APP NOTE

Application Note 12

Analog Passive RLC with Loss Optimization

Highlights
RLC Passive Networks
Inductor Parasitic Losses
Circuit Optimization
Sensitivity & Monte Carlo Analysis
Curve Editor

■ **Design Objective**
Allpole 5th Order RLC Lowpass
Elliptic 5th Order RLC Lowpass
100kHz Passband, ±1dB
80dB Stopband

This example will provide a demonstration of how to utilize the program to compensate for the parasitic losses of passive RLC networks. Two different examples are provided, an Allpole Lowpass and Elliptic Lowpass. However, the techniques which will be covered are applicable to any passive filter.

Passive filters perform their filtering function without the aid of active components. As a result both capacitors and inductors must be utilized along with resistors. For most designs suitable capacitor types can be selected for the application and frequency range involved, with minimal parasitic problems. However, inductors are far from ideal, and typically contain the largest amount of parasitic resistance and capacitance.

Because of this the program provides a special model for inductors which contains both series resistance and shunting capacitance. These two parasitic terms combine to form an equivalent Fo and Q value associated with the fundamental inductance.

Unfortunately even this lossy inductor model is only a crude approximation to the extremely complex behavior of real inductors. Most real inductors contain highly frequency dependent elements, with resistance increasing and inductance decreasing as the frequency increases.

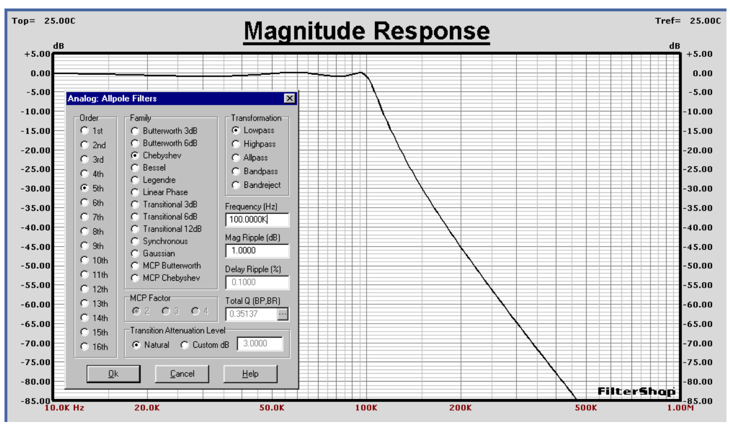
An advanced predictive model is planned for a future version of the program, which should greatly improve the modeling accuracy for passive networks.

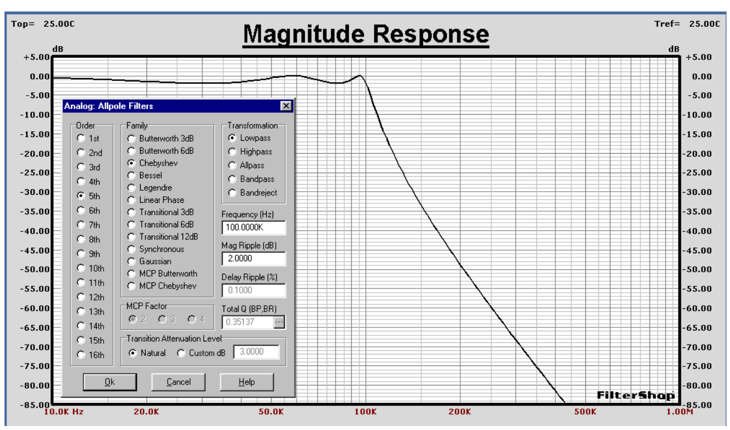
■ Allpole Lowpass Target

A 5th order Lowpass is required, with 1dB ripple. There are several types of families which can produce this kind of response, and here we will simply choose the common Chebyshev as an example. The response appears below.

The stopband reaches 80dB attenuation at approximately 425kHz. If we had a particular stopband edge frequency to meet, many different orders or family types could be tried until a suitable target was found.

Also note that the passband ripple occurs between 0dB and -1dB. Technically this is a peak max/min ripple of ±0.5dB with a base level of -0.5dB. Therefore a new target is produced using a ripple value of 2dB. This response is now 80dB down at 375kHz as shown below.



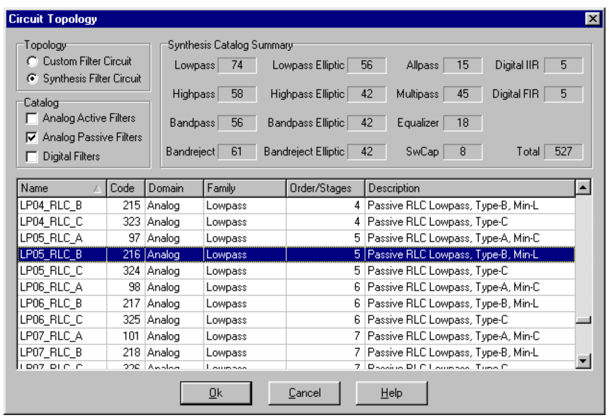


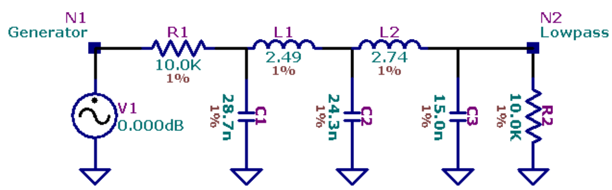
■ Allpole Lowpass Circuits

We now need to load one of the synthesis circuits suitable for this type of passive network. Looking at the catalog, we see that there are three different Allpole 5th order Lowpass circuits. Two are double terminated types, and one is a single terminated type.

Double terminated types always have insertion loss, but since our inductors have loss themselves, there is little to be gained in choosing the single terminated configuration. If we choose a double terminated circuit, we have the ability to adjust the input resistor to directly compensate for the resistance loss in the inductors.

The two different double terminated circuits are types *A* and *B*. Note that the description for type A is *Min-C* and for type B is *Min-L*. Each of the configurations can use either a minimum of capacitors or inductors. Since we generally want to use as few inductors as possible, it is often best to pick the Min-L configurations. Therefore we will choose *LP05_RLC_B* as our circuit. This is shown below.

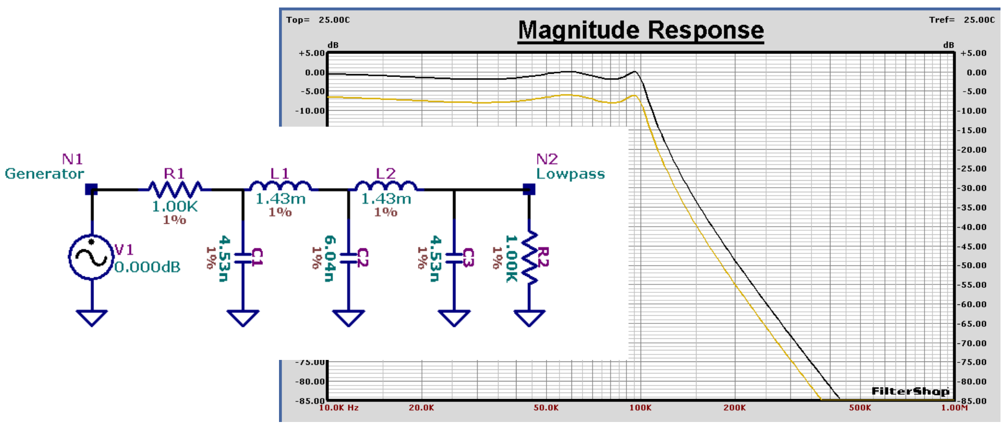


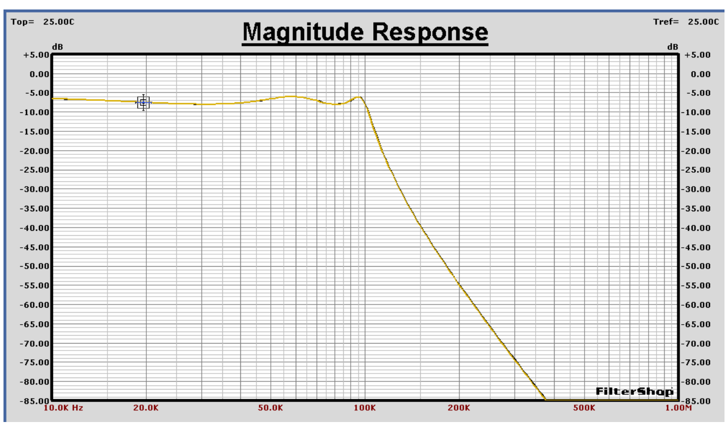


We have our target and circuit, so we are ready run Synthesis. We can choose whatever preset values we desire for R1, R2. For this circuit we will use identical values of 1K and 1K.

Note:
For many double terminated circuits, equal resistor value solutions will not be possible for all target functions. Some will require unequal ratios.

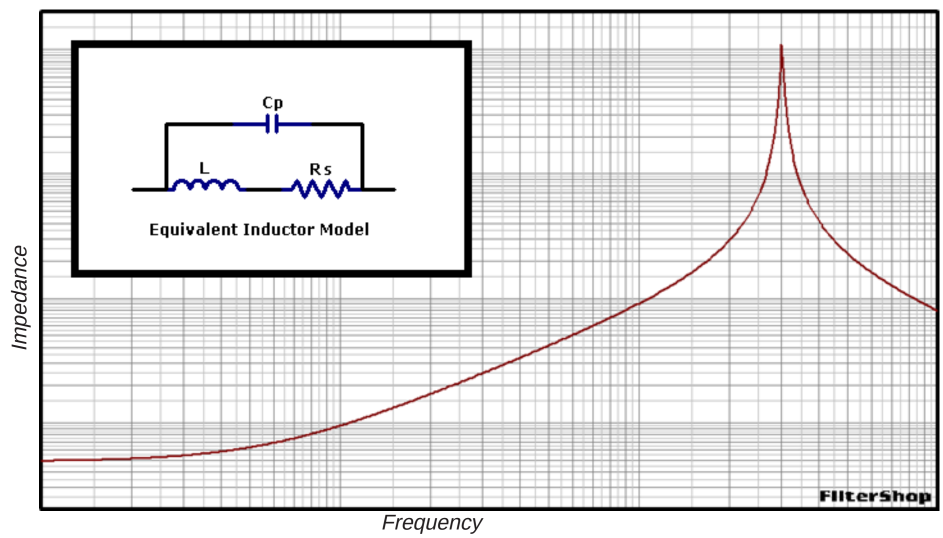
It is immediately obvious that the circuit response is -6dB, while the target of course was at 0dB. The target can be offset to the circuit response by locating the cursor along the passband, and then clicking the *Align* toolbutton usually found in the status bar. The curves match very close as shown below.





Synthesis produced equal values for both L1 and L2 of 1.43mH. However, the inductors are currently being modeled as virtually lossless. The default series resistance is 1u Ohm and the default shunt capacitance is 1f Farad. The equivalent circuit for the inductor is shown below.

The model used for the inductor includes a series resistance and a parallel capacitance. This produces an impedance curve similar to that shown below. The inductor only behaves as an inductor for frequencies in the middle of the spectrum.

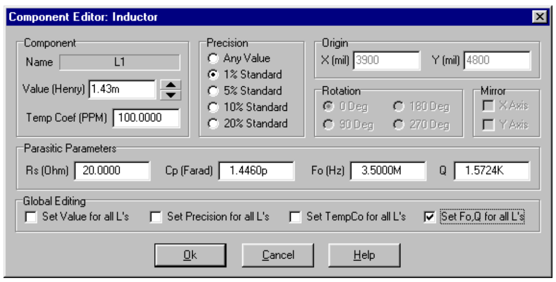


To model the losses in the inductors, we need to change the values of Rs and Cp for L1 and L2 into something more realistic. One way to approach this is to examine an actual catalog listing for parts that could be used. An axial half inch size inductor in this value range was found to have the following specs:

SRF= 3.5MHz Qmin= 60 Rdc= 18 Ohms

SRF is the Self Resonance Frequency. Qmin is the minimum Q at resonance, and Rdc is the coil's DC resistance. The resistance is actually frequency dependent, and the value given is for DC. The AC resistance at higher frequencies is larger. However, since the corner frequency of our filter is 100kHz, this is a small portion of the 3.5MHz resonance. The resistance will be slightly higher than Rdc.

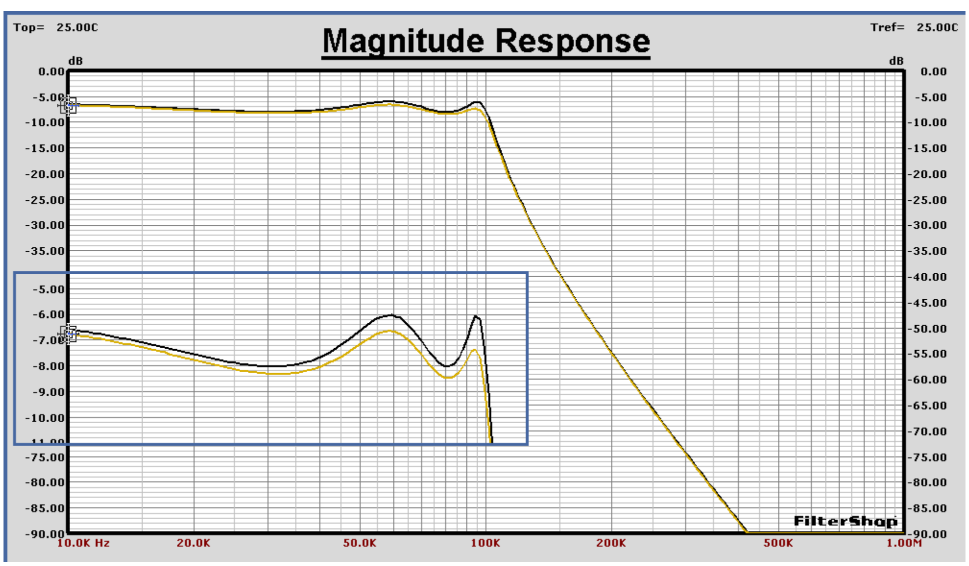
If we open the component editor on one of the inductors, we can change the Rs/Cp values. The equivalent resistance at 100kHz is unknown. However we can expect that it is going to be slightly higher than Rdc. We might make a guess and use a value of 20 Ohms.



We first enter the Fo frequency at 3.5MHz. This calculates the Cp value for us. Next we enter the Rs value of 20 Ohms. This updates the Q as 1500. We also enable the *Set Fo/Q for all Inductors* to copy the changes to L2 as well.

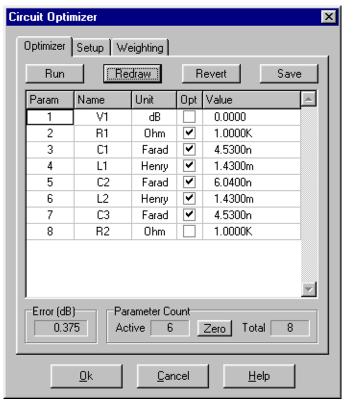
When the circuit is recalculated, the circuit response is shown below in Yellow, and the original target response in Black. There is now an average difference in the passband of about 0.5dB.

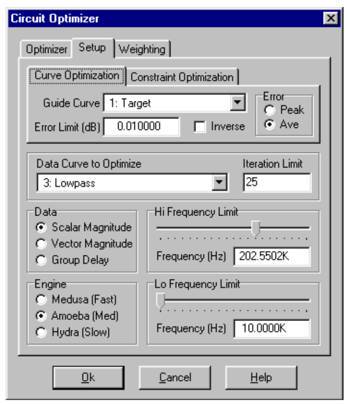
This difference is fairly small, and we can probably correct most of the response using a simple optimization with the original target. However, the circuit will no longer be capable of perfectly fitting the target everywhere, since it is not the same circuit due to the presence of the parasitic elements.



■ Allpole Lowpass Curve Optimization

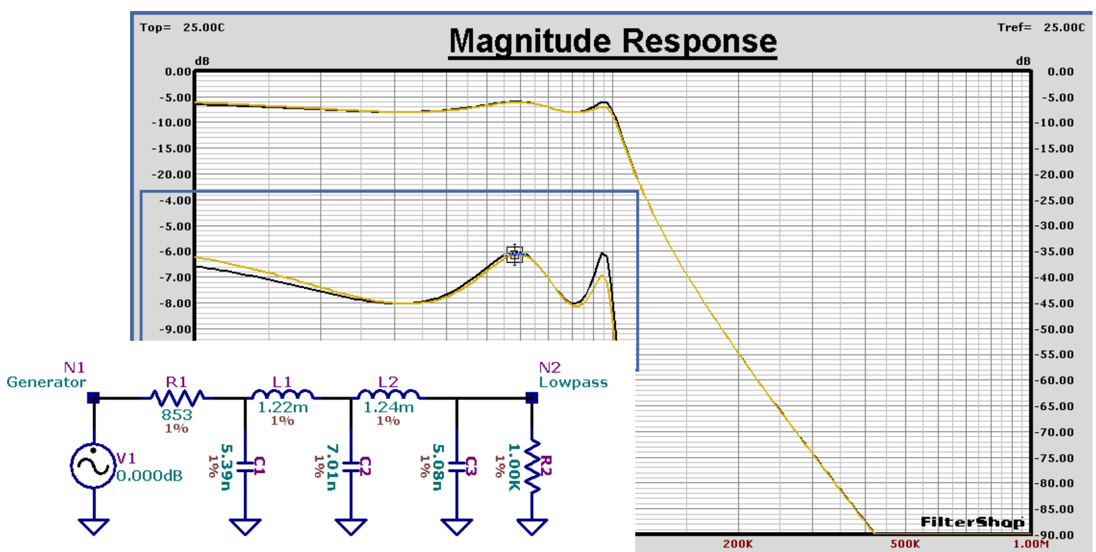
The target Data Curve is now copied to a Guide Curve to be used as the optimization objective. Since we are most interested in fixing the passband, the optimization will be limited to 10kHz to 200kHz with average error. The six components to be optimized are the L/C values along with R1. Since the inductor parasitic resistance appear in series with the inductors, R1 needs to be adjusted to fix the insertion loss.





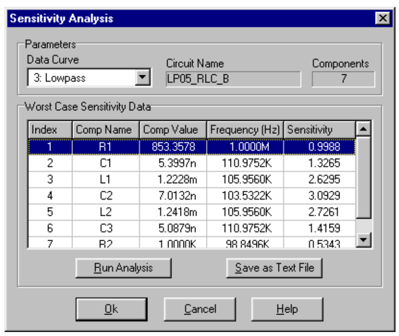
The circuit optimizer setup is shown here, along with the final result shown below. R1 has decreased as expected. Both of the inductors have dropped in value slightly, and the capacitors have increased.

The circuit response is once again very close to the original target. It would probably be pointless to attempt to adjust the response further unless we plan on using extremely accurate components.



An examination of the sensitivity shows a worst case value of about 3, for C2 as shown below. This is about what would be expected for a sharp Chebyshev type response. If a smoother target function had been selected the sensitivity values would have been reduced.

If we assume that the L/C values are to be built from 5% standard values, the precision of these can be changed. The values are rounded to those shown below, with the resulting response shown in the Magnitude graph.


Sensitivity Analysis

Parameters
Data Curve: 3: Lowpass | Circuit Name: LP05_RLC_B | Components: 7

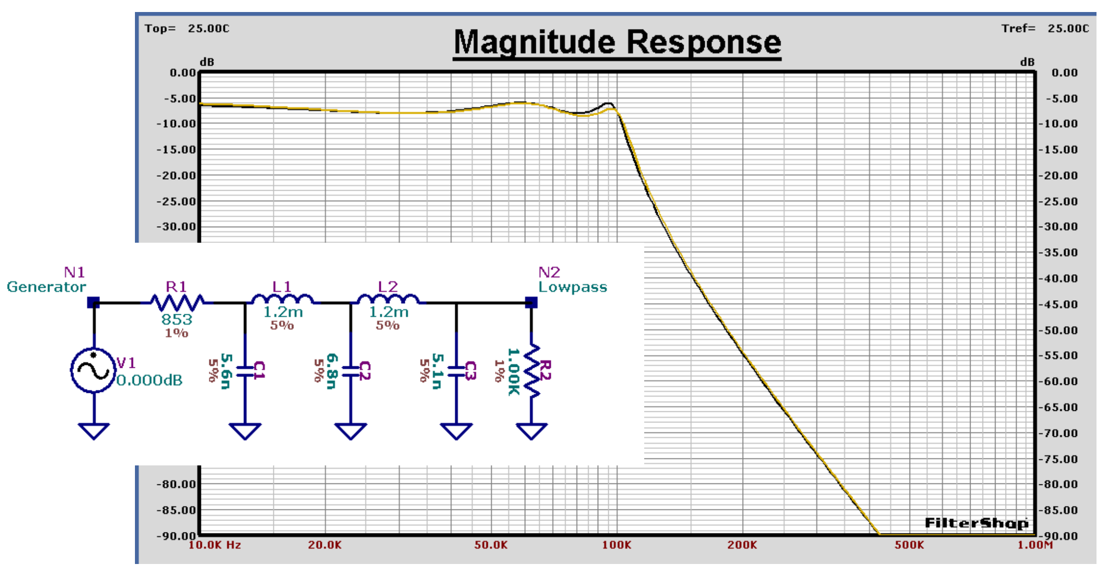
Worst Case Sensitivity Data

Index	Comp Name	Comp Value	Frequency (Hz)	Sensitivity
1	R1	853.3578	1.0000M	0.9988
2	C1	5.3997n	110.9752K	1.3265
3	L1	1.2228m	105.9560K	2.6295
4	C2	7.0132n	103.5322K	3.0929
5	L2	1.2418m	105.9560K	2.7261
6	C3	5.0879n	110.9752K	1.4159
7	R2	1.0000K	98.8496K	0.5343

Run Analysis | Save as Text File | Ok | Cancel | Help

The largest change occurs right at the edge of the passband. Controlling the knee of the response is clearly a direct function of the component precision.

This result is about what would be expected using through-hole components. The inductors of an SMT assembly are much smaller, and the losses are generally larger. This case is demonstrated next.

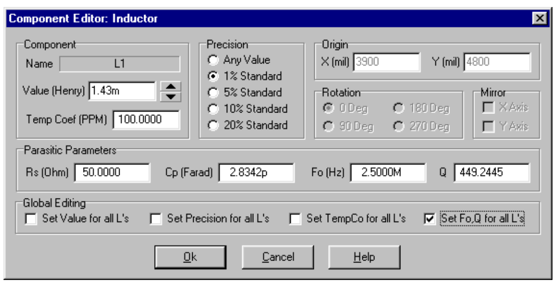


■ Allpole Lowpass with SMT Inductors

The previous circuit used typical data for the inductors representing through-hole type axial components. The circuit could also be constructed using SMT components. Due to the small size of SMT devices, it is difficult to realize inductors of large value. The inductors needed here are about 1mH which can be obtained.

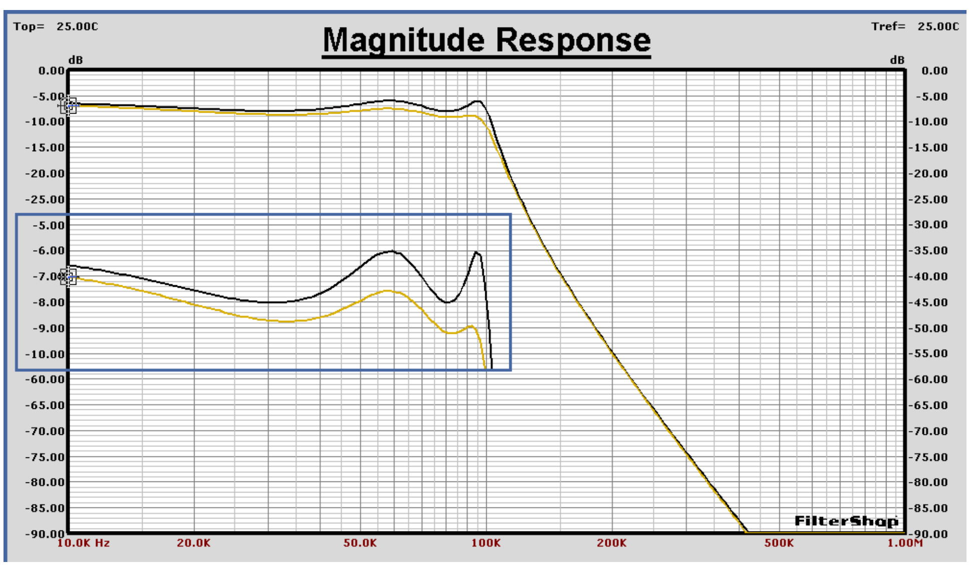
The data for a typical 1mH SMT inductor (case 1812) is as follows:

SRF= 2.5MHz Qmin= 30 Rdc= 40 Ohms



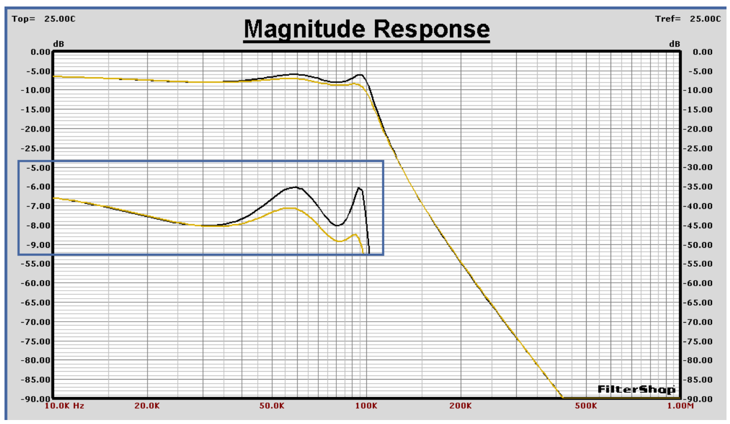
All of these parameters are considerably worse than those of the previous axial component. As before we will assume that the AC resistance at 100kHz will be slightly larger than the DC value, say 50 Ohms.

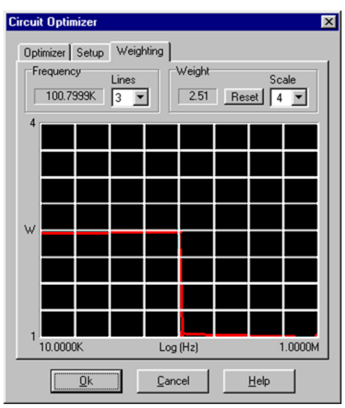
Using the original component values obtained from the previous synthesis, and the SMT inductor data, the response below is produced. The majority of the passband is in error by nearly 1.5dB, which is three times worse than the previous.



As before we can attempt to optimize the circuit with loss to the original target response. After this is done, the response curve is shown below.

Most of the curve has been moved towards the target with the exception of the region between 50kHz and 100kHz. Using average error the optimizer has tried to fit as many points as possible to the objective. However in this case it has become more difficult, and this region fails to reach the target.

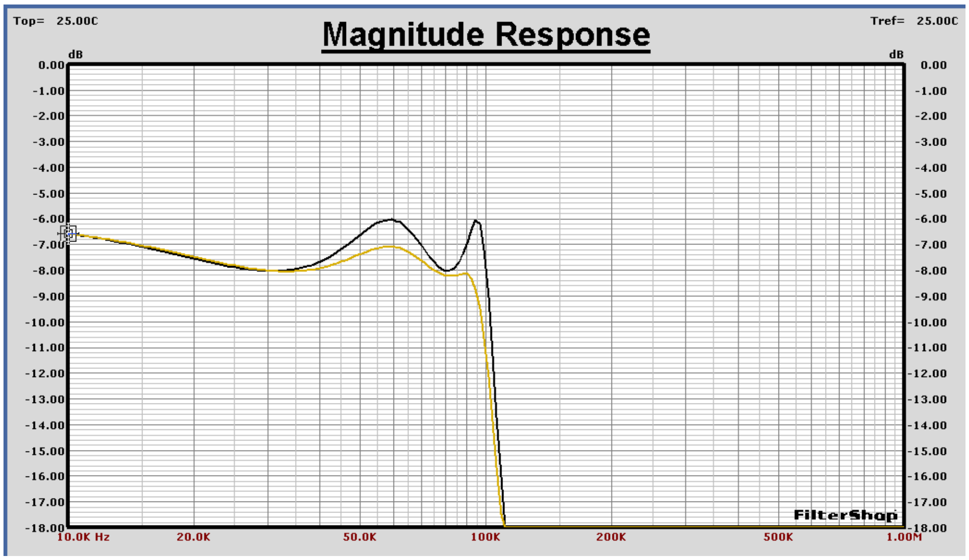


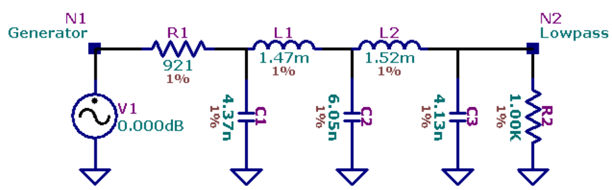


Since the average error is being driven down evenly across the entire 10kHz to 200kHz region, we can try to place more emphasis on the passband region. This can be done with weighting.

The weighting curve is edited to raise the passband region (up to 100kHz) to 2.0. This gives the passband twice the importance of the stopband.

The circuit is then reoptimized.





The magnitude response shown above has now been improved in the 50kHz to 100kHz region. However note that the response fails to reach 100kHz, and instead rolls off at 90kHz. Also note that the passband ripple no longer retains an equal ripple form. Due to the extra losses within the inductors, it is impossible for the circuit to perform as sharply as the original target near the knee.

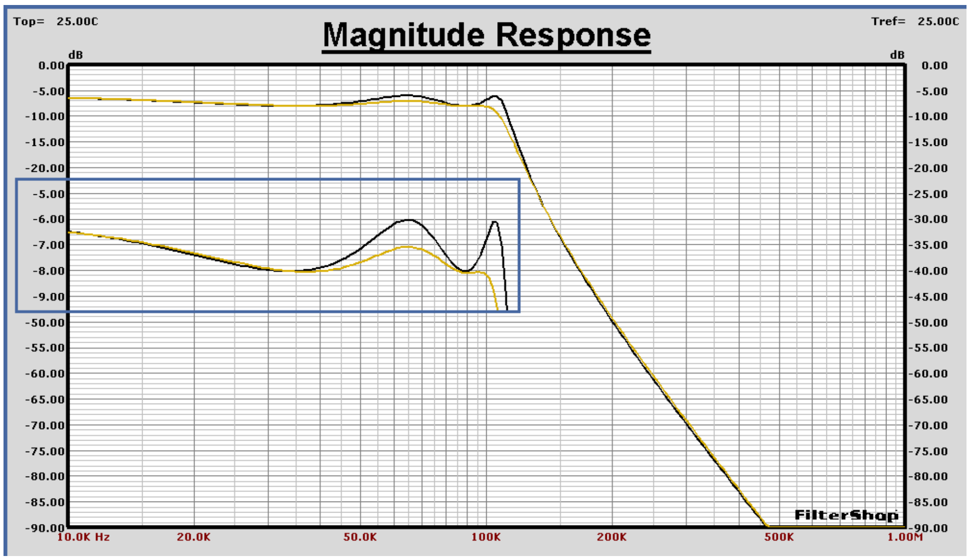
In order to reach the specified 100kHz passband, the target function must actually be moved up in frequency by about 10%, and the circuit reoptimized.

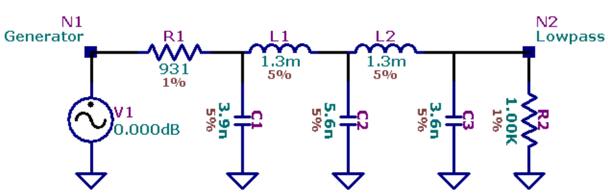
This results in the stopband edge also being increased by 10%, thus widening the transition region. This is a common situation caused by the introduction of loss into a passive filter - the transition region will typically increase.

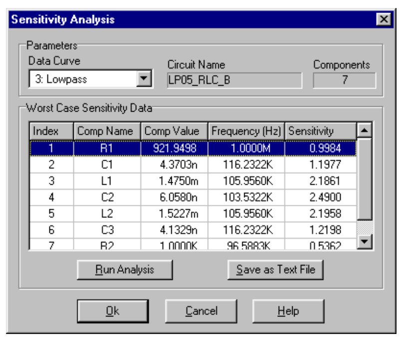
After a new target is generated with a corner frequency of 110kHz, copied to a Guide Curve, and the circuit reoptimized, the final response below is produced. The passband is now fully extended to 100kHz, and the stopband edge has increased to 425kHz.

The sensitivity is a bit better than the previous circuit with maximum S values of about 2.5 rather than 3. The final circuit with 5% L/C values is shown below.

For this SMT inductor example the transition band increased by about 10% due to the inductor losses.





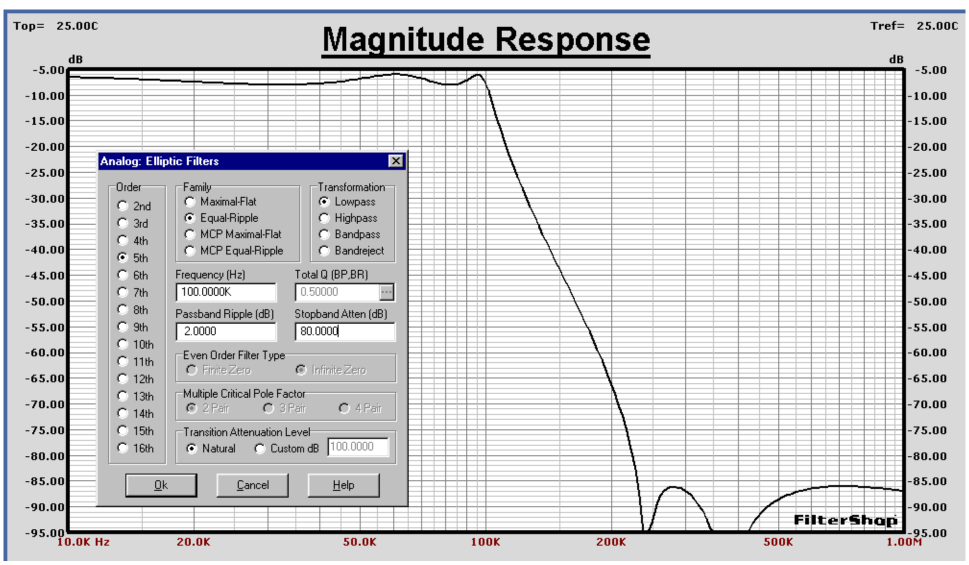


■ Elliptic Lowpass Target

The target for the Elliptic version of our Lowpass filter is similar to the Allpole, with passband ripple of 2dB, 80dB stopband, and we shall attempt to use the original corner frequency of 100kHz. To allow easy comparison with the Allpole Chebyshev, the standard Equal-Ripple family is selected. The Analog Elliptic dialog parameters and target response are shown below.

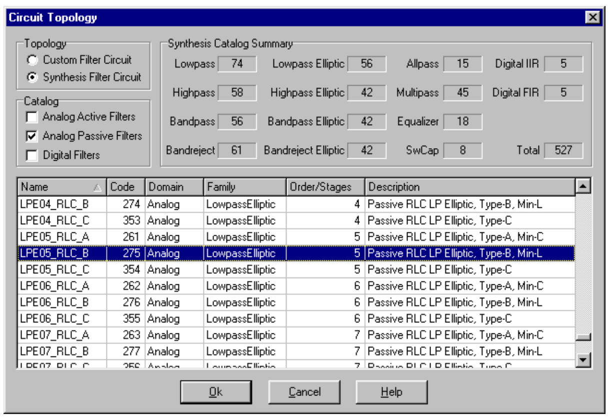
We have left the target offset at the -6dB level, since we will probably need it here again for this circuit. As with the Allpole, the Elliptic form will also have an insertion loss of 6dB.

Note that the presence of the two zeros in the stopband has now reduced the edge frequency to 225kHz, down from the previous of 425kHz. This is an improvement of almost 2:1, and demonstrates the powerful attenuation of elliptic filters.



■ Elliptic Lowpass Circuit

We will wish to use another minimum L type configuration for this Elliptic filter, so the *LPE_05_RLC_B* synthesis circuit is loaded. Synthesis is run, using 1k values for R1 and R2. The response of the circuit and the schematic are shown below.

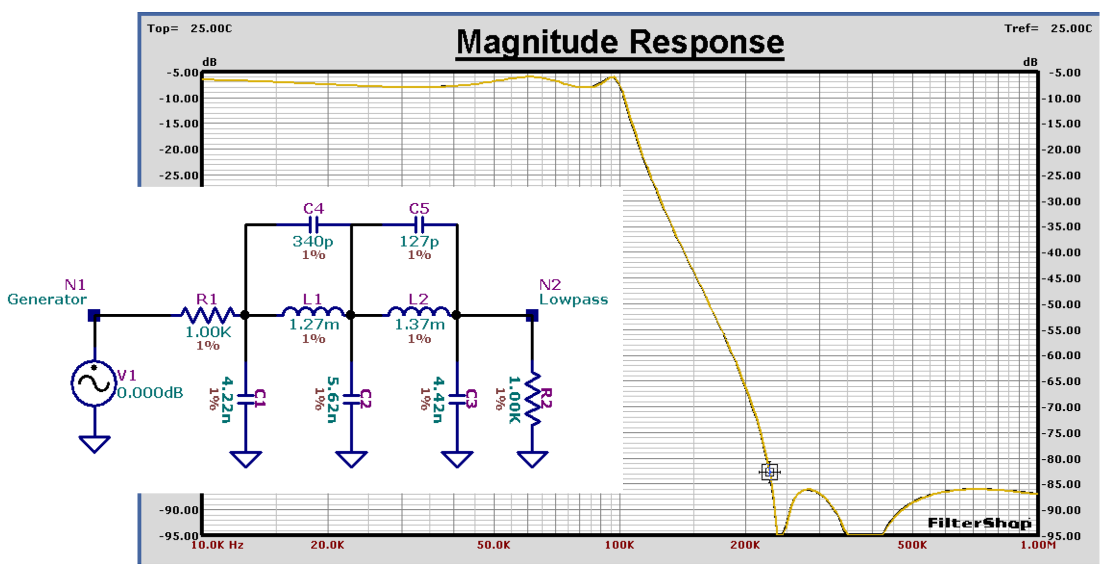


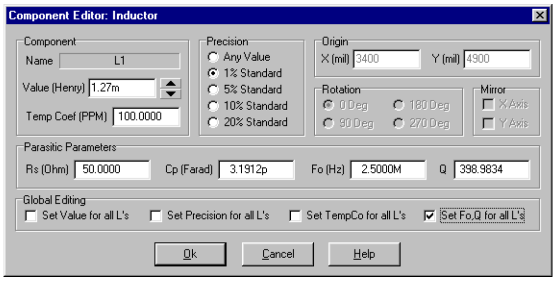
This Elliptic Lowpass requires only two additional capacitors over the previous Allpole circuit. The component values are also similar to the previous.

For this case we shall again assume that SMT components are used, and therefore the inductor specs are:

SRF=2.5MHz Qmin=30 Rdc=40 Ohms

As before we shall assume that the AC resistance at 100kHz is about 50 Ohms.



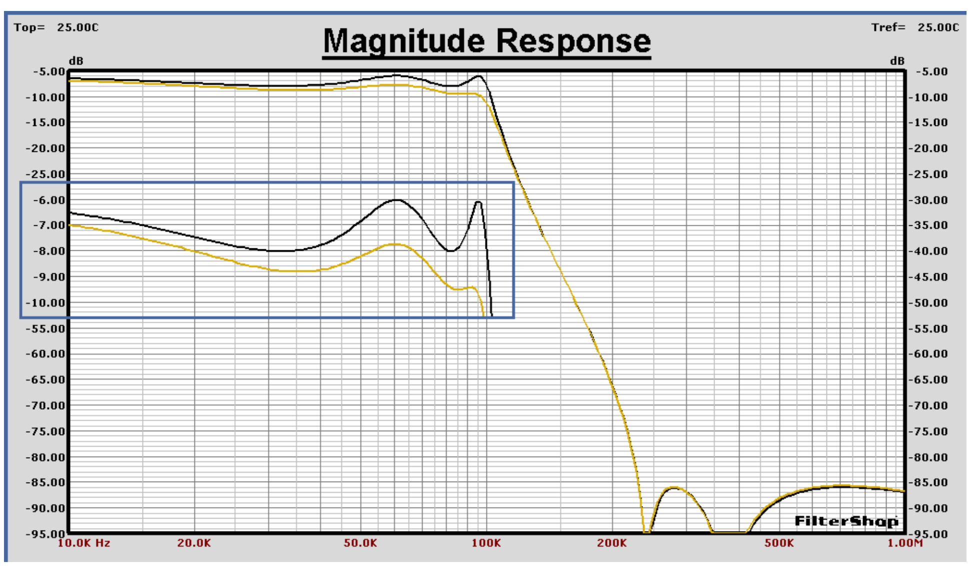


After the inductors are edited with the values Fo=2.5MHz and Rs=50 Ohms, and the circuit recalculated, the response shown below is produced in Yellow and the target in Black.

The response in the stopband is largely unaffected, but the passband shows similar problems as was the case for the Allpole circuit. The passband is 1.5dB below the target.

Optimization of an Elliptic response is somewhat different than for the Allpole case. We can reasonably expect that the transition region will widen, and this will result in changes to the locations of the zero frequencies. If we attempt to optimize to the Elliptic target as a single curve, the circuit response will be forced to match the exact same zero frequencies. This would be ineffective.

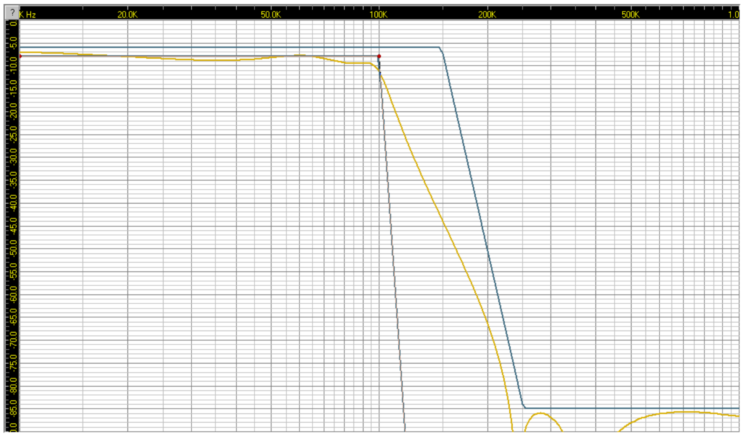
Since we know that the passband must remain within a ±1dB tolerance, and the stopband must remain below 80dB, the appropriate method of optimization is by Max/Min constraints. This allows the locations of the zeros to float, while maintaining the stopband attenuation at a minimum of 80dB.

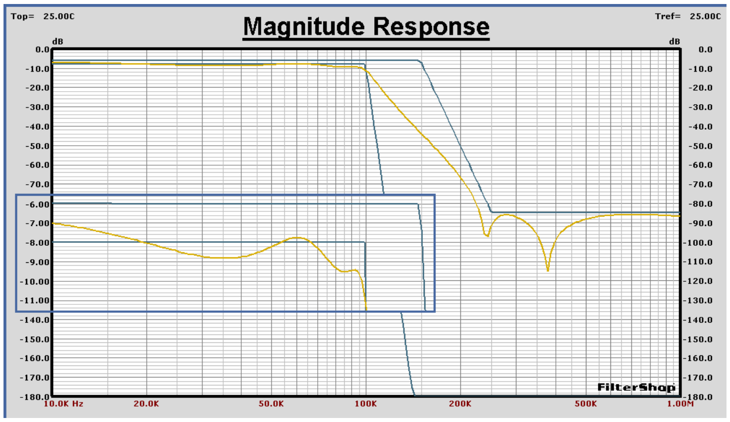


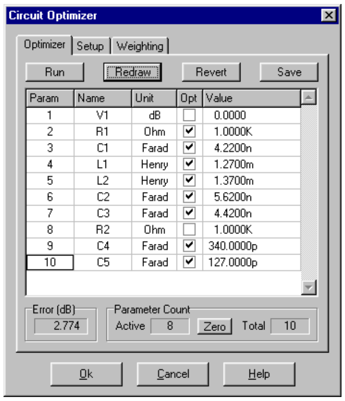
■ Elliptic Lowpass Constraint Optimization

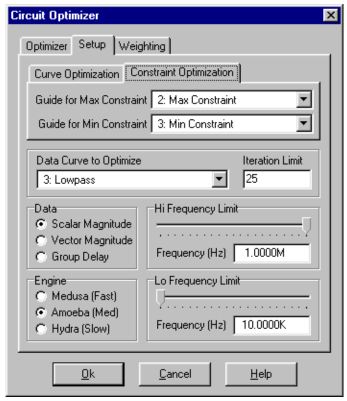
The *Curve Editor* is now used to created the Max/Min constraints, by copying some points from the circuit response and then editing the nodes. A window is created for the passband between -6dB and -8dB up to 100kHz. The Min constraint is the most critical here and will force the circuit response to reach the 100kHz corner.

The stopband edge for the Max constraint is set to -86dB at a frequency of 250kHz, slightly larger than the target edge of 225kHz. The Min constraint is taken below -200dB which causes the optimizer to ignore any levels below that value. This allows for the nulls in the stopband.







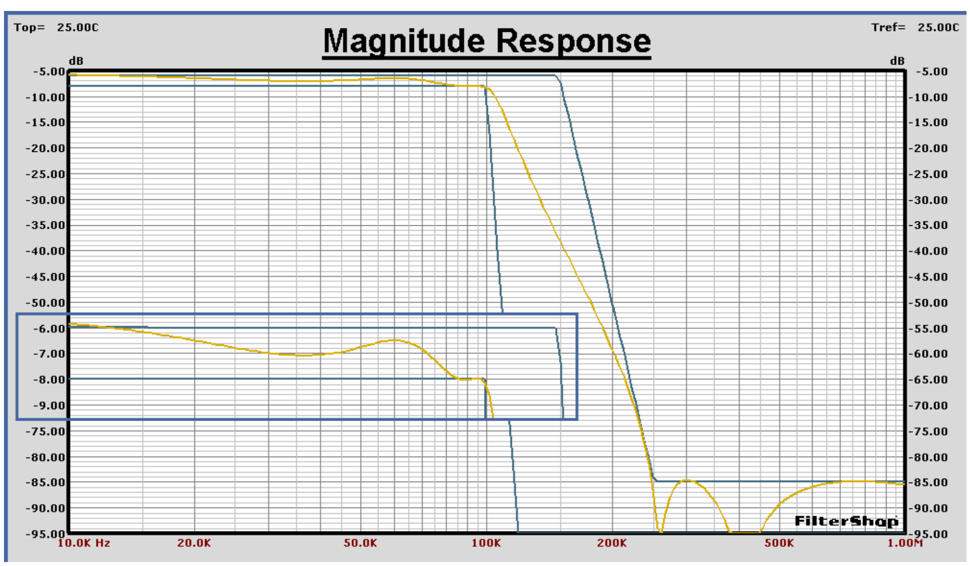


Eight components are selected for optimization including all L/C values and R1. R2 is not optimized to prevent the entire impedance of the circuit from sliding.

For constraint optimization the entire system frequency range of 10kHz to 1MHz must be used.

After optimization, the error could only be reduced to 0.15dB, indicating that the response could not be contained within the constraints.

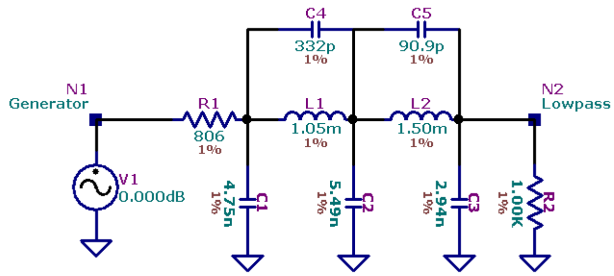
The magnitude graph below shows the result. It is easy to observe what points on the response curve touch various regions of the constraints. These are the critical bounds which control the shape of the response. One of the bounds is clearly the stopband edge frequency near 250kHz. One or more of the bounds must be relaxed if the circuit response is to fit within the constraints everywhere. We will move the stopband frequency a small amount from 250kHz to 260kHz.

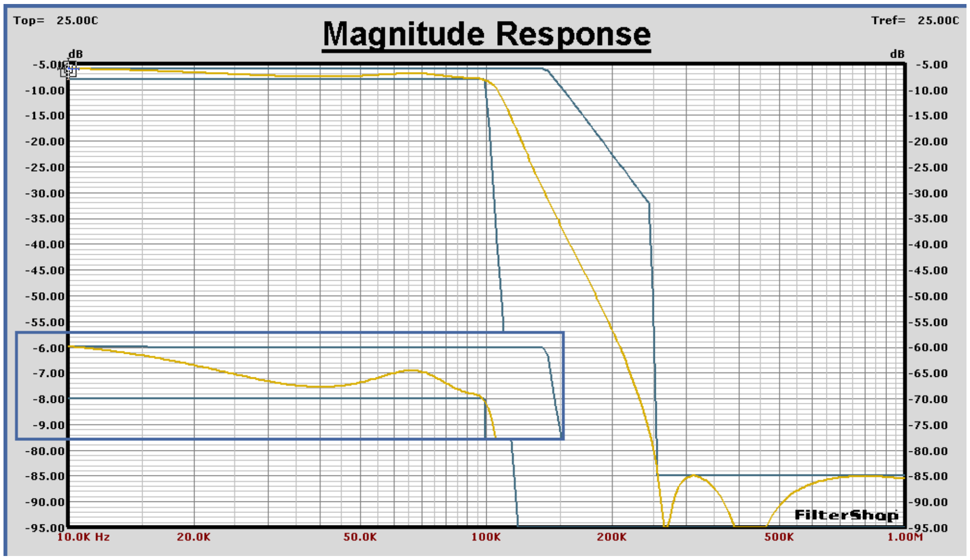


After the Max constraint is edited, and the circuit reoptimized, the results below are produced. This time the error was reduced to zero and the circuit response is contained entirely within the constraints.

The circuit schematic shows that L1 and L2 are about 1mH and 1.5mH respectively. The final response of this circuit yielded a stopband edge frequency of 260kHz, where the ideal target was 225kHz.

Due to the inductor losses the passband cannot maintain equal ripple response, but does meet the ±1dB specification.

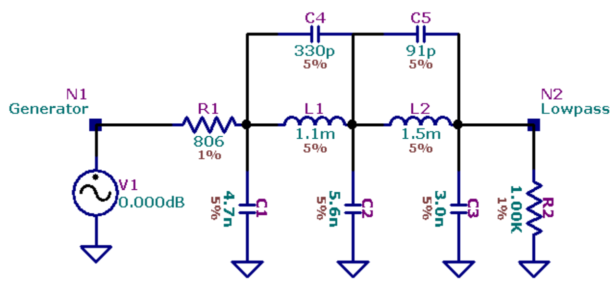


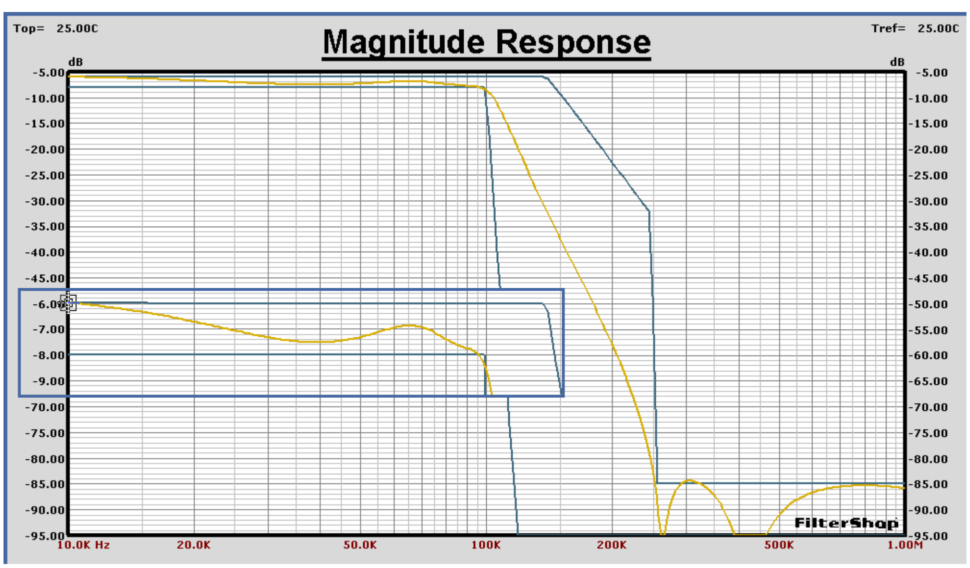


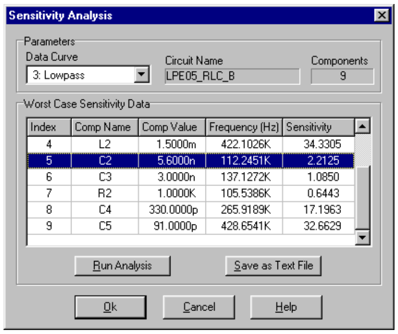
If we now select 5% precision for the capacitors and inductors, the schematic and response shown below are produced. Both the passband and stopband are only slightly changed.

The passband cuts the corner at 100kHz slightly sooner, and the stopband attenuation near 300kHz has a lobe which is over the -86dB Max constraint by 1dB.

The stopband lobes are directly controlled by the location of the zeros (nulls). The components L1/C4 and L2/C5 determine these two zero frequencies. The stability of the two zeros is a direct function of the precision used for these components.





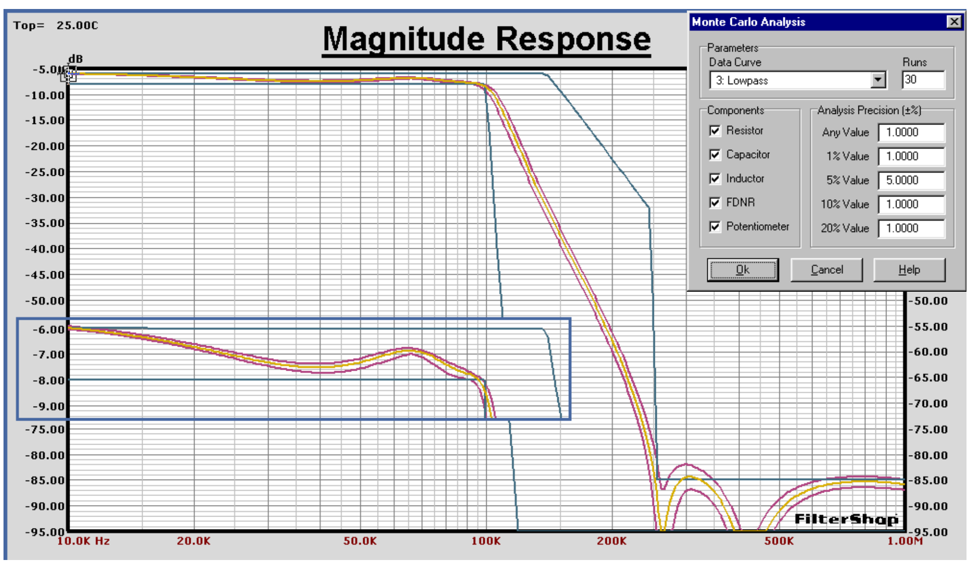


The *Sensitivity Analysis* now shows some very large values for a few of the components. Noting the frequencies, we can see that these values occur at the location of the zeros. The zeros of an Elliptic type response cause difficulty for evaluating sensitivity.

Since a zero produces a very sharp null in the response, any component change which shifts the zero frequency slightly produces a dramatic change in magnitude near the zero.

A more meaningful method of evaluating component variance for Elliptic type filters is by Monte Carlo analysis.

The circuit contains both 1% resistors and 5% inductors and capacitors. After 30 randomization runs, the max/min MC curves are shown below in Red. The passband only exceeds the ±1dB ripple spec near the 100kHz corner, and the stopband is mostly affected near the location of the first zero. The first zero is always the most critical in Elliptic filters.



Summary

The non ideal response of a filter due to the parasitic losses within passive components can be readily overcome through the use of optimization. Several different techniques have been demonstrated here, and have been shown to be very effective. Optimization provides a powerful method for obtaining the maximum performance from passive filters with non ideal components.

The inclusion of loss in circuit components demand that some design parameters be relaxed to allow other parameters to maintain the desired specifications. Passband ripple, stopband attenuation, or width of transition band are the typical choices for trade-off.

For passive filter design it is usually best to overstate the target criteria, since the lossy circuit will have degraded performance relative to an ideal circuit.

Allpole filters with moderate losses can generally be optimized using the single curve method. In some cases custom weighting can be helpful in controlling the location of mismatch to the objective. Elliptic filters typically require the constraint method which allow the zero frequencies to float.

This completes the Analog Passive RLC with Loss Optimization.