

About electrical filters

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Q: What is a filter?

A: Filters pass some things,
don't pass other things

Examples:

Oil

Air

Water

Optical

Electrical 😊

Electrical filter examples:

Receiver R.F. bandpass filters

Receiver I.F. bandpass filters

Audio filters

 Lowpass

 Bandpass

Diplexers

Harmonic (and 'TVI') (lowpass)

Filters for Field Day (bandpass) ☺

Some definitions

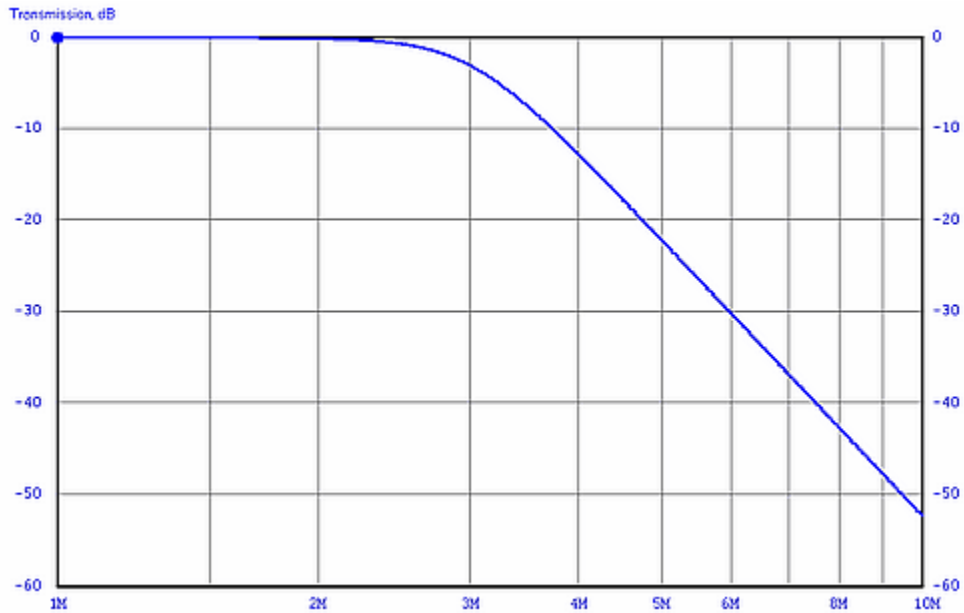
Passband:

The frequency range that we want to **pass** with some minimal attenuation

Stopband:

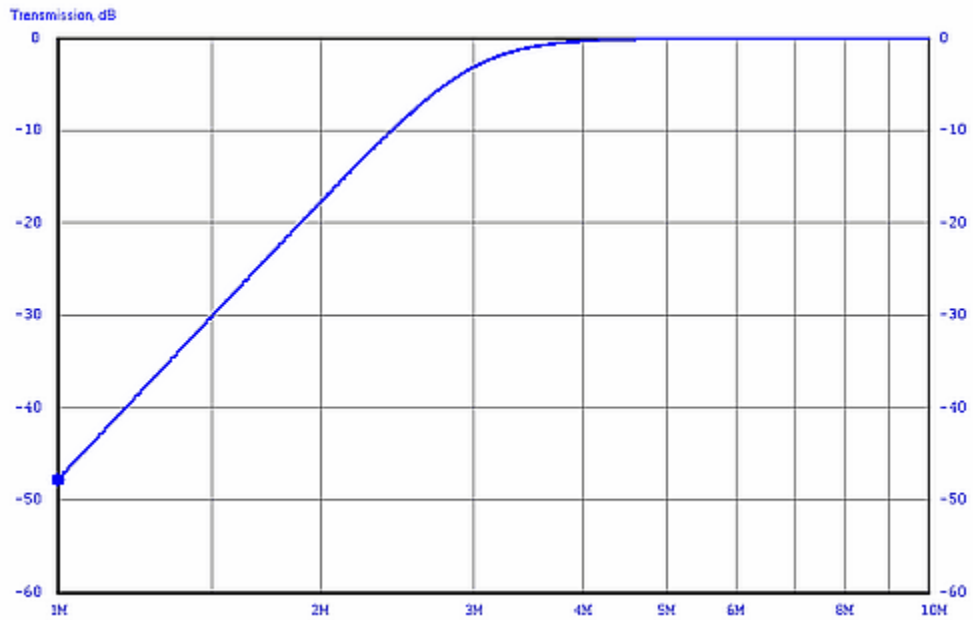
The frequency range that we want to **reject** to some extent

A **lowpass filter** response plot:



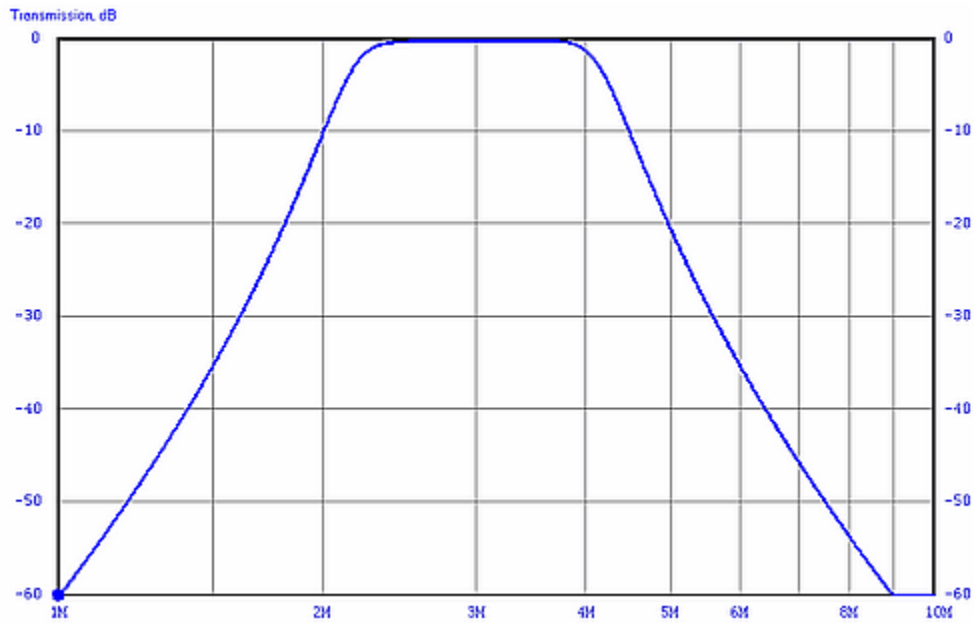
It *passes low* frequencies

A **highpass** filter response plot:



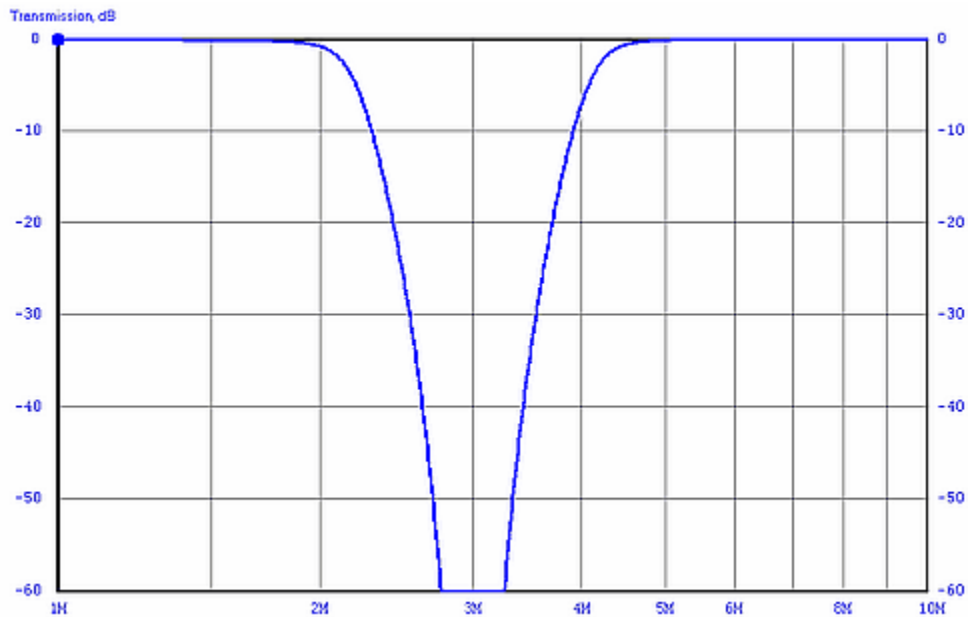
It *passes high* frequencies

A **bandpass** filter response plot:



It *passes a band* of frequencies 😊

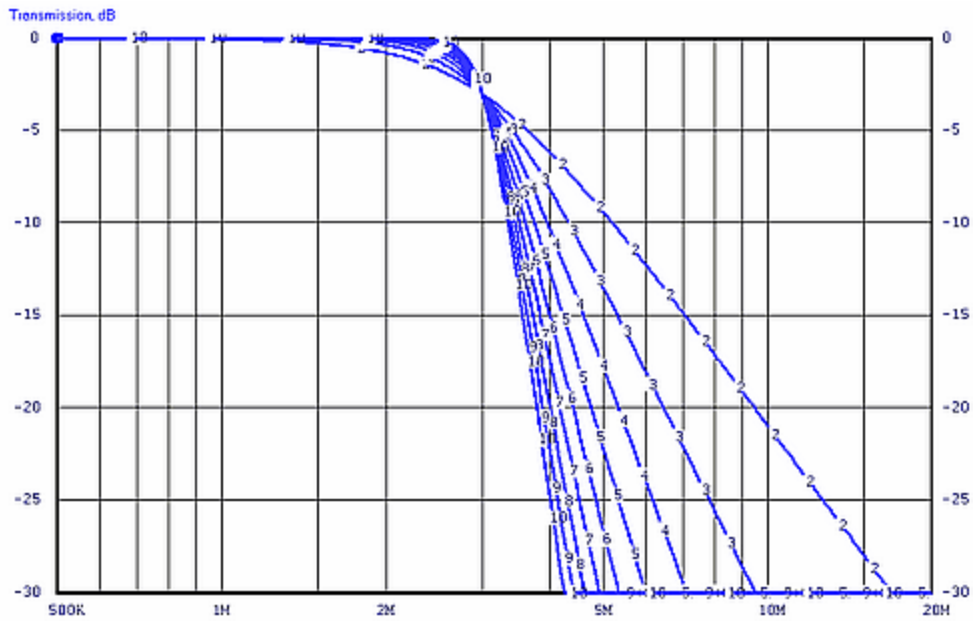
A **bandstop** filter response plot:



It **rejects a band** of frequencies

Also called **bandstop** or, if narrow, a notch filter

Filter order



Here we see the magnitude responses of filters with orders 2 to 10

More complicated filters – those of a higher order – descend into the stopband at a greater rate.

We'll look at order later . . .

FILTER FAMILIES

There is no single “best” way to develop the parts values for a filter.

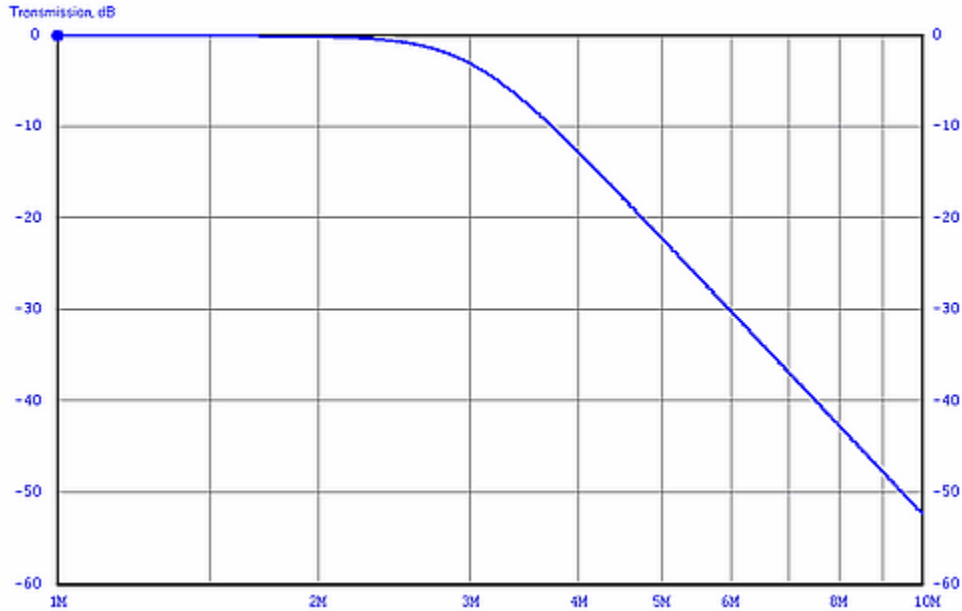
Examples of the tradeoff areas:

- Smoothness of passband response
- Sharpness of cutoff at bandedge
- Ultimate attenuation in the stopband
- Uniformity of time delay
- Uniformity of input impedance

Those areas are set by the “family” – the name of the mathematician who devised a particular design procedure.

Let's look at some of the common families.

The Butterworth family



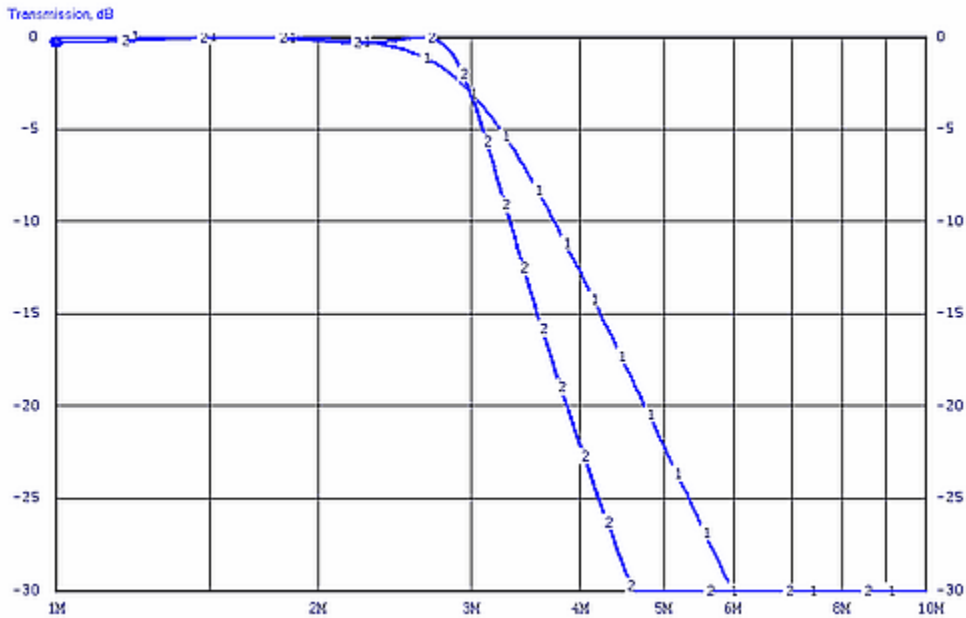
A Butterworth filter response example

It has a smooth passband and is also known as a Maximally Flat Gain or Maximally Flat Magnitude filter.

It has a moderate shape factor

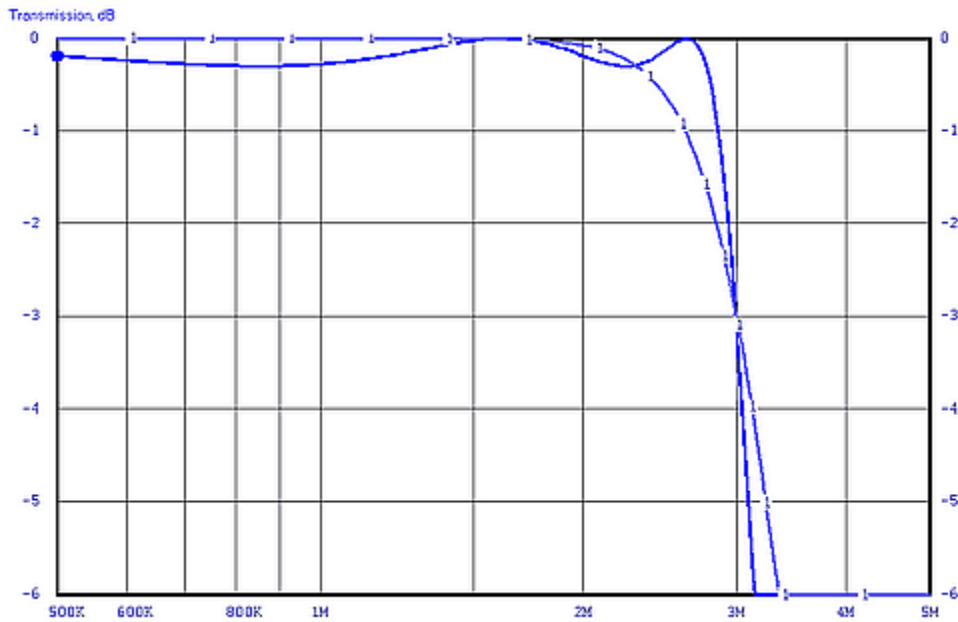
The Chebyshev family

We can get a better shape factor, a sharper descent into the stopband by allowing some magnitude ripple in the passband. This is done by using the Chebyshev family.



The plot (#1) showing the gentler cutoff is of a filter from the Butterworth filter. The plot (#2) showing the sharper cutoff is of a filter from the Chebyshev family; it has some moderate magnitude ripples in the passband.

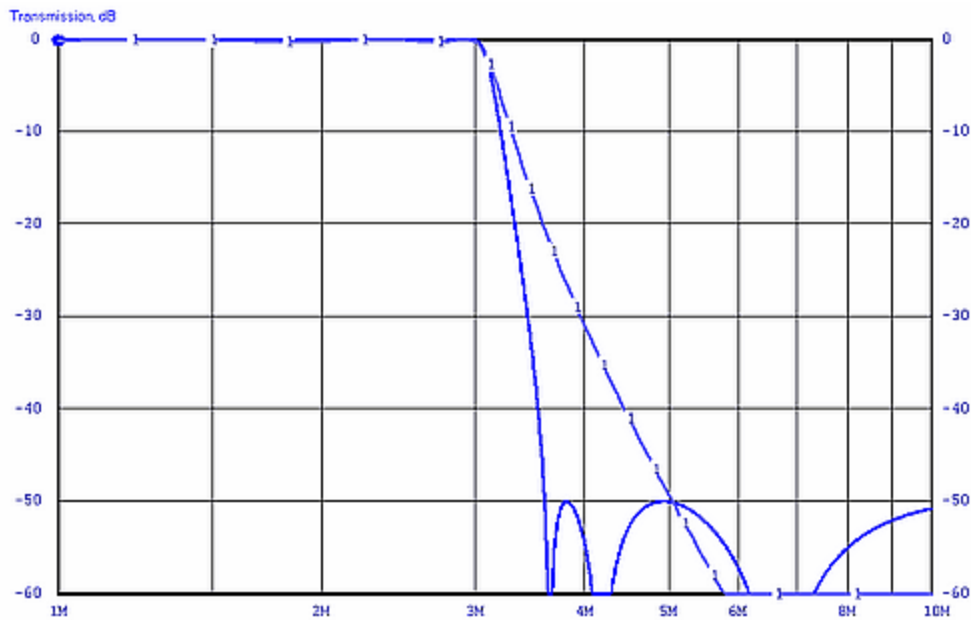
Here we are looking in detail at the passband and so we can see the smooth Butterworth filter (#1) magnitude plot and also the “ripply” Chebyshev magnitude plot (darker blue, with its sharper cutoff rate).



By allowing some passband ripple we can descend into the stopband at a somewhat greater rate.

The Cauer family

We can get an ***even steeper*** descent into the stopband by adding to the design some “traps” whose frequencies are carefully calculated. This is done by using the ***Cauer*** family.

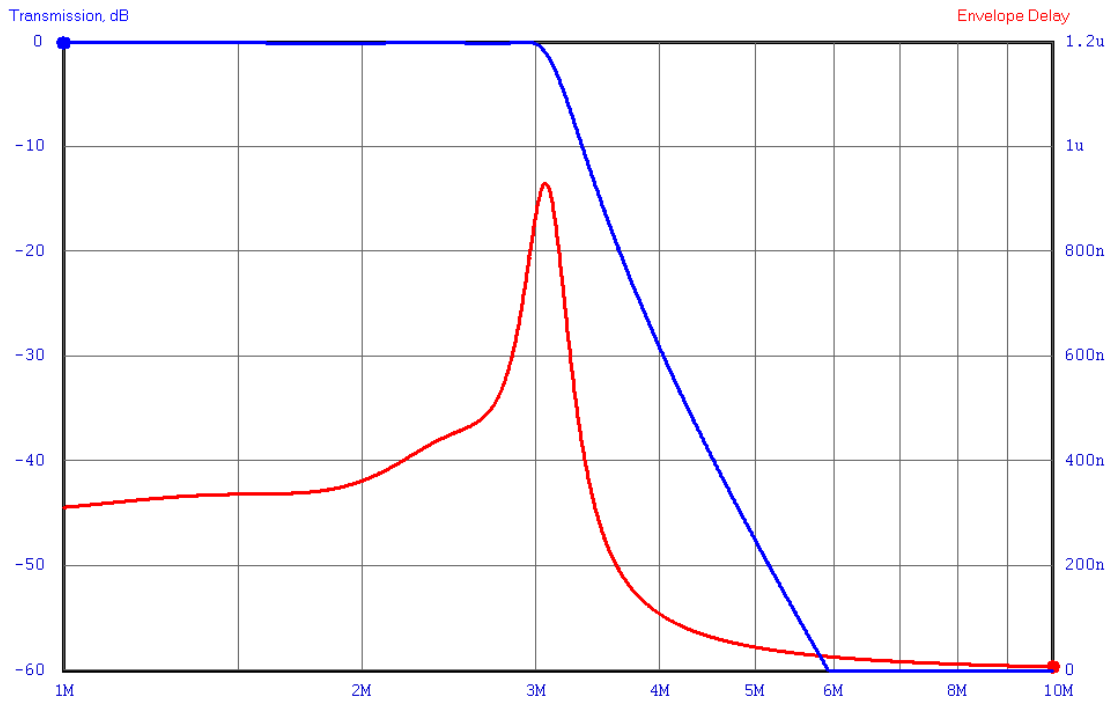


Chebyshev filter (#1) and a Cauer filter with its "traps" in the stopband

Time delay

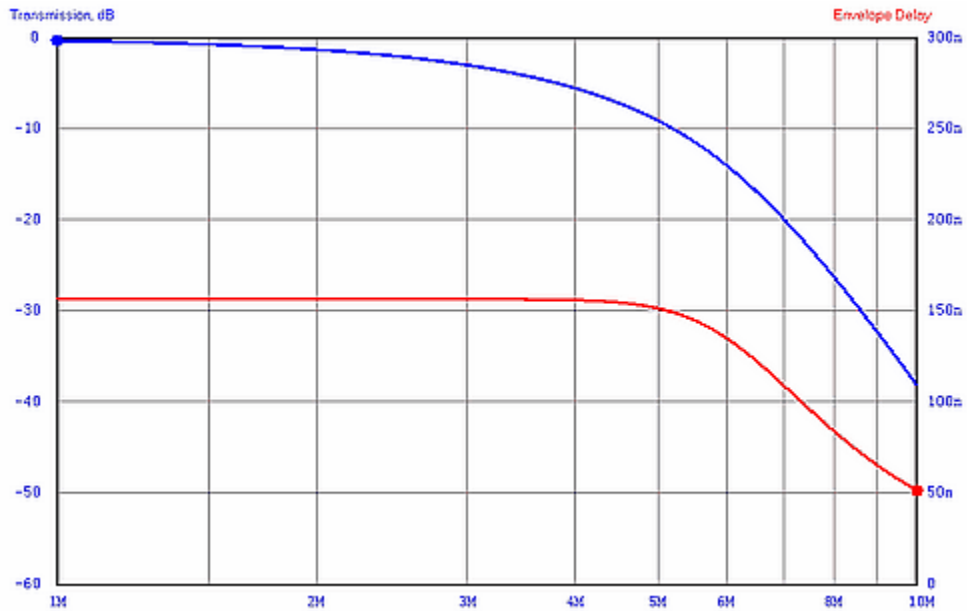
The signal going through a filter encounters a time delay.
This delay is generally greater at the bandedge(s).

Here we see the magnitude and time delay plots of a Chebyshev filter (ripple in the passband, sharp cutoff)



If a uniform time delay for signals throughout the passband is needed then the **Bessel** filter family should be selected

Here we see the magnitude response (blue) and time delay (red) of a Bessel filter:



Time delay (red) is rather constant.

Magnitude response (blue) is rather poor
(terrible, actually 😊).

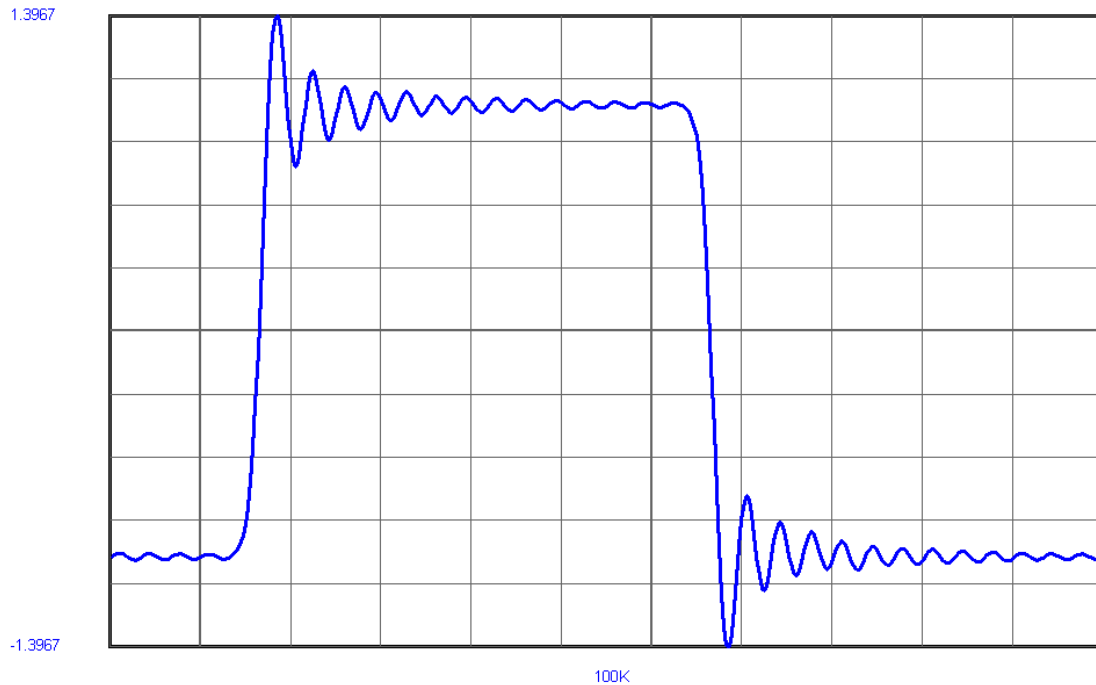
Transient response

Some applications require that a squarewave or other “digital” signal applied to the input of a lowpass design have a minimum overshoot as seen at the output.

Sharp cutoff filters make the signal appear to “ring” when you observe them with an oscilloscope.

“Morse code” should be considered to be a digital signal.

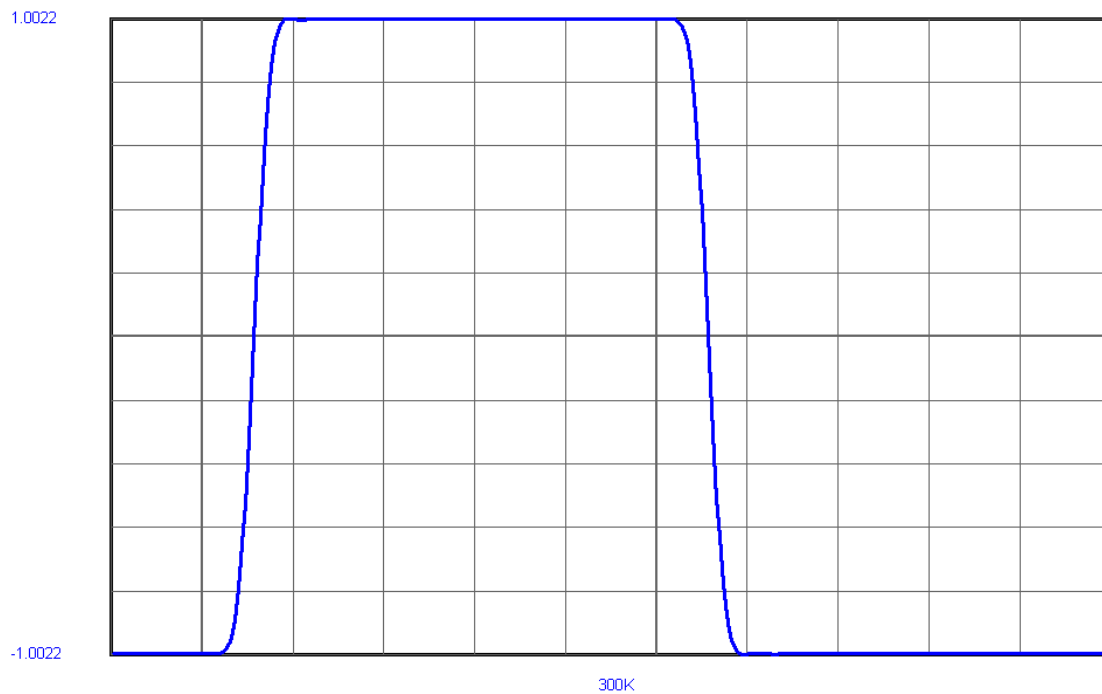
This is the appearance of a squarewave as it exits from a sharp-cutoff (Chebyshev) lowpass filter:



The squarewave is about 5% of filter cutoff frequency.

Bessel filters are relatively free of this problem.

This is the appearance of a squarewave as it exits from a Bessel lowpass filter.



The squarewave fundamental is about 10% of the filter cutoff frequency.

All of the traits mentioned so far apply to a filter regardless of how it is implemented:

- Using inductors and capacitors (*“lumped element”*)
- Using opamps with resistors and capacitors (*“active”*).
- Using microstrip or transmission lines
- Using Digital signal processing (DSP)

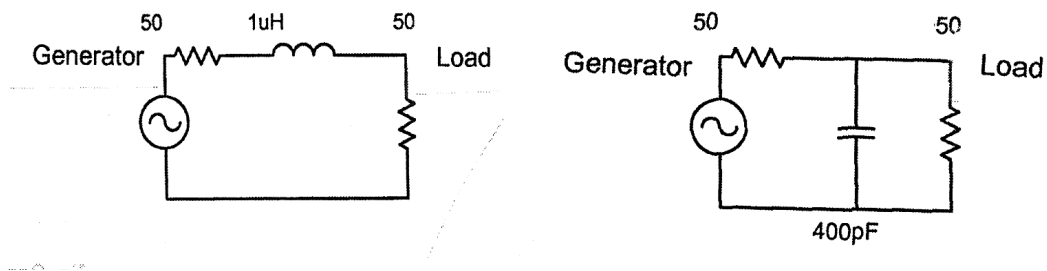
In general they are also true if the filter is implemented using other technologies; some DSP schemes behave differently.

For this discussion we'll ignore those “other” technologies and stick with filters made out of inductors and capacitors. They are called “Lumped Element” networks.

LUMPED-ELEMENT FILTERS:

LOWPASS

Let's look at filters fabricated using discrete inductors and capacitors, (which gives rise to their name of lumped-element). The basic idea behind filters built using inductors and capacitors is shown here:

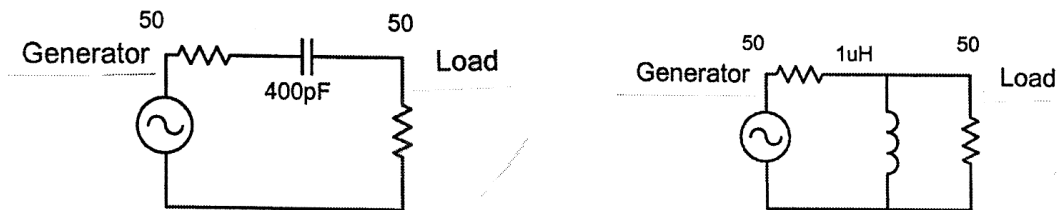


Illustrating the concept of a **lowpass** filter.

Elementary lowpass filter formed using a series inductor (a) and an elementary lowpass filter formed using a shunt capacitor (b).

Highpass

A highpass filter passes signal above its cutoff frequency and attenuates those below. The basic idea behind the highpass filter is shown here:



Elementary highpass formed using (a) a series capacitor and (b) a shunt inductor

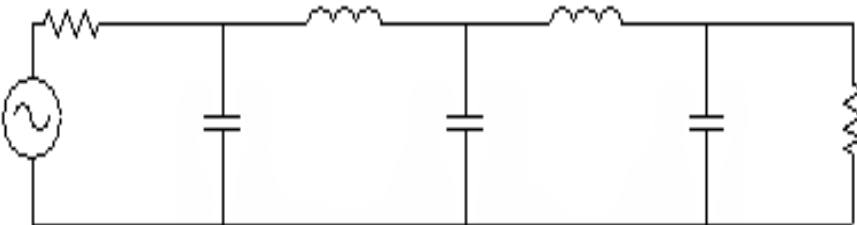
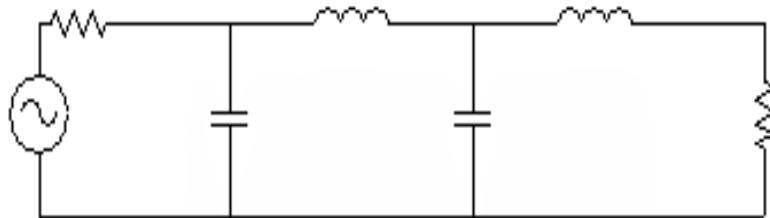
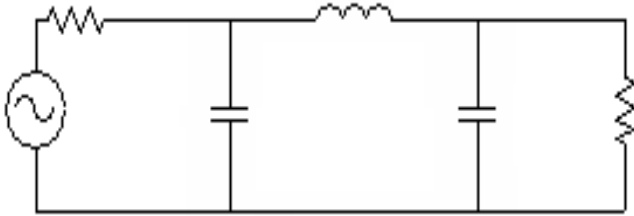
In each case, signals above the cutoff are passed with minimum attenuation while signals below the cutoff are attenuated, in a manner similar to the action of a lowpass filter.

Filter order

“Order” refers to the number of ***branches*** in a filter.

Next we will see examples with 3, 4, and 5 branches.

Here we see lowpass filters with orders of 3, 4 and 5.



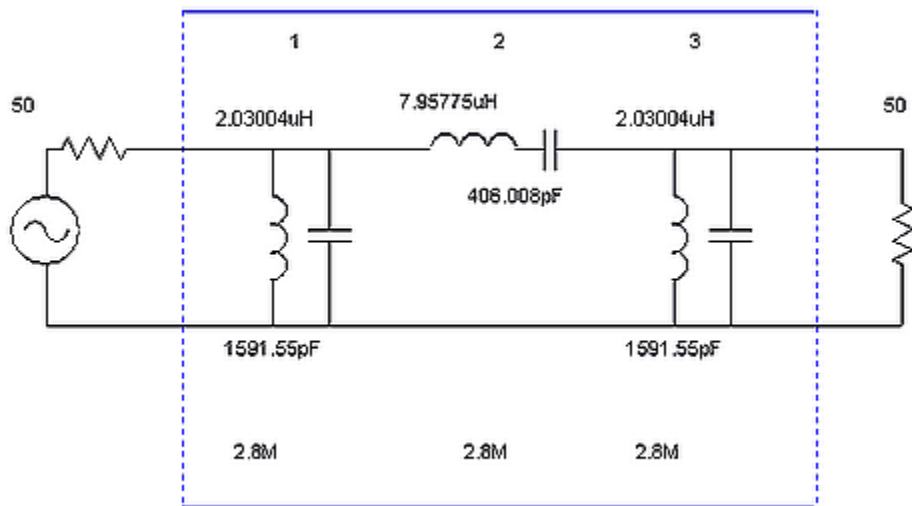
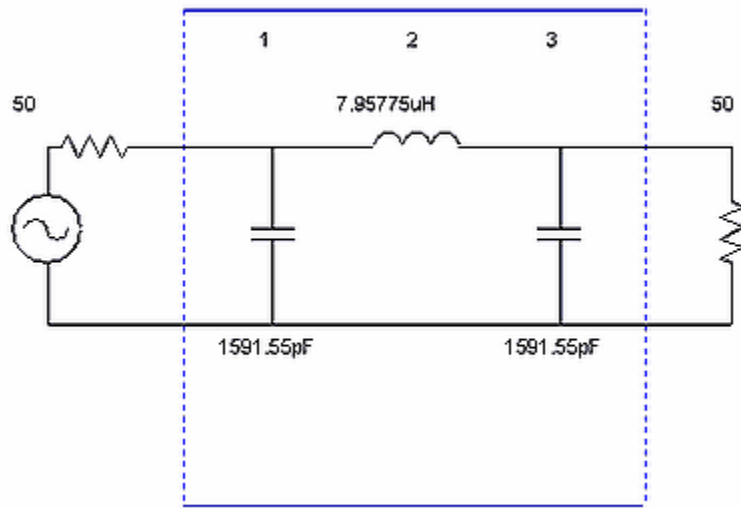
LOWPASS TO BANDPASS TRANSFORM

A lowpass design is defined (in part) by specifying a bandwidth.

A **bandpass** design can be defined in part by specifying a bandwidth and also a ***center frequency***.

Then it can be converted from a lowpass to a bandpass by the simple expedient of resonating each of the elements to the filter's center frequency. There are sometimes problems with this simplistic approach but in general it is valid.

Next we will see a lowpass filter and right below it is a bandpass filter made from it.

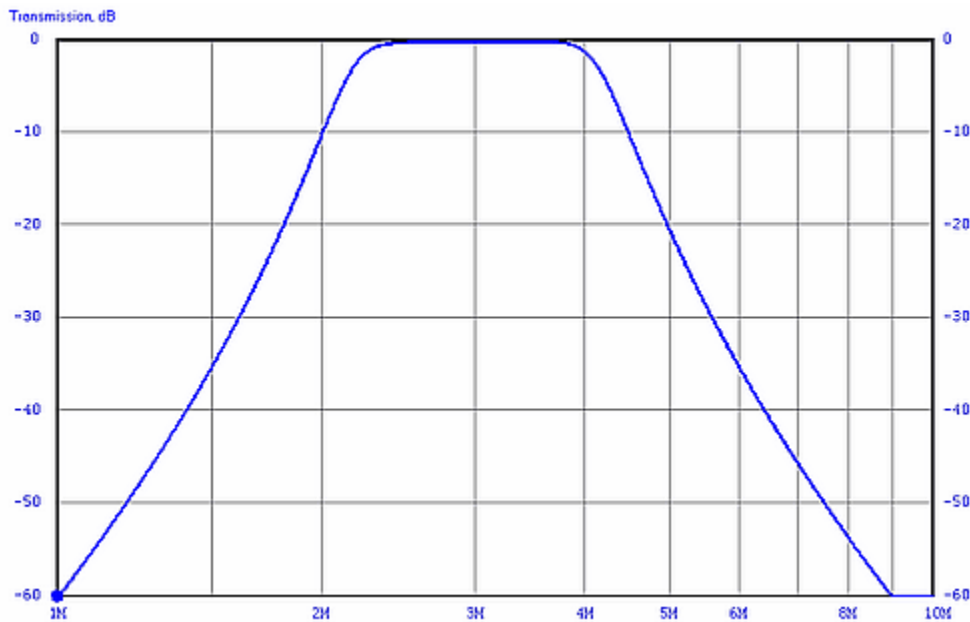


Top: a lowpass with a bandwidth of 2 MHz

Bottom: resonating the parts results in a bandpass

That filter has a bandwidth of 2 MHz centered on 2.8 MHz.
The L-C pairs are resonated at that center frequency.

The magnitude response plot of this kind of bandpass filter is symmetrical on a frequency scale that is logarithmic.
Rephrased: the magnitude response of that filter is *geometrically-symmetrical* about its center.



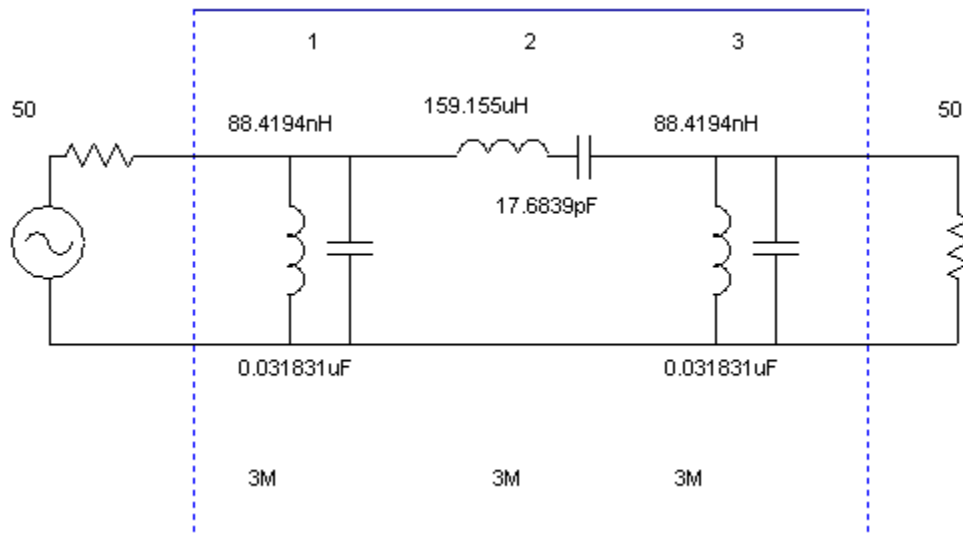
Bandpass filter response plot resulting from that classic lowpass-to-bandpass conversion.

REFINEMENTS IN BANDPASS DESIGN

That classic textbook method of transforming a lowpass to a bandpass, while simple, yields awkward-value components in the case of a narrowband bandpass filter.

This situation can be avoided by using various manipulations. They are tedious to do manually and so are best done using a computer.

If we design a bandpass centered at 3 MHz with a width of 100 kHz using this method, we get a filter with awkward parts values shown here:

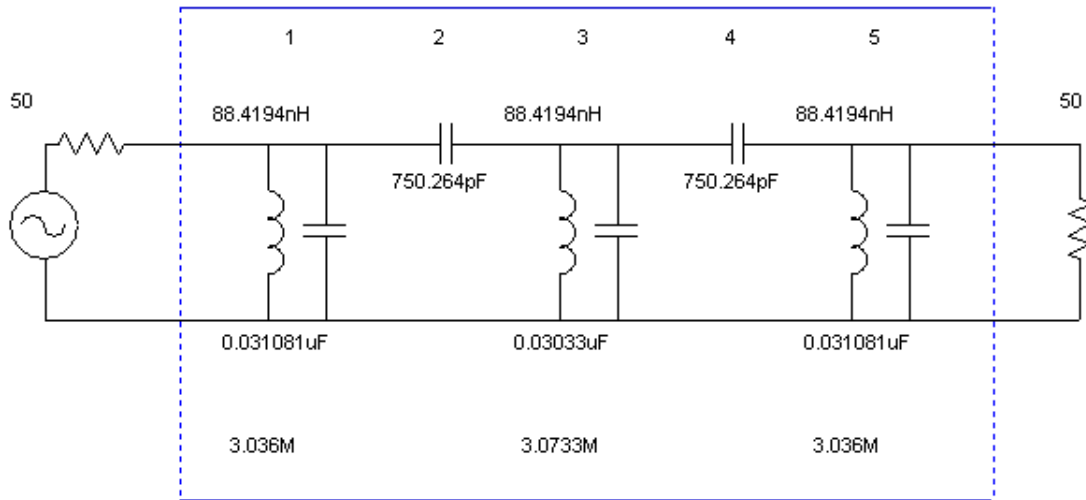


Narrowband filter from simple transform

Some of the L and C values are very large or small.

By "very small" here, take note of the shunt inductors. An inch of wire (about 2.54 cm) is about 15 nanohenries. That shunt inductor is about 4 inches of wire, about 10 cm. Kind of small for a 3 MHz filter.

A better approach is to change the topology to a ***nodal-capacitor-coupled*** design:



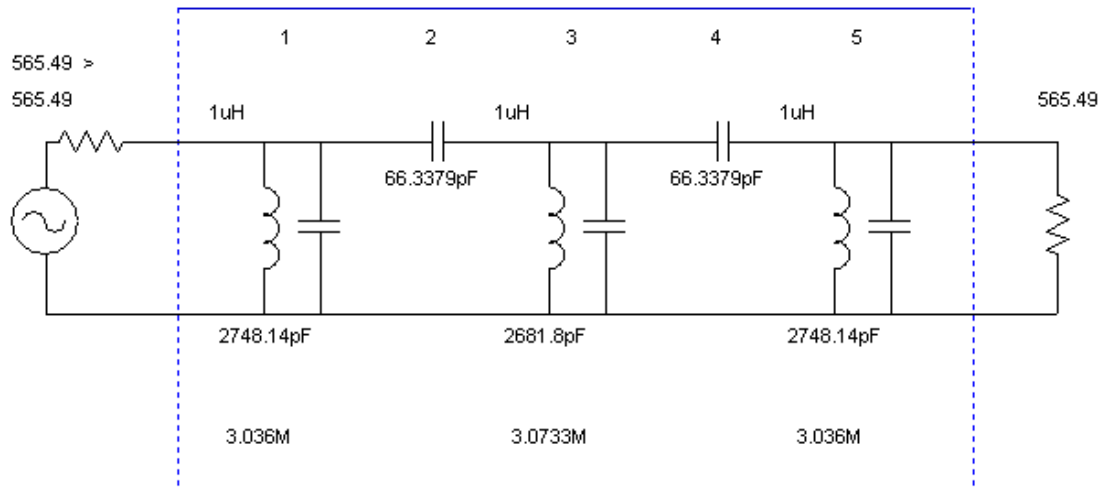
Perhaps somewhat more practical BUT:

- the shunt capacitors' values are large for the center frequency of 3 MHz. It is quite possible that a .03 uF capacitor is self-resonant at 3 MHz, destroying its effectiveness.
- the inductors are still small in value, as discussed.

We can dramatically improve both of those problems by **scaling the impedance** of the filter upward.

This is done by designing the filter with a specified impedance of, say, 500 ohms instead of the usual 50 ohms.

Such a higher-impedance version of the filter looks like this:



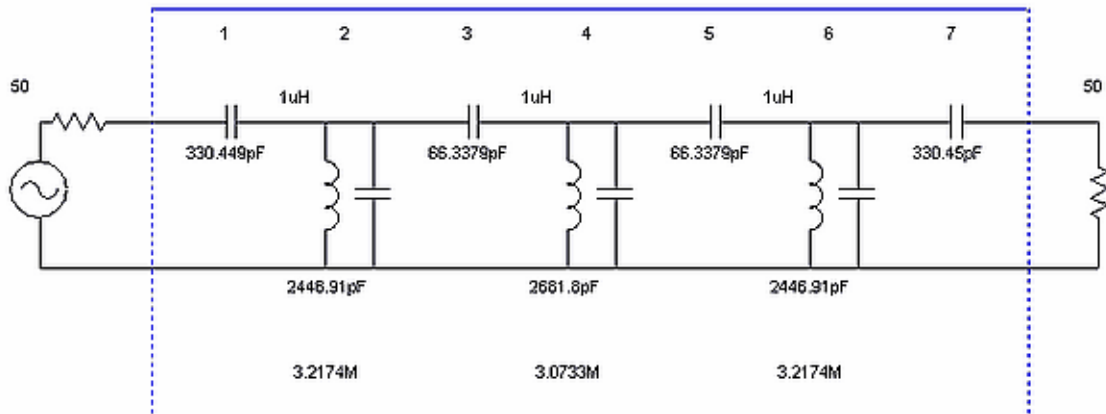
We have changed the inductors to exactly 1 uH. Now the component values are quite satisfactory **but they are for a 565.49-ohm filter** 😞

We want it to work in a 50-ohm system.

So how do we make it work in a 50 ohm system?

By *impedance matching*.

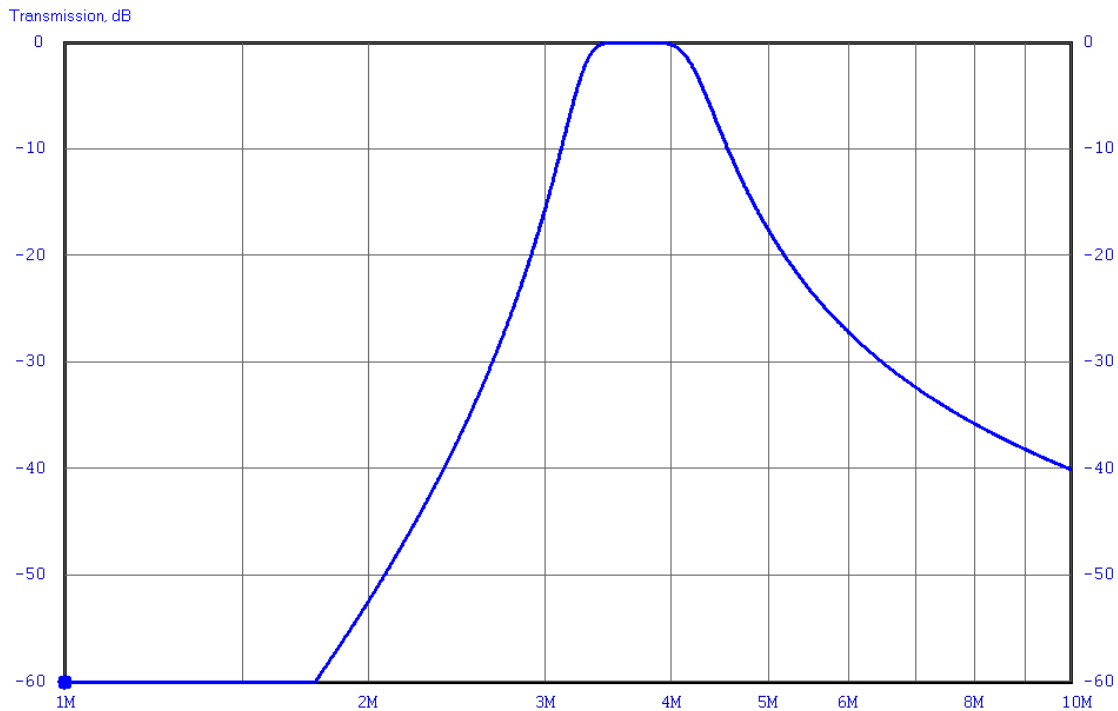
Here is the result of matching:



To match that 565.45 ohm filter to 50 ohms we added some capacitors at the input and output.

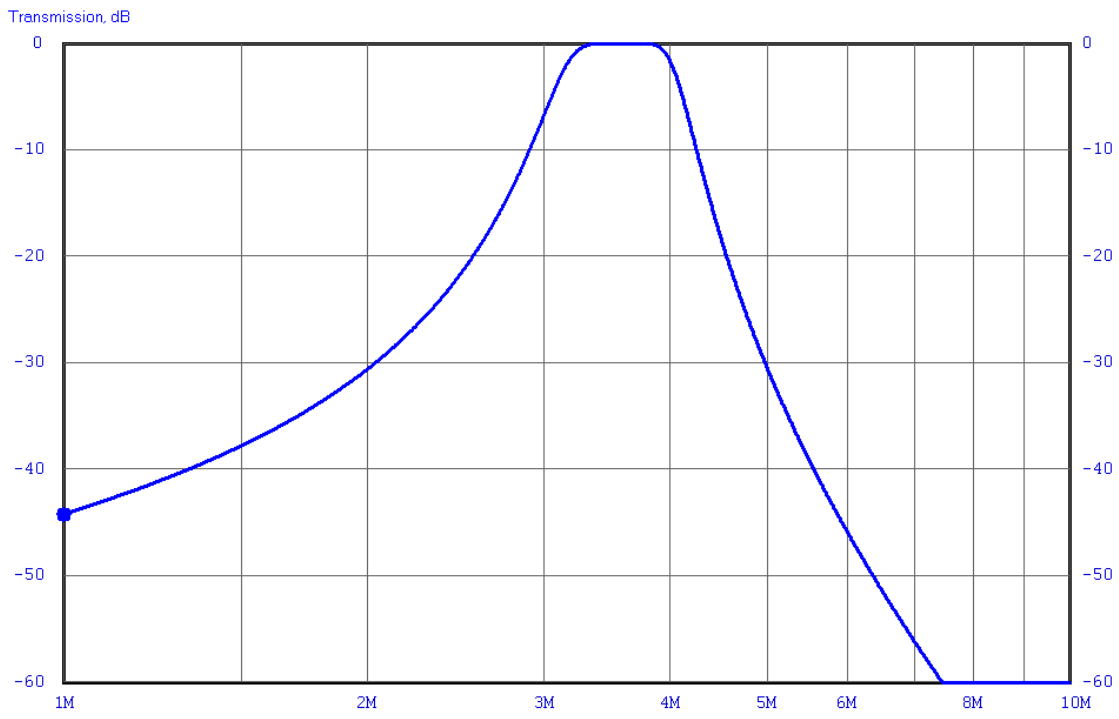
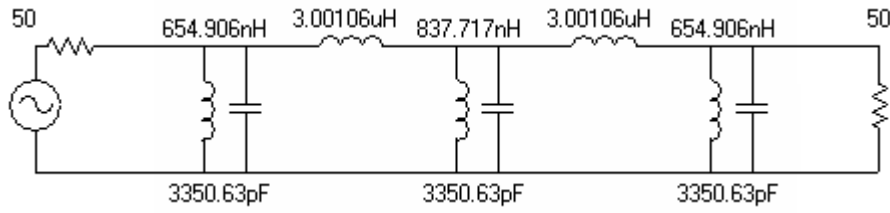
This is the kind of topology used in a radio receiver in its preselector in the front end, or in its I.F. system or anywhere else that a **narrow** (percentage-wise) filter is needed.

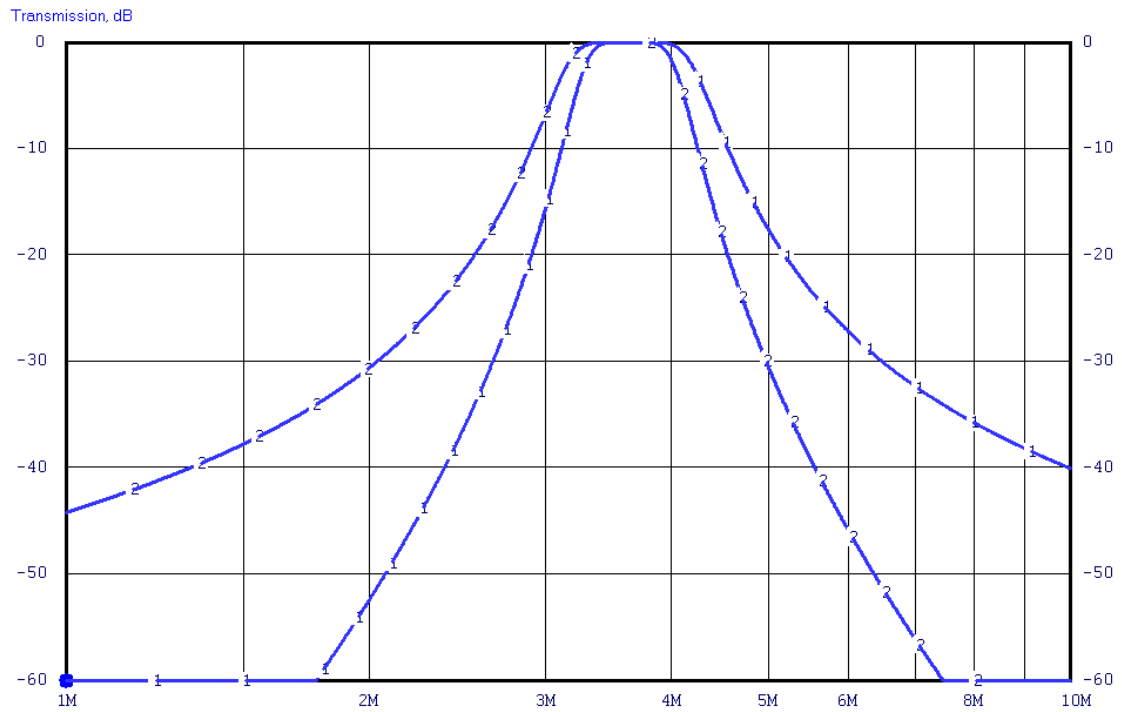
An interesting thing happens when the bandwidth of that filter is increased significantly. The response becomes lopsided as seen here:



Notice, please, that this oddity happens only when the bandwidth is significant in terms of percentage, as shown here.

By using coupling **inductors** the schematic looks like this:





Different topologies, different shapes to the responses,
Different component counts (capacitors vs inductors)

Component values

When a filter is designed “by the book” as shown so far, the component values will invariably be uncommon. The component vendors won't be able to supply 654.906 nH inductors nor will they be to supply 3350.63 pF capacitors.

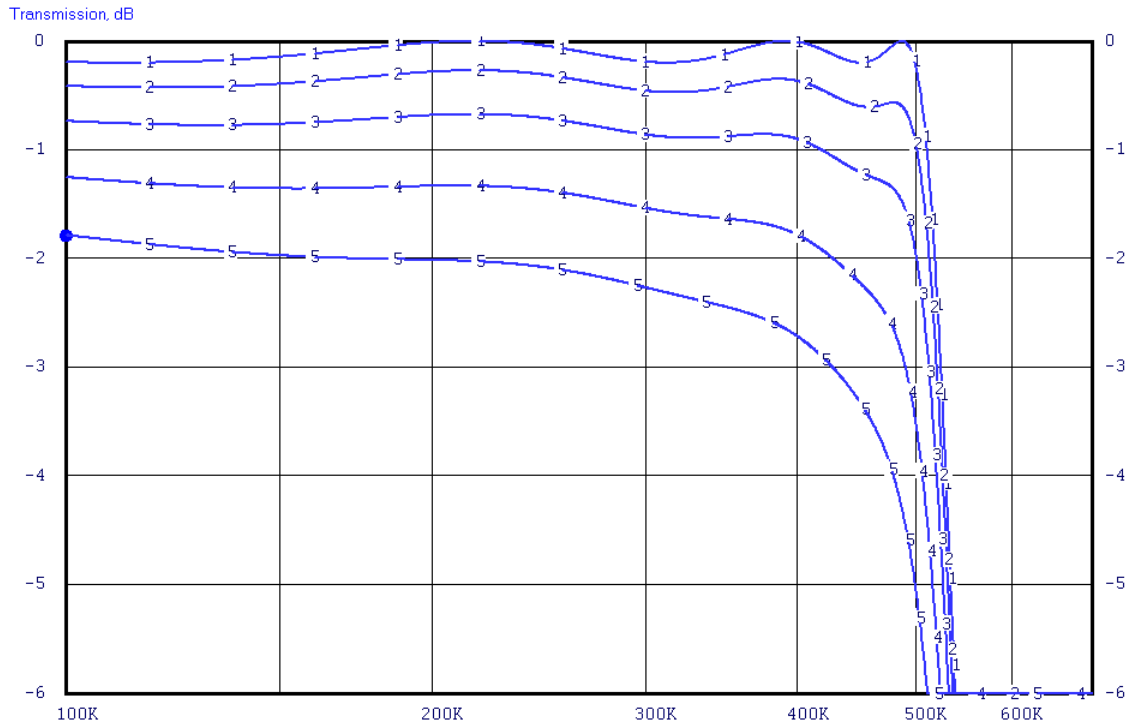
The nearest 5% values can sometimes be substituted but it is always wise to analyze the resulting response using a computer. Or use a program to substitute the nearest 5% values and "see what happens."

EFFECT OF COMPONENT Q

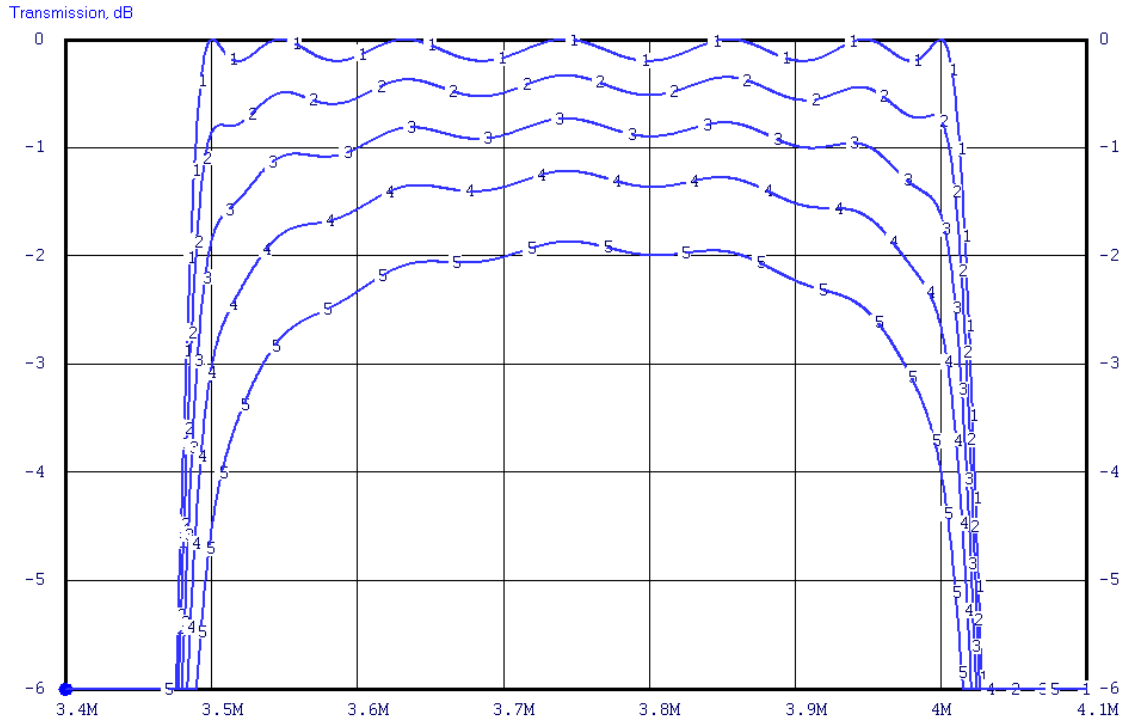
When components with less-than-ideal characteristics are used to fabricate a filter, the performance will also be less than ideal. One such item about which we should be concerned is component “Q.”

Low-Q components cause a loss in the filter and they also cause the edges to become “rounded.”

Here we see the effect of inductor Q on a lowpass filter as we vary the inductor Q values from high (upper plot) to low (bottom plot).



Effect of inductor Q values on a moderately narrow bandpass, same situation. Band edges are most affected but midband loss also takes a hit as inductor Q is reduced:



SIDE EFFECTS OF PASSBAND RIPPLE

Especially in radio frequency (RF) applications it is desirable to design a filter such that the impedance seen looking into the input side remains fairly constant over the passband.

Passband Ripple (dB):	VSWR, (V/V):	Return loss, (dB):
.0005	1.022	39.38
.001	1.031	36.37
.002	1.044	33.36
.005	1.07	29.39
.01	1.101	26.38
.02	1.145	23.37
.05	1.24	19.41
.1	1.355	16.42
.2	1.539	13.46
.5	1.984	9.636
1	2.66	6.868

Passband ripple, VSWR and return loss shown together.

As the passband ripple specification is increased, both the input VSWR and return loss degrade. If those latter items are of importance it follows that a low-ripple design should be used.

Choosing a family

When you want the flattest possible magnitude response, no ripple at all in the passband, choose the Butterworth family. The resulting magnitude response will also have a relatively gentle corner from passband into the stopband.

When a lowpass filter with constant time delay throughout the passband is needed then the Bessel family should be used.

The magnitude response is quite poor, having a rolloff rather than a sudden cutoff at the bandedge.

When a sharper cutoff is needed then choose the Chebyshev family.

A small amount of ripple must be allowed in the passband. More allowed ripple yields better rate of descent into the stopband.

Remember the earlier comment about input VSWR and return loss being affected by the ripple specification.

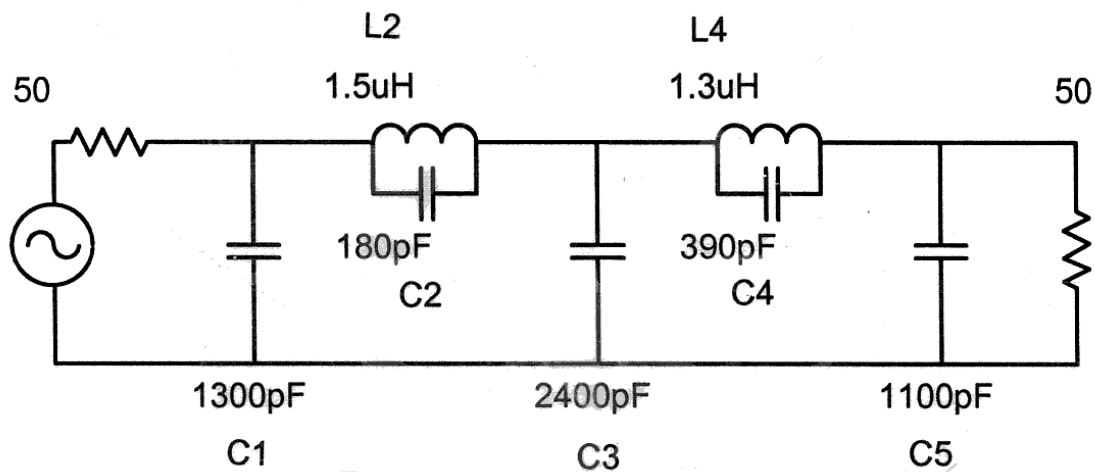
OPTIMIZED HARMONIC FILTERS

Lowpass filters should be placed at the output of radio transmitters

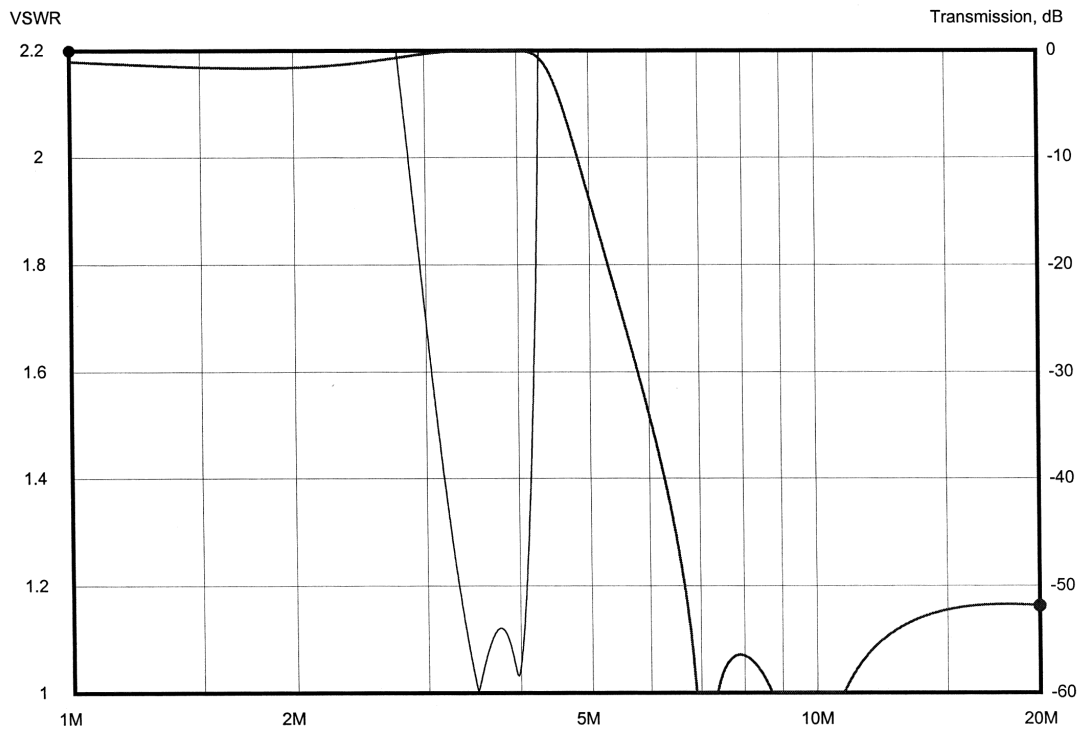
These are commonly designed to pass a single band and provide attenuation at harmonics of that band sufficient to meet the regulatory requirements.

The basic approach is to use a computer to optimize the performance in the passband (a single amateur band) while simultaneously maximizing the attenuation at the second and third harmonic of that same band. When this is done the higher harmonics will also be well within spec.

The schematic of this filter along with parts values for the 3.5 to 4.0 MHz amateur band is shown here:



VSWR and magnitude responses of the filter shown:



Component values for the 160-meter through the 6-meter amateur bands are shown in the following table. The capacitors are shown in pF and the inductors in uH. The capacitors are the nearest 5% values; both the nearest 5% and the exact inductor values are shown.

Band:	C1:	L2 5%:	L2 Exact:	C2:	C3:	L4 5%:	L4 Exact:	C4:	C5:
160m	2400	3.0	2.88	360	4700	2.4	2.46	820	2200
80m	1300	1.5	1.437	180	2400	1.3	1.29	390	1100
60m	910	1.0	1.029	120	1600	0.91	0.889	270	750
40m	680	0.75	0.783	91	1300	0.62	0.631	220	560
30m	470	0.56	0.563	68	910	0.47	0.462	160	430
20m	330	0.39	0.381	47	620	0.33	0.316	110	300
17m	270	0.30	0.306	36	510	0.27	0.262	82	240
15m	220	0.27	0.262	30	430	0.22	0.225	68	200
12m	200	0.24	0.241	27	390	0.20	0.204	62	180
10m	180	0.20	0.206	24	330	0.18	0.172	56	150
6m	91	0.11	0.108	13	180	0.091	0.091	30	82

Values for the optimized harmonic filters

Using the nearest-5% inductor values will result in satisfactory operation. If the construction method is such that exact-value (i.e., adjustable) inductors can be used then the "Exact" values are preferred. These values were obtained from the program "SVCfilter."

FILTER DESIGN AND ANALYSIS SOFTWARE

The following programs have both design and analysis capability:

Elsie – www.TonneSoftware.com

AADE Filter Design And Analysis – www.aade.com