractical for several reasons. The shunt capacitors (0.0318 μF) will probably have poor characteristics at the center frequency of 3 MHz because of the series inductance likely to be present in a practical capacitor of that value. Similarly, because of parasitic capacitance, the series inductor (159 μH) will certainly have a parallel self-resonance that is quite likely to alter the filter's response. For a nar-

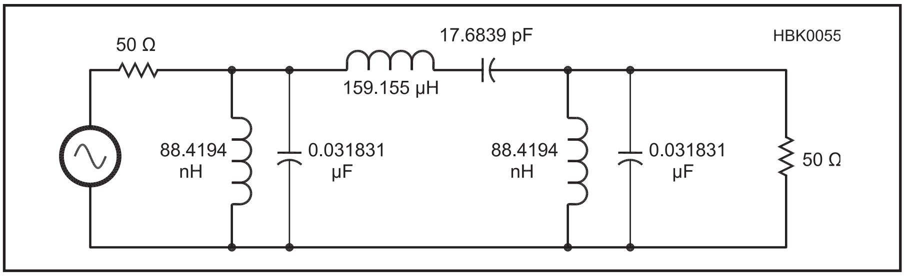


Figure 8 — This band-pass filter, centered at 3 MHz with a bandwidth of 100 kHz, was designed using a simple transformation. The resulting component values make the design impractical, as discussed in the text.

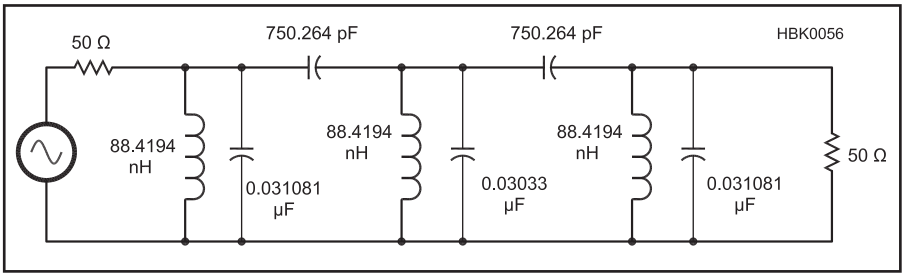


Figure 9 — A narrowband band-pass filter using a nodal-capacitor-coupled design improves component values somewhat.

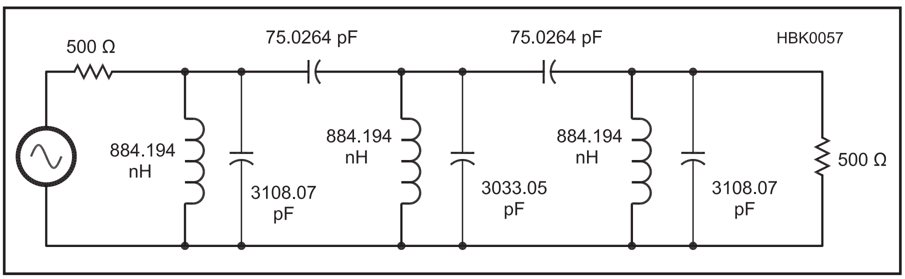


Figure 10 — The filter in Figure 9 scaled to an impedance of 500 Ω.

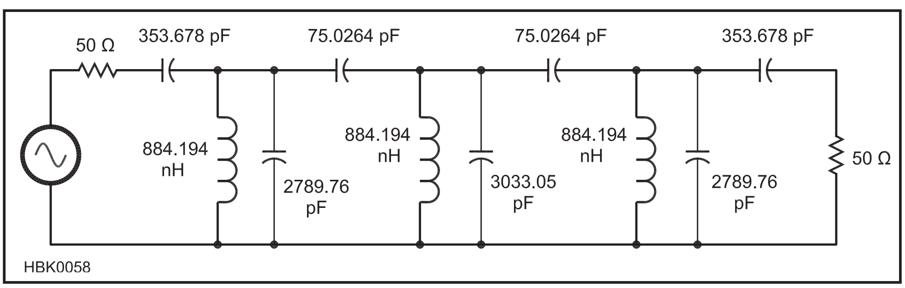


Figure 11 — Final design of the narrowband band-pass filter with 50 Ω terminations.

rowband band-pass filter, this method of transformation from low-pass to band-pass is not practical. (See the **RF Techniques** chapter for a discussion of parasitic effects.)

A better approach to narrowband band-pass filter design may be found by changing the filter topology. There are many different filter topologies, such as the LC "ladder" filters discussed in the preceding sections. One such topology is the *nodal-capacitor-coupled* design and **Figure 9** shows how the filter in Figure 8 can be redesigned using such an approach.

Some component values are improved, but the shunt capacitor values are still quite large for the center frequency of 3 MHz. In this case, the technique of *impedance scaling* offers some improvement. The filter was originally designed for a 50-Ω system. By scaling the filter impedance upwards from 50 to 500 Ω, the reactances of all elements are multiplied by a factor of 500 / 50 = 10. (Capacitors will get smaller and inductors larger.) The 0.03-µF capacitors will decrease in value to only 3000 pF, a much better value for a center frequency of 3 MHz. The shunt inductor values and the nodal coupling capacitor values (about 75 pF in this case) are also realistic. The 500 Ω version of the filter in Figure 9 is shown in **Figure 10**.

From a component-value viewpoint this is a better design, but it must be terminated in 500 Ω at each end. To use this filter in a 50-Ω system, impedance matching components must be added as shown in **Figure 11**. This topology is typical of a radio receiver front-end preselector or anywhere else that a narrow — in terms of percentage of the center frequency — filter is needed.

When the nodal capacitor-coupled band-pass topology is used for a filter whose bandwidth is wide (generally, a bandwidth 20% or more of the center frequency, f_0, resulting in a filter $Q = f_0 / BW$ less than 5), the attenuation at frequencies above the center frequency will be less than below the center frequency. This characteristic should be taken into account when attenuation of harmonics of signals in the passband is of concern. The filter shown in **Figure 12A** is designed to pass the amateur 75 meter band and suffers from this defect. By going to the *nodal inductor-coupled* topology

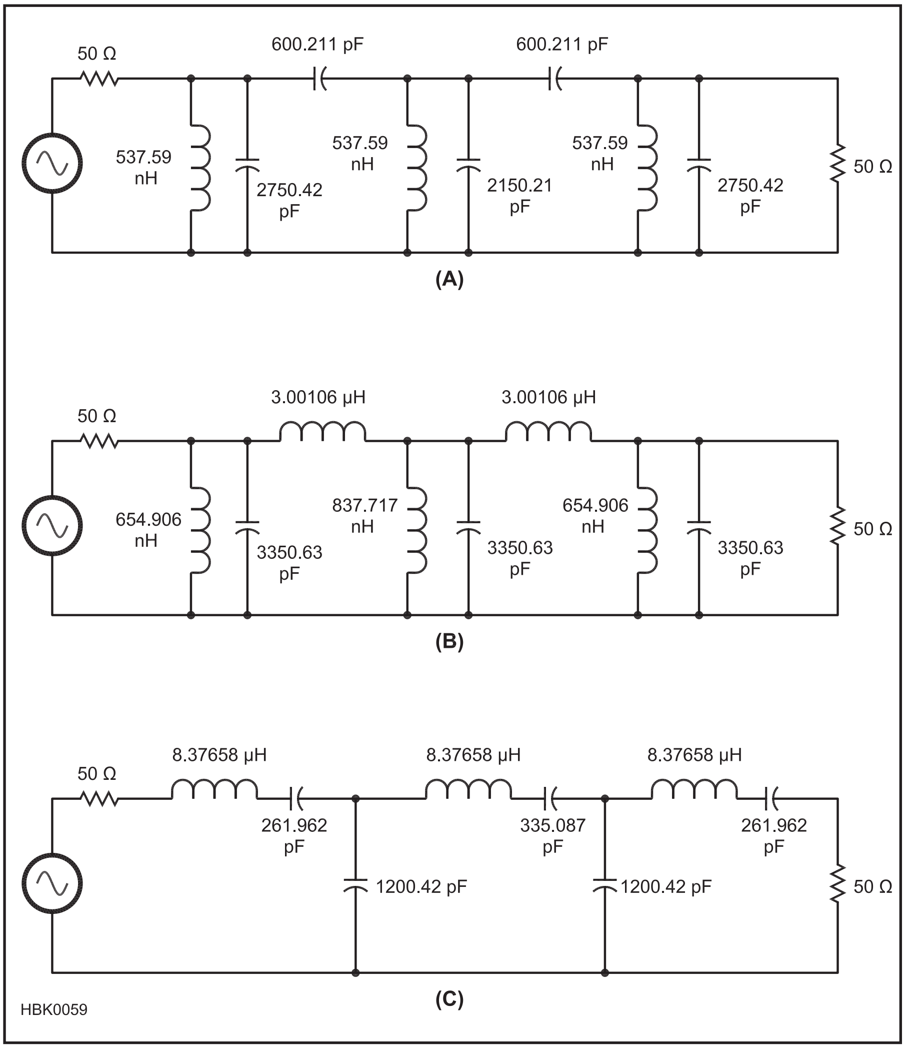


Figure 12 — Three band-pass filters designed to pass the 75 meter amateur band. The nodal-capacitor-coupled topology is shown at A, nodal-inductor-coupled at B, and mesh capacitor-coupled at C.

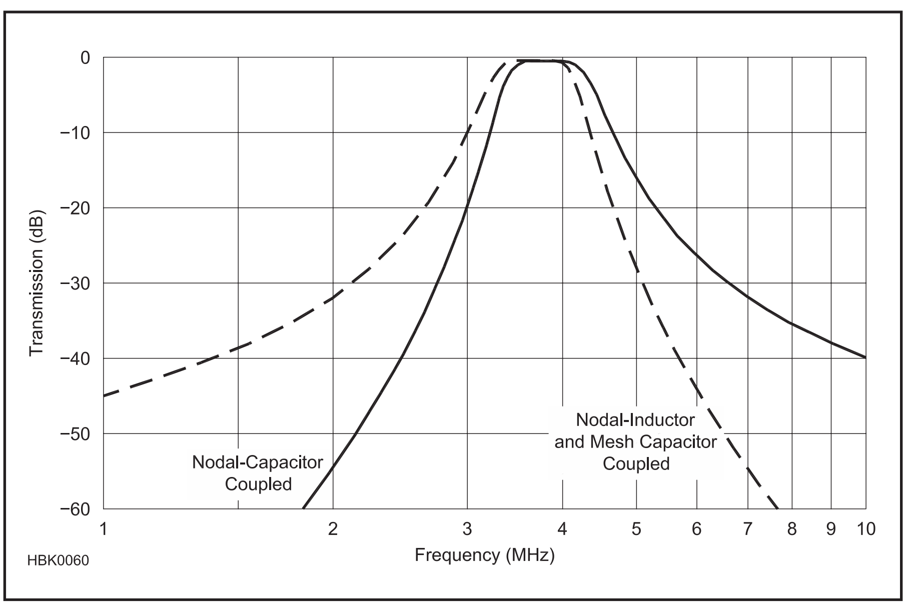


Figure 13 — Responses of the filters in Figure 12.

we can correct this problem. The resulting design is shown in Figure 12B. Another way to accomplish the task is by going to a *mesh capacitor-coupled* design as shown in Figure 12C. The last two designs have identical magnitude responses.

Two other topologies are shown for comparison. The design in Figure 12B has only three capacitors (a minimum-capacitor design) while the design in Figure 12C has only three inductors (a minimum-inductor design).

The magnitude response of the capacitor-coupled design in Figure 12A is shown in **Figure 13** as the solid line. The designs in Figure 12B and C have magnitude responses as shown in Figure 13 as a dashed line. Note that the rolloff on the high-frequency side is steeper for the designs in Figure 12B and C. This will be the case for those filters with relatively wide (percentage-wise) designs. Such a design would be useful where harmonics of a signal are to be especially attenuated. It might also improve image rejection in a receiver RF stage where high-side injection of the local oscillator is used.

2 Normalized Values

The equations used to design filters are quite complex, so to ease the design process, tables of component values have been developed for different families of filters. Developing a set of tables for all possible filter requirements would be impractical, so *tables of normalized values* are used based on a low-pass filter with a bandwidth of 1 radian per second and with 1-Ω input termination impedance. Performance requirements for the desired filter are *normalized* to 1 rad/sec bandwidth and 1-Ω terminations and the tables used to determine the various component values for those frequencies and impedance. That filter is then transformed to the desired response if necessary — high-pass, band-pass, etc. Then the filter is converted to the desired frequency and impedance by *denormalizing* or *scaling* the component values with another set of transformations. In this way, a (relatively) small set of tables can be used to design filters of any type as you'll see in the following examples.

Summarizing, the table-based design process consists of:

- Determining performance requirements.
- Normalizing the requirements to a 1-Hz, 1-Ω, low-pass response.
- Selecting a family and order.
- Obtaining normalized component values from the tables.
- Transforming the filter to the desired response.
- Denormalizing the component values for frequency and impedance.

2.1 Filter Family Selection

The tables presented here are for low-pass filters from different families (Butterworth, Bessel, Chebyshev and Cauer), with various specifications for passband ripple and so on. In the normalized tables, capacitor values are in farads (F) and inductor values are in henries (H). These are converted to actual component values through the process of denormalization described below.

The Butterworth family (described by normalized component values in **Table 1**) is used when there should be no ripple at all in the passband, so that the response is to be as flat as possible. This trait is particularly apparent near dc for the low-pass response, at the center frequency for a band-pass response, and at infinity for the high-pass response. The resulting magnitude response will also have a relatively gentle transition from the passband into the stop band.

When a low-pass filter with constant group delay throughout the passband is desired then the Bessel family, whose normalized component values are shown in **Table 2**, should be used.

The Chebyshev family is used when a sharper cutoff is desired for a given number of components and where at least a small amount of ripple is allowable in the passband. The Chebyshev filter tables are broken into groups according to logically chosen values of passband ripple. The tables presented here are for passband ripple values of 0.01 dB (**Table 3**, for critical RF work), 0.044 dB (**Table 4**, an intermediate value offering 20 dB of return loss or 1.2:1 VSWR) and 0.2 dB (**Table 5**, for audio and less-critical work where a steeper rolloff into the stop band is of primary concern). Some published tables show figures for passband ripple values less than 0.01 dB. These are difficult to implement because of the tight component tolerances required to achieve the expected responses.

When steepness of rolloff from passband into stop band is the item of greatest importance, then the Cauer filter family is used. Cauer filters involve a more complicated set of choices. In addition to selecting a passband ripple, the designer must also assign a stop band depth (or stop band frequency). Some of the items interact**;** they can't all be selected arbitrarily.

The most likely combinations of items to be chosen for Cauer filters are presented in **Tables 6** to **17**. These tables are for passband ripple values of 0.01, 0.044 and 0.2 dB (the same values that were chosen for the Chebyshev family) and stop band depths of 30, 40, 50 and 60 dB. The frequency at which the attenuation first reaches the design stop band depth value is shown in the final column, labeled F_{stop}. As with the Chebyshev filters, some published tables show ripple values of less than 0.01 dB but such designs are difficult to implement in practice because of the tight tolerances required on all of the components.

DESIGN EXAMPLE — CHEBYSHEV LOW-PASS

Here is an example of using normalized-value tables to design a low-pass Chebyshev filter with 0.01 dB of passband ripple, a bandwidth of 4.2 MHz, a rolloff requirement of 25 dB of attenuation one octave above cutoff, and an input termination of 50 Ω. **Figure 14** illustrates the attenuation to be expected for various orders (N) of a Chebyshev low-pass filter with 0.01 dB of passband ripple. The next step is to determine the lowest order that can meet the requirements for roll off. Based on the rolloff requirement, a fifth-order filter is the lowest order filter for which the attenuation curve is below 25 dB at twice the normalized cutoff frequency of 1. (If 14 dB of attenuation one octave above the cutoff frequency had been required, a fourth-order filter would suffice.)

Figure 15 shows the schematic of a fifth-order low-pass filter that will meet the requirements. (If a higher- or lower-order filter is required, add or subtract elements, beginning with G(1) at the filter input, with capacitors as the parallel or shunt elements and inductors as the series elements.)

Next, refer to Table 3 to obtain the normalized component values for the 1-Ω and 1 radian/second low-pass filter. Choosing the table row with component values for Order = 5, G(1) is 0.7563, G(2) is 1.305, G(3) is 1.577, G(4) is 1.305 and G(5) is 0.7563. The last value, R_{load}, is used to calculate the output termination.

The equations to calculate the actual component values are shown in Figure 15A. Ω_c is the denormalizing factor used to scale the normalized filter component values to the desired frequency

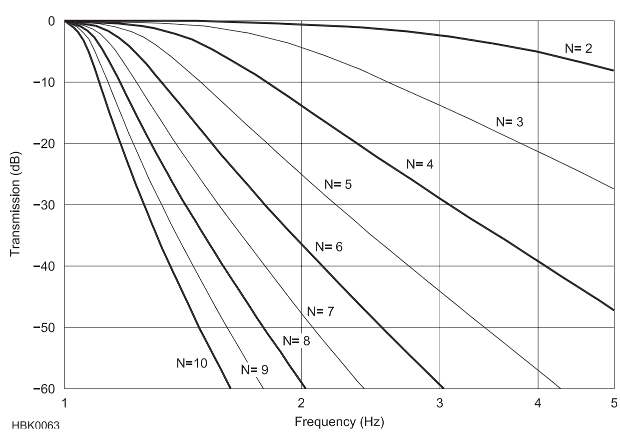


Figure 14 — This graph shows transmission for Chebyshev low-pass filters with 0.01 dB passband ripple filters with orders from 2 through 10. For a given order, higher passband ripple values will have higher attenuation (less transmission) at a given frequency while Butterworth filters will have less attenuation at a given frequency.

$\Omega_c = 2\pi\ F_{width}$ (1)

In this case, $\Omega_c = 2 \times 3.1416 \times 4.2 \times 10^6 = 26.389 \times 10^6$. R is the filter's input termination, in this case 50 Ω. The termination on the output side of the filter will be the input termination value multiplied by R_{load}. In this case, $R_{load} = 1$, so the input and output terminations are equal. (Chebyshev *even-ordered* low-pass and high-pass filters have an output termination different from the input, as shown in the last column under R_{load}.) After denormalizing, the resulting component values are shown in Figure 15B. At this point in a table-based design process, the closest available standard value or adjustable components would be used to fabricate the actual circuit.

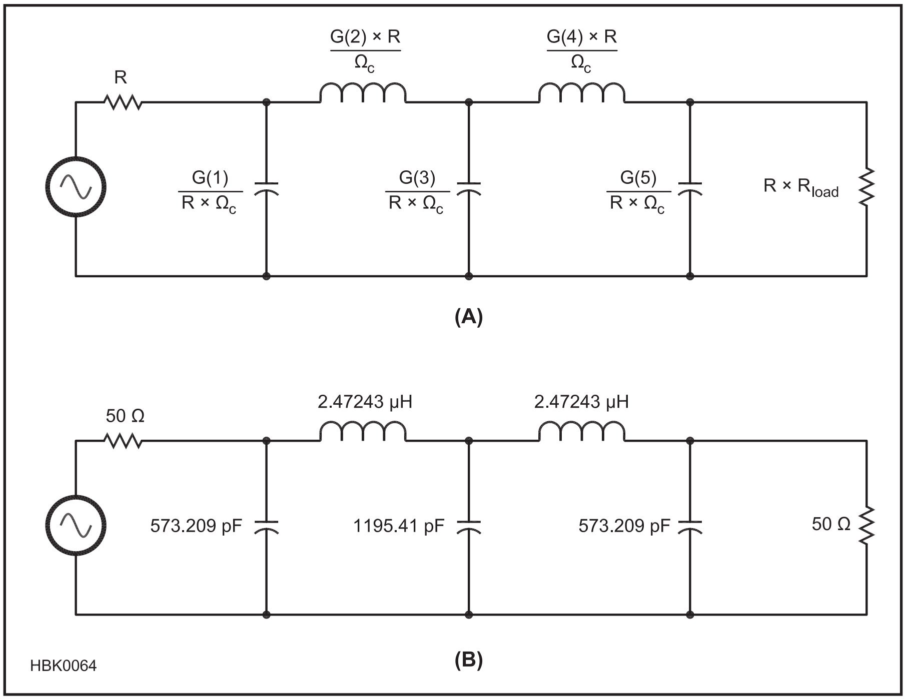


Figure 15 — Design example for a Chebyshev low-pass filter using the normalized filter tables. The topology and design equations are shown at A, with the resulting calculated parts values at B.

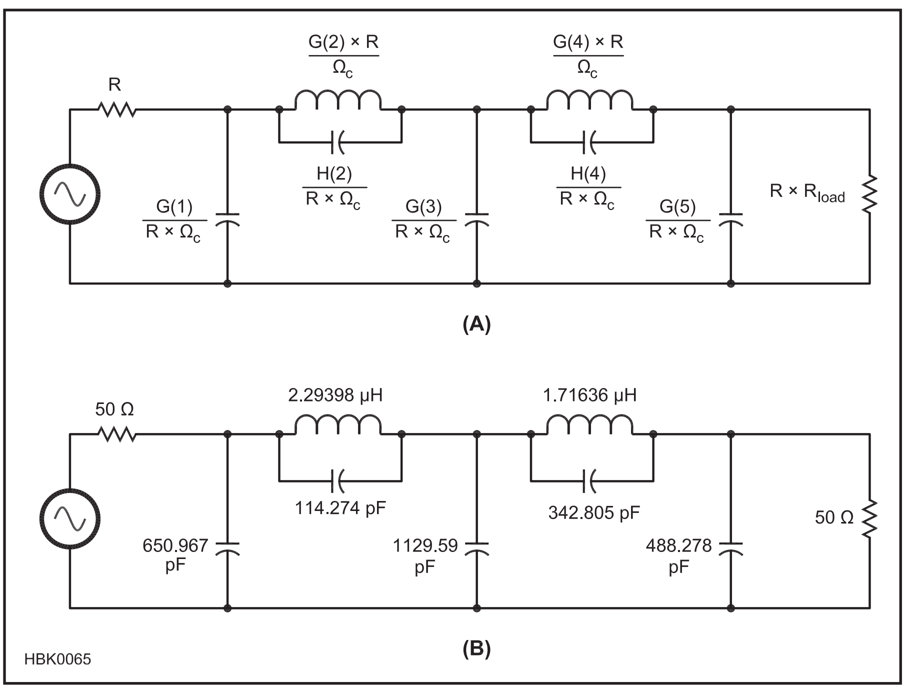


Figure 16 — Design example for a Cauer low-pass filter using the normalized filter tables. The topology and design equations are shown at A, with the resulting calculated parts values at B.

DESIGN EXAMPLE — CAUER LOW-PASS

The design of a Cauer low-pass filter is very similar to the design of a Chebyshev, but it has added capacitors across the series inductors to form the traps that create the stop band notches. Graphs showing the stop band performance or loss of the various Cauer filters in the tables are impractical because of the large number of options to be chosen.

This example illustrates the design of a fifth-order Cauer capacitor-input low-pass filter with 0.044 dB passband ripple and 40-dB stop band depth. The input termination will be 50 Ω and the ripple bandwidth will again be 4.2 MHz.

Figure 16 shows the filter schematic. The first step is to obtain from Table 11 the normalized 1-Ω and 1 radian/second component values. Choosing the table row of component values for Order = 5, G(1) is 0.8597, G(2) is 1.211, G(3) is 1.491, G(4) is 0.9058 and G(5) is 0.6448. In addition, the "trap" capacitor values must be retrieved. The trap capacitors are shown as "H" values. H(2) is 0.1509 and H(4) is 0.4527. The output termination is 1 and so is the same as the input termination.

The filter schematic with the denormalization equations appears in Figure 16A. Ω_c and R have the same definitions as in the previous example. The resulting actual component values for the required frequency and impedance are shown in Figure 16B.

DESIGN EXAMPLE — HIGH-PASS BUTTERWORTH

The design of a high-pass filter will now be illustrated. Figure 14 can be used to estimate the response of a high-pass design just as it was for a low-pass. The only manipulation that needs to be done is to use the *reciprocal* of frequency when estimating the magnitude response. For example, if the attenuation requirement for the high-pass filter is for 10 dB of attenuation at 0.2 times the cutoff frequen-cy, then when using the low-pass filter response graphs, look up the attenuation at 1/0.2 = 5 times the cutoff frequency, instead.

For this example, we will design a fourth-order capacitor-input Butterworth high-pass response with the 3-dB cutoff frequency at 250 Hz and system impedance of 600 Ω. The filter schematic is shown in **Figure 17**. (Remember that even-order ladder filters can have either a series or parallel element at the input.)

The normalized values for the low-pass response are taken from Table 1, and the design equations are shown in Figure 17A. From the table row of component values for Order = 4, the value for G(1) is 0.7654, G(2) is 1.848,

Table 1

Butterworth Normalized Values

Order	*G(1)*	*G(2)*	*G(3)*	*G(4)*	*G(5)*	*G(6)*	*G(7)*	*G(8)*	*G(9)*	*G(10)*	*G(11)*	R_{load}
3	1	2	1									1
4	0.7654	1.848	1.848	0.7654								1
5	0.618	1.618	2	1.618	0.618							1
6	0.5176	1.414	1.932	1.932	1.414	0.5176						1
7	0.445	1.247	1.802	2	1.802	1.247	0.445					1
8	0.3902	1.111	1.663	1.962	1.962	1.663	1.111	0.3902				1
9	0.3473	1 1.532	1.879	2	1.879	1.532	1	0.3473				1
10	0.3129	0.908	1.414	1.782	1.975	1.975	1.782	1.414	0.908	0.3129		1
11	0.2846	0.8308	1.31	1.683	1.919	2	1.919	1.683	1.31	0.8308	0.2846	1

Table 2

Bessel Normalized Values

Order	*G(1)*	*G(2)*	*G(3)*	*G(4)*	*G(5)*	*G(6)*	*G(7)*	*G(8)*	*G(9)*	*G(10)*	R_{load}
3	2.203	0.9705	0.3374								1
4	2.24	1.082	0.6725	0.2334							1
5	2.258	1.111	0.804	0.5072	0.1743						1
6	2.265	1.113	0.8538	0.6392	0.4002	0.1365					1
7	2.266	1.105	0.869	0.702	0.5249	0.3259	0.1106				1
8	2.266	1.096	0.8695	0.7303	0.5936	0.4409	0.2719	0.0919			1
9	2.265	1.086	0.8639	0.7407	0.6306	0.5108	0.377	0.2313	0.078		1
10	2.264	1.078	0.8561	0.742	0.6493	0.5528	0.4454	0.327	0.1998	0.0672	1

Table 3

Chebyshev Normalized Values

Passband ripple 0.01 dB

Order	*G(1)*	*G(2)*	*G(3)*	*G(4)*	*G(5)*	*G(6)*	*G(7)*	*G(8)*	*G(9)*	*G(10)*	*G(11)*	R_{load}
3	0.6292	0.9703	0.6292									1
4	0.7129	1.2	1.321	0.6476								0.9085
5	0.7563	1.305	1.577	1.305	0.7563							1
6	0.7814	1.36	1.69	1.535	1.497	0.7098						0.9085
7	0.7969	1.392	1.748	1.633	1.748	1.392	0.7969					1
8	0.8073	1.413	1.782	1.683	1.853	1.619	1.555	0.7334				0.9085
9	0.8145	1.427	1.804	1.713	1.906	1.713	1.804	1.427	0.8145			1
10	0.8196	1.437	1.819	1.731	1.936	1.759	1.906	1.653	1.582	0.7446		0.9085
11	0.8235	1.444	1.83	1.744	1.955	1.786	1.955	1.744	1.83	1.444	0.8235	1

Table 4

Chebyshev Normalized Values

Passband ripple 0.044 dB

Order	*G(1)*	*G(2)*	*G(3)*	*G(4)*	*G(5)*	*G(6)*	*G(7)*	*G(8)*	*G(9)*	*G(10)*	*G(11)*	R_{load}
3	0.855	1.104	0.855									1
4	0.9347	1.293	1.581	0.7641								0.8175
5	0.9747	1.372	1.805	1.372	0.9747							1
6	0.9972	1.413	1.896	1.55	1.729	0.8153						0.8175
7	1.011	1.437	1.943	1.621	1.943	1.437	1.011					1
8	1.02	1.452	1.969	1.657	2.026	1.61	1.776	0.8341				0.8175
9	1.027	1.462	1.986	1.677	2.067	1.677	1.986	1.462	1.027			1
10	1.031	1.469	1.998	1.69	2.091	1.709	2.067	1.633	1.797	0.8431		0.8175
11	1.035	1.474	2.006	1.698	2.105	1.727	2.105	1.698	2.006	1.474	1.035	1

Table 5

Chebyshev Normalized Values

Passband ripple 0.2 dB

Order	*G(1)*	*G(2)*	*G(3)*	*G(4)*	*G(5)*	*G(6)*	*G(7)*	*G(8)*	*G(9)*	*G(10)*	*G(11)*	R_{load}
3	1.228	1.153	1.228									1
4	1.303	1.284	1.976	0.8468								0.65
5	1.339	1.337	2.166	1.337	1.339							1
6	1.36	1.363	2.239	1.456	2.097	0.8838						0.65
7	1.372	1.378	2.276	1.5	2.276	1.378	1.372					1
8	1.38	1.388	2.296	1.522	2.341	1.493	2.135	0.8972				0.65
9	1.386	1.394	2.309	1.534	2.373	1.534	2.309	1.394	1.386			1
10	1.39	1.398	2.318	1.542	2.39	1.554	2.372	1.507	2.151	0.9035		0.65
11	1.393	1.402	2.324	1.547	2.401	1.565	2.401	1.547	2.324	1.402	1.393	1

Table 6

Cauer Normalized Values

Passband ripple 0.01 dB, Stop band depth 30 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.5835	0.8848	0.06895	0.5835							1	3.524
4	0.4844	0.954	0.1799	1.109	0.6392	0					1	2.215
5	0.6173	1.106	0.1913	1.264	0.7084	0.6533	0.3403				1	1.418
6	0.4158	0.936	0.3958	1.074	0.7642	0.7979	0.9396	0.7292	0		1	1.252
7	0.6095	1.117	0.2497	1.027	0.5503	1.459	0.8809	0.5513	1.175	0.1594	1	1.105

Table 7

Cauer Normalized Values

Passband ripple 0.01 dB, Stop band depth 40 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.6074	0.9299	0.03092	0.6074							1	5.12
4	0.5463	1.057	0.09503	1.144	0.634	0					1	2.885
5	0.6678	1.179	0.1179	1.359	0.9065	0.3574	0.4904				1	1.687
6	0.5089	1.063	0.2549	1.208	0.992	0.4761	1.066	0.7275	0		1	1.416
7	0.6636	1.197	0.173	1.186	0.7766	0.8845	1.04	0.7415	0.7093	0.3321	1	1.191

Table 8

Cauer Normalized Values

Passband ripple 0.01 dB, Stop band depth 50 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.6194	0.9518	0.01415	0.6194							1	7.47
4	0.5813	1.116	0.05176	1.165	0.6309	0					1	3.797
5	0.7007	1.225	0.07357	1.432	1.045	0.2096	0.5872				1	2.045
6	0.5739	1.156	0.168	1.317	1.167	0.3023	1.157	0.7255	0		1	1.634
7	0.7019	1.252	0.122	1.319	0.9711	0.5823	1.192	0.899	0.4614	0.4575	1	1.309

Table 9

Cauer Normalized Values

Passband ripple 0.01 dB, Stop band depth 60 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.6246	0.9617	0.00652	0.6246							1	10.94
4	0.6011	1.15	0.02862	1.178	0.629	0					1	5.025
5	0.7209	1.254	0.04608	1.482	1.137	0.1269	0.6486				1	2.514
6	0.6191	1.222	0.1121	1.399	1.296	0.1978	1.223	0.7238	0		1	1.913
7	0.7283	1.291	0.08673	1.425	1.131	0.3982	1.322	1.024	0.312	0.5489	1	1.463

Table 10

Cauer Normalized Values

Passband ripple 0.044 dB, Stop band depth 30 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.7873	0.9891	0.09924	0.7873							1	2.788
4	0.6172	1.046	0.2284	1.239	0.8101	0					1	1.883
5	0.794	1.119	0.2452	1.353	0.6862	0.8268	0.4694				1	1.286
6	0.5391	0.9646	0.4632	1.064	0.7337	0.9564	0.9908	0.8958	0		1	1.171
7	0.7808	1.11	0.3034	1.058	0.4585	1.892	0.8492	0.5271	1.379	0.2962	1	1.065

Table 11

Cauer Normalized Values

Passband ripple 0.044 dB, Stop band depth 40 dB

Order	G(1)	G(2)	H(2)	G(3)	G(4)	H(4)	G(5)	G(6)	H(6)	G(7)	R_{load}	F_{stop}
3	0.8229	1.05	0.04455	0.8229							1	4.02
4	0.6958	1.176	0.1209	1.287	0.8064	0					1	2.429
5	0.8597	1.211	0.1509	1.491	0.9058	0.4527	0.6448				1	1.504
6	0.6471	1.112	0.299	1.227	0.9893	0.5657	1.126	0.8992	0		1	1.304
7	0.8479	1.204	0.2085	1.242	0.6828	1.118	1.045	0.7251	0.833	0.4797	1	1.132

Table 12
Cauer Normalized Values
Passband ripple 0.044 dB, Stop band depth 50 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	0.8401	1.079	0.02038	0.8401							1	5.85
4	0.7411	1.253	0.06596	1.316	0.8039	0					1	3.178
5	0.9012	1.269	0.094	1.594	1.064	0.2658	0.761				1	1.803
6	0.724	1.22	0.1977	1.362	1.192	0.3584	1.227	0.9004	0		1	1.487
7	0.8928	1.27	0.1462	1.401	0.8857	0.7262	1.232	0.8927	0.5426	0.6158	1	1.229

Table 13
Cauer Normalized Values
Passband ripple 0.044 dB, Stop band depth 60 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	0.8481	1.093	0.0094	0.8481							1	8.553
4	0.767	1.297	0.0365	1.333	0.8025	0					1	4.192
5	0.9275	1.307	0.05888	1.667	1.172	0.1613	0.8371				1	2.199
6	0.7782	1.298	0.1323	1.465	1.346	0.2346	1.301	0.9008	0		1	1.725
7	0.9275	1.317	0.104	1.531	1.056	0.4957	1.395	1.027	0.3689	0.7207	1	1.359

Table 14
Cauer Normalized Values
Passband ripple 0.2 dB, Stop band depth 30 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	1.116	0.9996	0.1584	1.116							1	2.207
4	0.8176	1.087	0.3037	1.335	1.065	0					1	1.61
5	1.084	1.031	0.3443	1.482	0.5907	1.153	0.6819				1	1.18
6	0.7319	0.9415	0.5675	1.024	0.6677	1.186	1.002	1.149	0		1	1.106
7	1.065	1.01	0.4035	1.124	0.3345	2.756	0.8246	0.451	1.785	0.5138	1	1.036

Table 15
Cauer Normalized Values
Passband ripple 0.2 dB, Stop band depth 40 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	1.174	1.08	0.07104	1.174							1	3.147
4	0.9224	1.254	0.1607	1.399	1.067	0					1	2.047
5	1.175	1.14	0.2106	1.686	0.8175	0.6264	0.8974				1	1.351
6	0.8638	1.107	0.3667	1.221	0.9522	0.6869	1.139	1.164	0		1	1.21
7	1.156	1.116	0.2739	1.35	0.5366	1.558	1.073	0.6422	1.069	0.7205	1	1.084

Table 16
Cauer Normalized Values
Passband ripple 0.2 dB, Stop band depth 50 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	1.203	1.118	0.03253	1.203							1	4.554
4	0.9842	1.355	0.08773	1.438	1.067	0					1	2.654
5	1.233	1.211	0.1309	1.842	0.9885	0.3676	1.047				1	1.595
6	0.9599	1.23	0.2433	1.387	1.19	0.4317	1.246	1.173	0		1	1.36
7	1.213	1.192	0.1904	1.548	0.7322	0.9884	1.313	0.8105	0.694	0.8771	1	1.161

Table 17
Cauer Normalized Values
Passband ripple 0.2 dB, Stop band depth 60 dB

Order	*G(1)*	*G(2)*	*H(2)*	*G(3)*	*G(4)*	*H(4)*	*G(5)*	*G(6)*	*H(6)*	*G(7)*	R_{load}	F_{stop}
3	1.216	1.137	0.01501	1.216							1	6.64
4	1.02	1.413	0.04859	1.46	1.067	0					1	3.484
5	1.272	1.256	0.08207	1.953	1.108	0.2237	1.149				1	1.924
6	1.029	1.32	0.1634	1.517	1.375	0.2818	1.328	1.178	0		1	1.56
7	1.257	1.244	0.1348	1.716	0.9025	0.6672	1.527	0.9477	0.4718	1.001	1	1.269

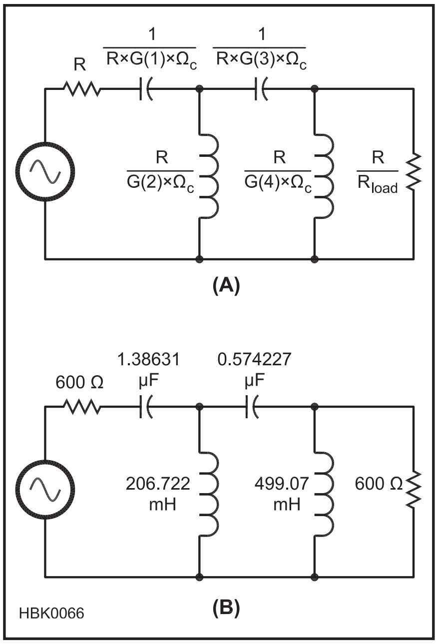


Figure 17 — Design example for a Butterworth high-pass filter using the normalized filter tables. The topology and design equations are shown at A, with the resulting calculated parts values at B. For a Cauer family high-pass, trap capacitors would be inserted in series with the shunt inductors. Their value is calculated by the same expression as the series capacitors, but using the *H(n)* values from the Cauer tables.

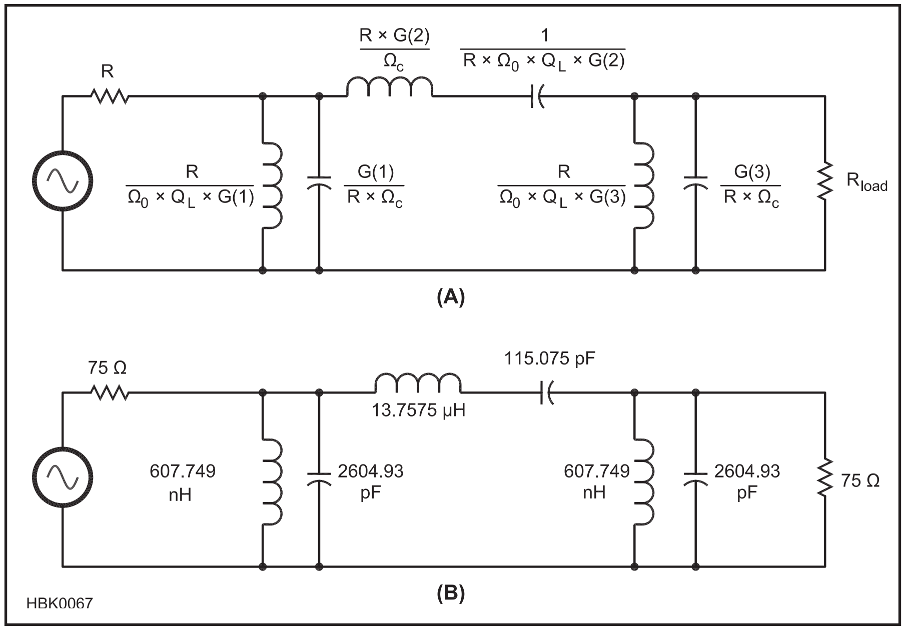


Figure 18 — Design example for a Chebyshev wide band-pass filter using the normalized filter tables. The topology and design equations are shown at A, with the resulting calculated parts values at B.

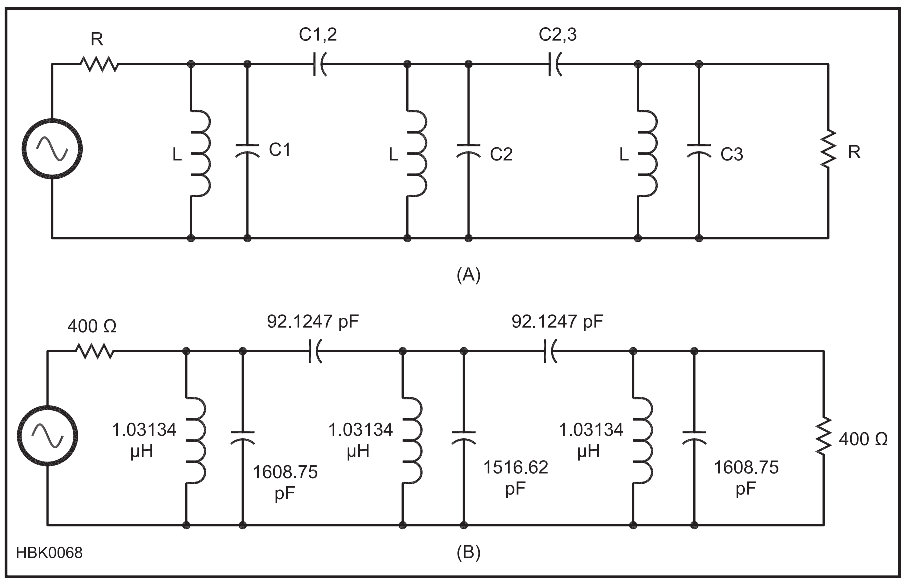


Figure 19 — Design example for a Chebyshev narrow band-pass filter using the normalized filter tables. The topology is shown at A and the design equations are given in the text, with the resulting calculated parts values at B.

G(3) is 1.848 and G(4) is 0.7654.

Ω_c is computed the same way as in the previous examples. For the high-pass configuration, the output termination is based on the *reciprocal* of R_{load}. In this case, the table shows that the output termination is 1, so it is the same as the input. (Unlike the Chebyshev family, the output termination for the Butterworth family is always the same as the input termination.) Figure 17B shows the resulting denormalized component values for the actual filter.

DESIGN EXAMPLE — WIDE BAND-PASS

The design of a band-pass filter of appreciable percentage bandwidth will be looked at next. For the purposes of this discussion, "appreciable" means a bandwidth of 20% of the center frequency or higher (a filter Q of 5 or less).

Figure 18 shows this example, a third-order shunt-input Chebyshev type with 0.2 dB of passband ripple with an input termination of 75 Ω. The center frequency is to be 4 MHz and the ripple bandwidth is to be 1 MHz. Again, Figure 14 can be used to determine the required filter order, bearing in mind that it is precise for passband ripple of 0.01 dB.

The normalized values for the low-pass are taken from Table 5. Choosing the table row of component values for Order = 3, the value for G(1) is 1.228, G(2) is 1.153 and G(3) is 1.228.

In the equations used to calculate the actual parts values, Q_L is the loaded Q. This is the ratio of F_{center} to F_{width}. Note that in this topology both Ω_c and Ω_o are used. Ω_c is defined as in the previous examples, while

$$\Omega_o = 2\pi F_{center} \qquad (2)$$

The filter schematic with the denormalizing equations appears in Figure 18A, and calculated values for the actual filter are shown in Figure 18B.

DESIGN EXAMPLE — NARROW BAND-PASS

Narrow band-pass filters involve more calculations than wide band-pass types. The filter topology used in this discussion is shown in **Figure 19** — a set of shunt-connected paralleltuned resonators coupled by relatively small-value coupling capacitors.

This example will be for a band-pass filter with a bandwidth of 200 kHz, centered at 3.8 MHz, using the Chebyshev family with a passband ripple of 0.044 dB. The order will be three, and the normalized values are found in Table 4.

As in the wide band-pass example, the equations used to calculate the actual parts values use Q_L (the loaded Q), which is the ratio of F_{center} to F_{width}. Once again both Ω_c and Ω_o are used as before The same inductor, L, is used for each resonator. The value of that inductor is given by:

$$L = \frac{R}{\Omega_o \times Q_L \times G(1)} \tag{3}$$

Each resonator has a basic tuning capacitor whose value is given by:

$$C_{basic} = \frac{G(1)}{R \times \Omega_c} \tag{4}$$

Next calculate the inter-resonator coupling capacitors:

$$C1,2 = \frac{G(1)}{R \times \Omega_o}\sqrt{\frac{1}{G(1) \times G(2)}} \tag{5}$$

$$C2,3 = \frac{G(1)}{R \times \Omega_o}\sqrt{\frac{1}{G(2) \times G(3)}} \tag{6}$$

The actual shunt tuning capacitors for each resonator are then the basic tuning capacitor minus the coupling capacitors on each side, as shown here:

$C1 = C_{basic} - C1,2$

$C2 = C_{basic} - C1,2 - C2,3$

$C3 = C_{basic} - C2,3$

The completed design is shown in Figure 19B. It should be evident how to extend this procedure to higher-order filters.