

# Electronic filters design tutorial - 3

## High pass, low pass and notch passive filters

In the first and second part of this tutorial we visited the band pass filters, with lumped and distributed elements.

In this third part we will discuss about low-pass, high-pass and notch filters.

The approach will be without mathematics, the goal will be to introduce readers to a physical knowledge of filters. People interested in a mathematical analysis will find in the appendix some books on the topic.

\* **The constant K low-pass filter:** it was invented in 1922 by George Campbell and the meaning of constant K is the expression:

$$ZL * ZC = K = R^2$$

ZL and ZC are the impedances of inductors and capacitors in the filter, while R is the terminating impedance. A look at fig.1 will be clarifying.

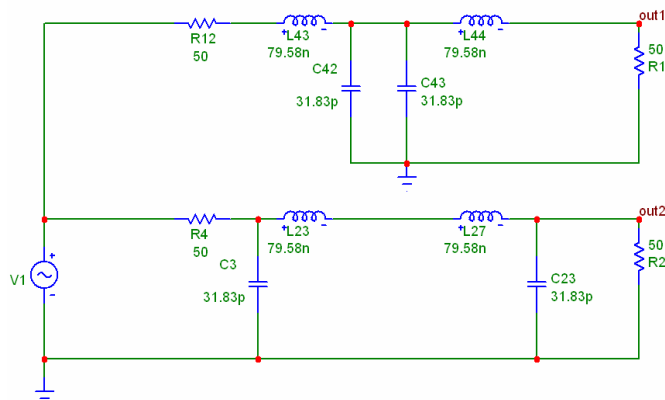


Fig 1

The two filter configurations, at T and  $\pi$  are displayed, all the reactance are 50  $\Omega$  and the filter cells are all equal. In practice the two series inductors in the  $\pi$  will be replaced with a single one with twice the value, and the two capacitors in parallel in the T, again will be replaced with a single one holding two times the value.

All the elements are calculated for a 50  $\Omega$  reactance at 100 MHz

In fig 2 we connected multiple sections of constant K filter, from 3<sup>rd</sup> to 9<sup>th</sup> order, to see the response in relation to the order of the filter.

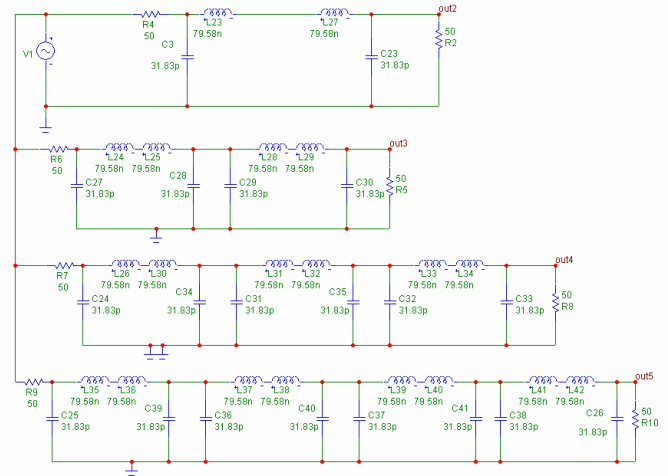


Fig.2

Running the simulation we can see the response of the filter in fig.3

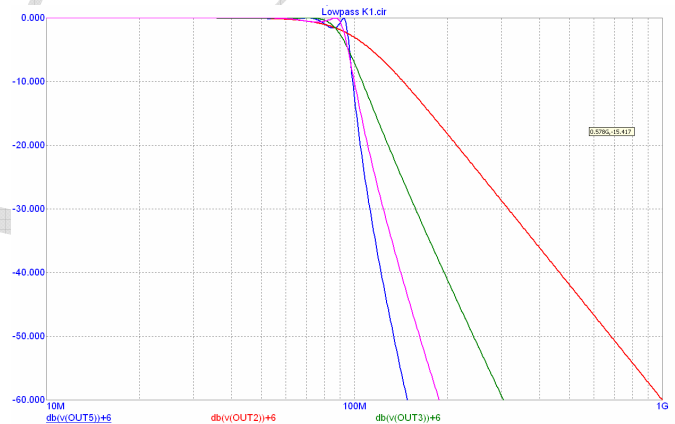


Fig.3

It is clear that the sharpness of the response increase as the order of the filter increase. The ripple near the edge of the cutoff moves from monotonic in 3<sup>rd</sup> order to ringing of about 1.7 dB for the 9<sup>th</sup> order. This due to the mismatch of the various sections that are connected to a 50  $\Omega$  impedance at the edges of the filter and connected to reactive impedances between cells.

The 3 dB cutoff moves from 100 MHz for the 3<sup>rd</sup> order to 90 MHz for the 5<sup>th</sup> order, and 95 MHz for the 9<sup>th</sup> order.

The constant K filter is useful because all components are equal, so calculation is very easy and the production requires less parts.

However other mathematical approximations exist that exhibit better performance in flatness or sharp cutoff, or flat group delay.

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In fig.5 we collect one type for each of the following, all of the 7<sup>th</sup> order for comparison: constant K, Butterworth, Chebyshev, Elliptic (Cauer) and Gaussian.

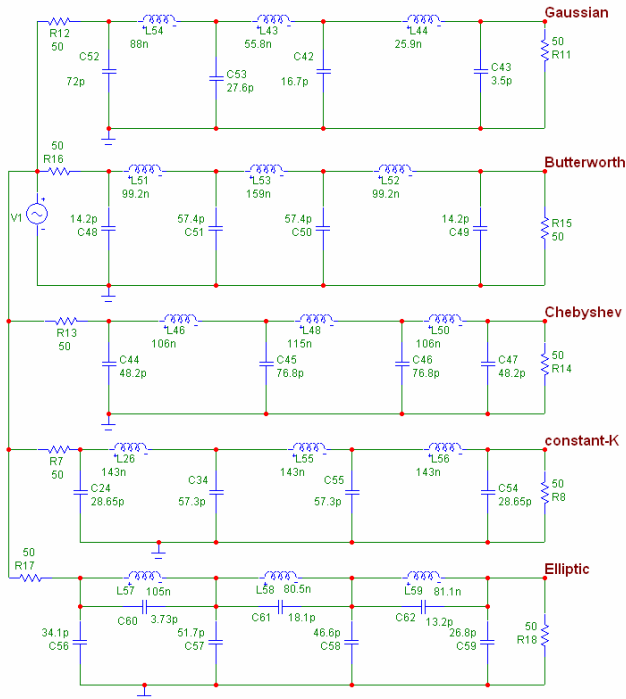


Fig.5

All the filters have the cutoff at 100 MHz, but the frequency response is quite different. On fig.6 we can see the different slope of filters.

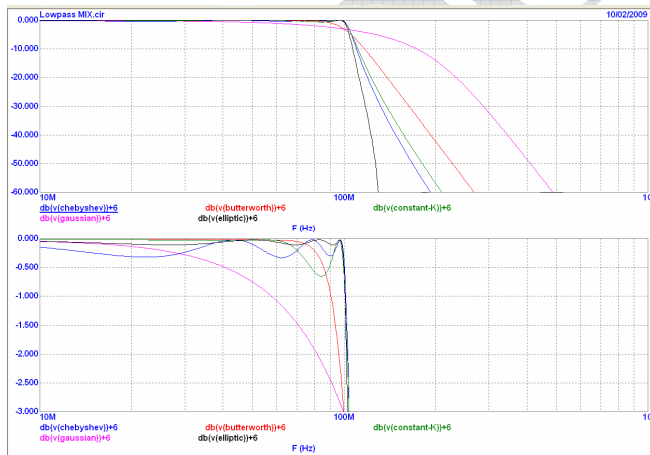


Fig.6

The elliptic filter clearly has the best performance, having the sharper cutoff, and a ripple of only 0.12 dB (black trace), the second in sharp cutoff is Chebyshev (blue) with a ripple of 0.3 dB. The third is Constant K, with a cutoff similar to Chebyshev, but with a ripple of 0.7 dB.

The fourth is Butterworth, which is extremely flat in the BW up to 80 MHz, but has poor cutoff. The worst in cutoff is the gaussian filter, which has a very smooth cutoff, but the group delay is flat (fig.7), while in the other filters GD is not flat. This means that if non sinusoidal signals are passing through a non Gaussian filter, they will be highly distorted. In fig.7 the GD is displayed for the various filter.

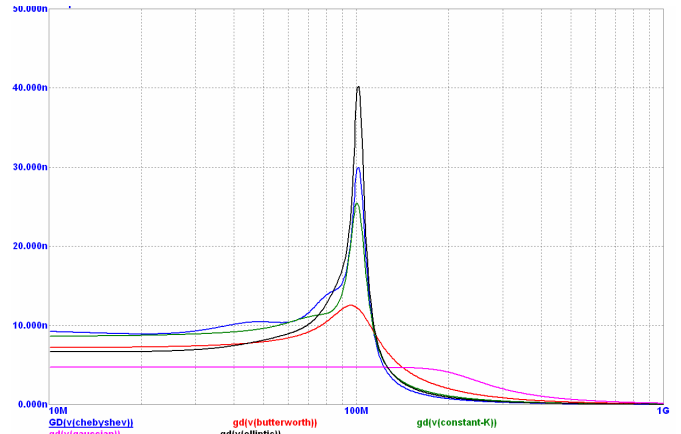


Fig.7

The Gaussian filters however will be discussed deeply in the 5<sup>th</sup> section of this tutorial, because Gaussian filter, called also filters for time domain are very important for filtering digital data.

In fig.7 you can see that group delay of gaussian filter (pink) is flat at 4.7 nsec., while the elliptic filter is the worse with a peak of 40 nsec delay at cutoff.

Low pass filter are used practically everywhere, since they clean-up the signals from harmonics. All the transmitters, being low or high power end with a low pass filter before the antenna.

### \* How can we calculate a low pass filter to comply with a certain regulation?

For example many regulations specify a maximum spurious emission of 250nW (or - 36 dBm) over 1GHz. If your transmitter has a power of 10mW (10 dBm) the require attenuation of harmonics is at least 46 dB.

If you measure the harmonics of your transmitter, and you find that the maximum level is - 5 dBm, you can evaluate that the attenuation of the filter should be at least 31 dB (-36 to -5 dBm). If you are a clever engineer may be you take a 5 dB margin for production and specify the filter with an attenuation of 36 dB.

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Unfortunately things goes wrong and Mr Murphy is smiling.

The harmonics of the transmitter when connected to an antenna via a low pass filter are very different from the 50Ω case.

The filter itself operate in a different way fed with a non sinusoidal signal, and the attenuation will be different, moreover the output of the final stage even if matched to 50Ω, will be different in impedance, and the antenna also will be practically different from 50Ω.

But the dramatic effect will be the connection of the filter to the final stage: the harmonics that originally in the test travelled directly to the load, now are reflected back to the final stage, generating stationary waves, which can add or subtract, generating at some frequencies very high harmonics.

Two topologies of filter exist, one with a series inductor and the other with shunt capacitor (Fig.1), the configuration with series inductor will be the approximation of an open circuit for the harmonics, while the shunt capacitor will approximate a short for harmonics.

Depending on the topology of the circuit one of the two filter will operate better than the other, maybe with higher efficiency, more flatness in the bandwidth, and higher harmonic rejection.

However, as a rule of thumb, be prepared to add 20 to 25 dB more attenuation of the filter in order to obtain good results.

### \* Practical cutoff of filters

If we manufacture a 1W transmitter (+30 dBm) with the same regulation we have to cut off harmonics of at least 66 dB (from +30 to -36 dBm). Does practical filter obtain this type of attenuation?

We can take the elliptic filter of fig.5 and simulate it with all the parasitic of the components ad of the circuit (approximate values of parasitic are described in tutorial 1).

In fig.8 all the parasitic of the elliptic filter has been added, in red appears the parasitic of components and in black the parasitic of the PCB. The components are size 0603 for capacitors and Coilcraft midi spring for inductors, the PCB is 1.6mm thick and the 1.2 nH inductors are the parasitic inductances of the metallised holes to the ground plane, the 0.30 and 0.35 pF capacitors are the parasitic capacitances of components pads to the ground plane. The inductances of the tracks are neglected in this example since components are placed very close.

In fig.9 we can see the response of the filter, adding parasitic the insertion loss in the passband increase up to 0.5 dB, an acceptable value.

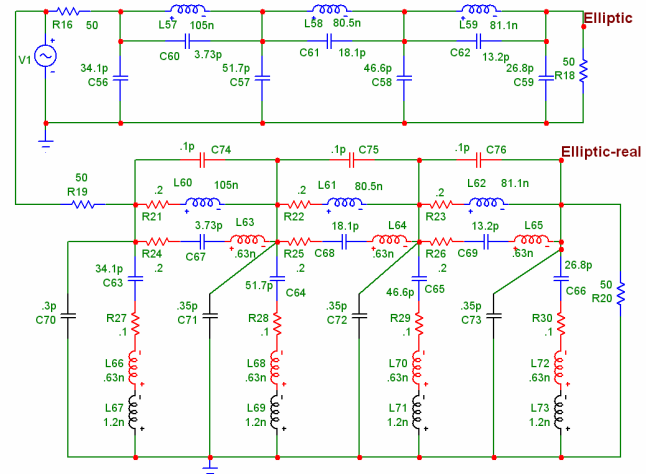


Fig.8

The dramatic difference is instead that while the ideal filter exhibit an attenuation between 60 and 70 dB from 140 MHz to 2 GHz (black trace), the real filter has a parasitic response from 1 to 2 GHz in which the attenuation drop from over 70 dB to 5 - 10 dB (red trace).

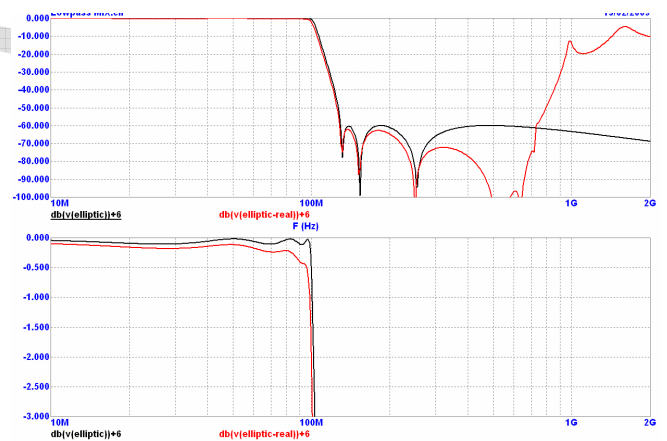


Fig.9

May be that at frequencies of 1 GHz and above the harmonics of the transmitter had already fallen down to a level lower than -36 dBm, but however the filter at these frequencies would not work at all.

We are speaking of a filter with correct layout, where the inductors are not coupling together, and each capacitor is going to ground plane with its own hole.

What happen if a clever engineer think to connect all the grounded capacitors with a second ground plane on the top? The answer is in fig.10 where all the parasitic vias inductors are connected together.

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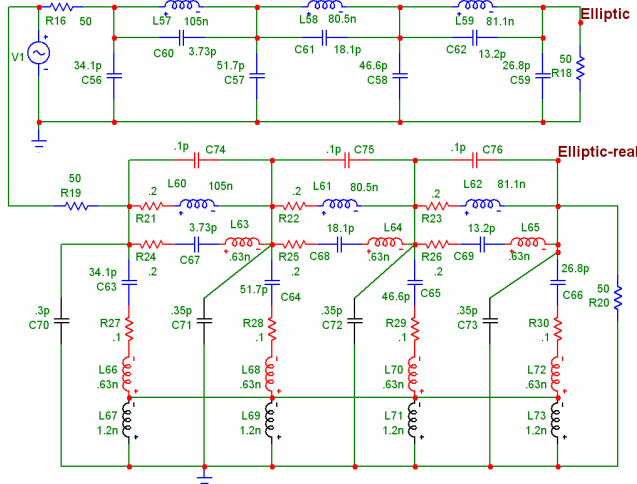


Fig.10

L67, L69, L71 and L73 are connected together, simulating a ground plane on the top of the PCB. The response is in fig.11.

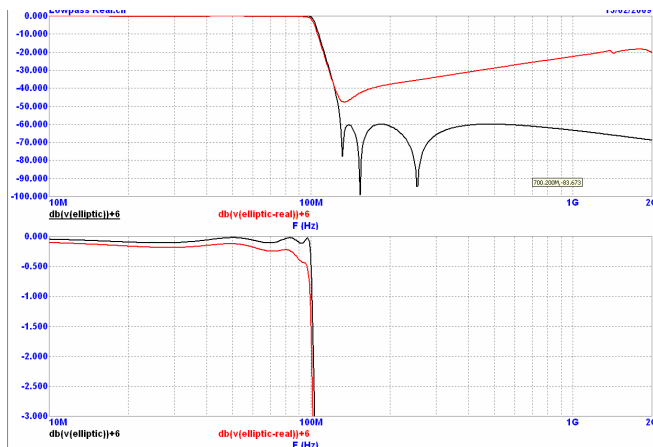


Fig.11

It can be seen that the response of the filter is completely killed by this connection. Attenuation has a maximum of 48 db at 150 MHz with a gradual decrease up to 20 dB at 1GHz. Clearly the layout is very important.

**\* Could we improve the response of the filter?**

Without great change in the layout or the type of components, the answer is yes, we can greatly improve the response of the filter:

- 1) We can reduce the thickness of the PCB from top layer to ground plane, or alternatively increase the number of via holes from one per capacitor as in the example to two or three per capacitor.
- 2) We can split each capacitor to ground in two capacitors with half the value. In this

way the series inductance of 0.63 nH typical of 0603 case size will be halved.

In fig. 12 we run a simulation with the circuit of fig.8, but the inductance in series with capacitors halved (two capacitors half in value, instead of one), and two grounding holes per capacitor. In this way L66, L68, L70 and L72 decrease to 0.31 nH and L67, L69, L71 and L73 decrease four times to 0.3 nH. The response is in fig.12.

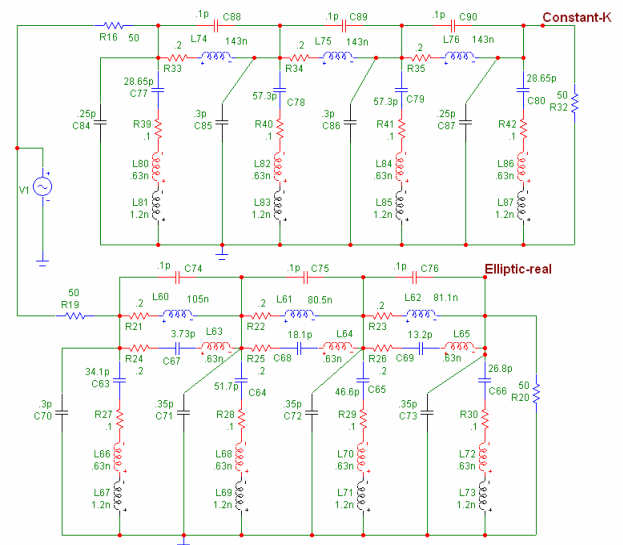


Fig.12

The spurious response peak, previously at 1 GHz, has moved up to 2.2 GHz (note the frequency response has been simulated up 4 GHz now).

**\* To increase the performance we can change the topology**

The elliptic filter has a very sharp cutoff, but the filter is prone to spurious response, caused by the resonating capacitors in parallel to the inductors.



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Fig.13

Our old constant K filter in this case has better performances, in fig.13 you can see the layout with parasitic, and in fig.14 you can see the frequency response.

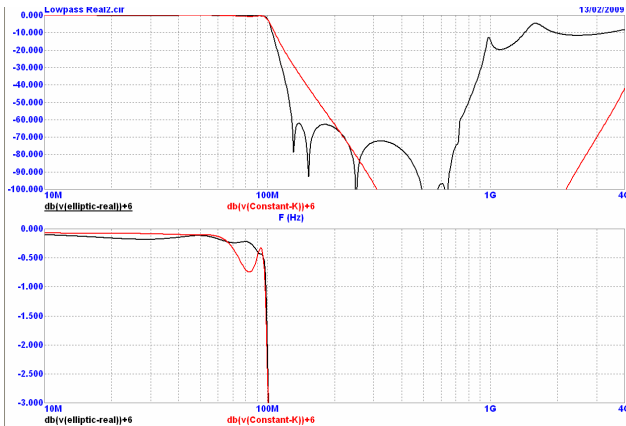


Fig.14

In the red trace you can see that the constant K filter has smooth roll off, but the spurious response are far superior, being over 100 dB up to 2.2 GHz and rising to 43 dB at 4 GHz. This is made without doubling the shunt capacitors and the ground holes.

The in BW loss instead are worst than the elliptic filter: 0.7 dB instead of 0.4 dB. But we can work a little to improve constant K filter, decreasing loss and improving cutoff sharpness. In fig. 15 you can see the diagram.

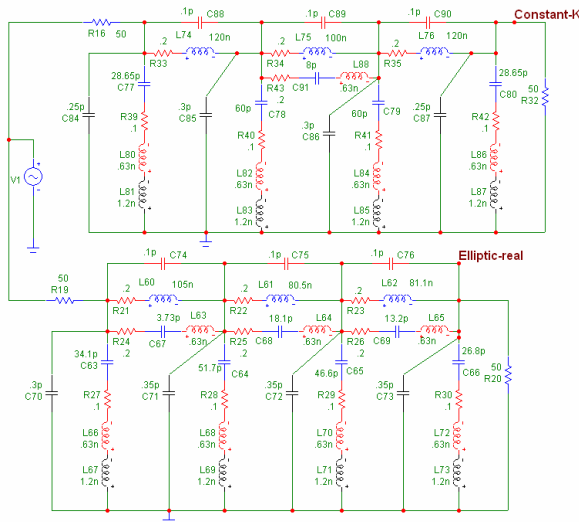


Fig.15

The central inductor L75 has been made resonating at 180 MHz, connecting in parallel to it C91, to increase sharpness of the filter.

In band loss has been improved changing the values of inductors L74 and L76,

while C78 and C79 has been increased to compensate for the resonance of L 75.

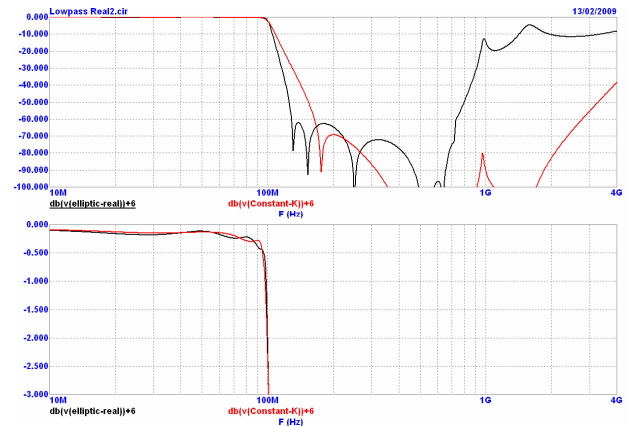


Fig.16

It can be seen that the cutoff of the modified constant K has become sharper (red trace), up to 70 dB at 200 MHz, and a small return now is present at 1 GHz (80 dB). The in BW loss has improved to 0.35 dB (even better than elliptic, 0.4dB).

**\* The constant K filter is a good starting point for designing filter with characteristics as your need.**

## \* High power filters

A broadcast TV transmitter has a power in the order of 10-30 KW, one of the technology permitting management of this power is the tubular filter.

The tubular filter is similar to strip-line filter, and in effect it is calculated in the same way.

The main difference is that it is constructed with cascaded section of low impedance section (say 5Ω for a 50Ω line) which are capacitive and high impedance section which are inductive (100 Ω, for example) these filter are constructed with cylindrical sections of different diameters, assembled in a tube. Usually the insulation is Teflon for the low impedance sections and air for the high impedances pieces.

These filter can be designed with constant K or Chebyshev response, the other responses are less used.

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In fig.17 we can see a seventh order filter with a cutoff at 750 MHz.

The diameter is usually chosen in a way the filter can withstand maximum rated power. Resistive loss are very low, and in this case the lossless design is normally used.

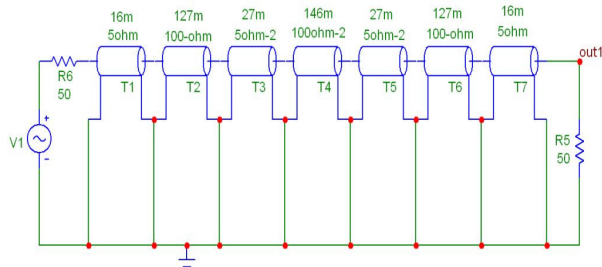


Fig.17

Each line has its own impedance indicated, while the number on top of each line express their length in a decimal of wavelength (250m being a  $\frac{1}{4} \lambda$ ). The simulation of the filter appear in fig.18.

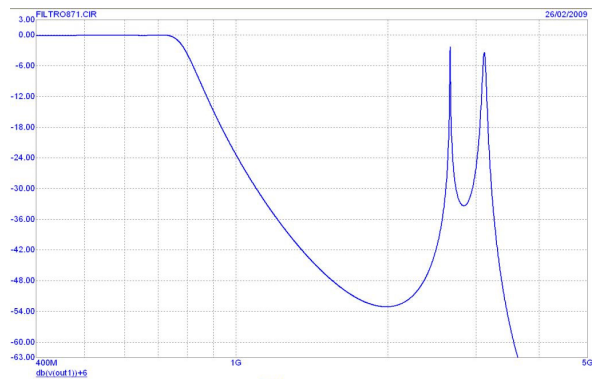


Fig.18

We can see that while the loss is practically immeasurable, the cutoff bandwidth has ugly spurious response at 2.65 and 3.11 GHz.

**\*This is the standard behaviour of filters made with distributed components.**

Maybe the harmonics of your 30KW transmitter are quiet low in that frequency band, and you can keep the filter as is. But usually happens that substantial harmonics are present in the spurious band.

Two different remedies are possible, one you can connect a second low pass filter with a higher cutoff (i.e. 1500 MHz) and in this way the combined response will cut the ugly returns.

A second possibility is to make the filter elliptical, placing the low impedance sections

in parallel instead of in series to the filter (fig. 19)

Obviously the construction is more complex, the filter now cannot be a simple tube.

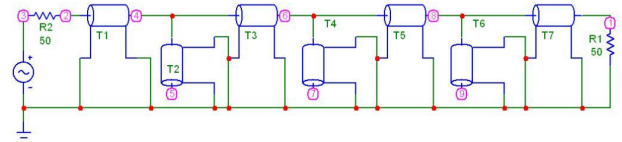


Fig.19

We can see in fig.20 that the spurious response is far better than before, note that the first spurious response now are 18 dB under the fundamental response and they are narrower than the previous case.

You can see however that at higher frequencies spurious responses are present over 5 GHz.

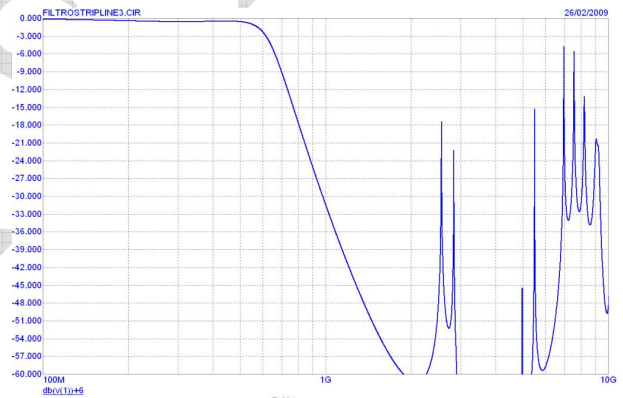


Fig.20

We can again improve the response of the filter substituting the parallel lines T2, T4 and T6 with three couples of lines with identical total length but with two different length each couple. In fig. 21 you can see the realisation of the filter.

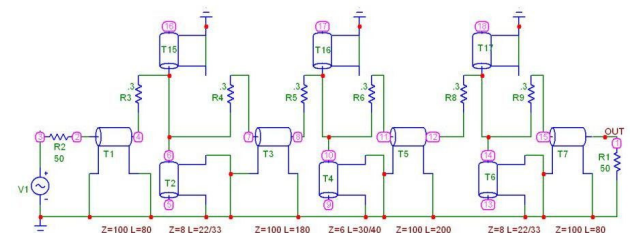


Fig.21

Some loss has been inserted in the circuit with resistors, and this also help to reduce spurious response, considering than in practical circuits the extreme narrow band spurious response will be lower than simulated.

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On fig. 22 the response of the filter. We can see that spurious responses has been greatly attenuated, but at the expense of more circuit complexity.

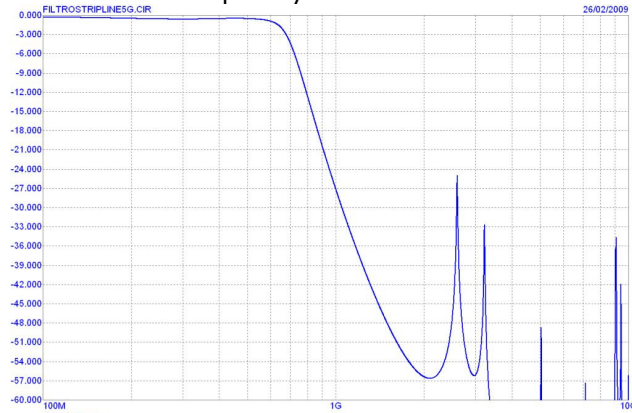


Fig.22

## High pass filters

The way to transform a low pass filter in a high pass one is very easy, if we look at fig.23, where the constant K filters of fig.1 (out 1 and out2) are transformed in high pass (out 3 and out 4) merely changing the positions of inductors with capacitors and vice-versa.

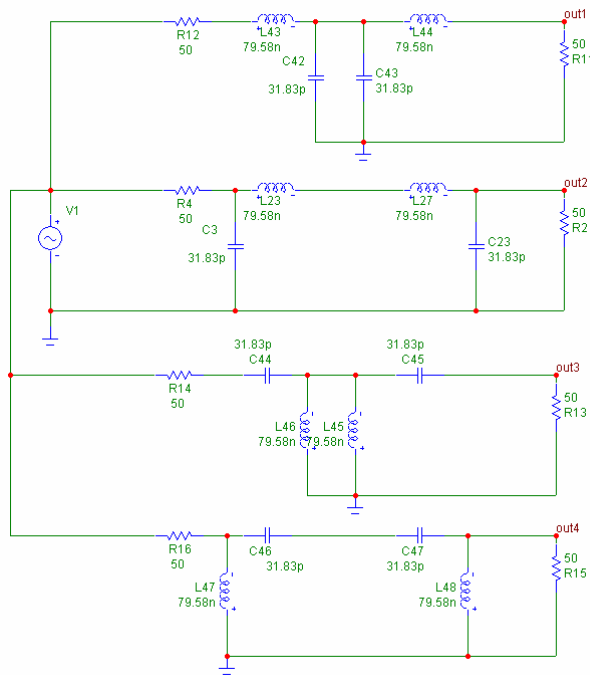


Fig.23

On fig.24 we can see the response of the filters.

The two top traces display low pass and high pass of out 1 and out 3 (series element first). Response is complementary and the 3 dB point at 100 MHz is common for both filters. Bottom traces (out 2 and out 4) represent the filters with parallel element first, and are of course perfectly equal to the previous case.

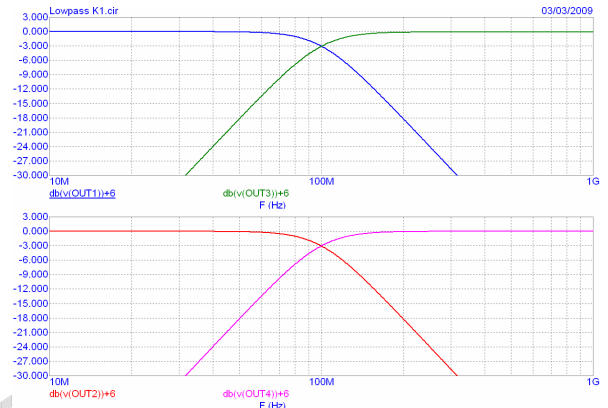


Fig.24

With constant K the play is easy since all the elements are equal and 50Ω in reactance, but what happens if we want to transform for example a Butterworth low pass in a high pass?

\*Again the transformation is quite easy, you have to replace each capacitor with an inductor which exhibit the same reactance at cutoff, and to replace each inductor with a capacitor of the same reactance at cutoff. Of course the sign of the reactance will be opposite, but the value will be the same:

$$L_{LP} \rightarrow C_{HP} = 1 / L_{LP} \omega^2$$

$$C_{LP} \rightarrow L_{HP} = 1 / C_{LP} \omega^2$$

The frequency of cutoff is in case of Butterworth the 3 dB point.

In fig.25 we can find the transformation in high pass of the Butterworth low pass of fig.2.

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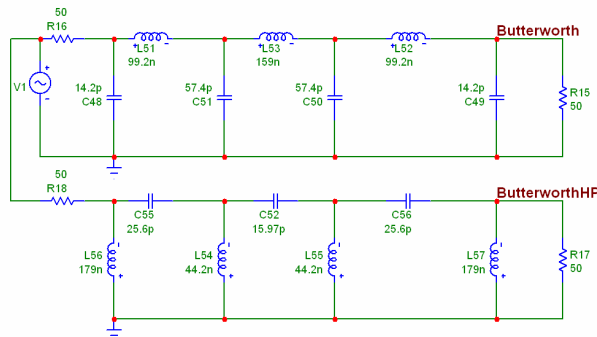


Fig.25

The response is in fig.26 and matches perfectly the low pass characteristics, crossing the response exactly at 100 MHz at the 3 dB point.

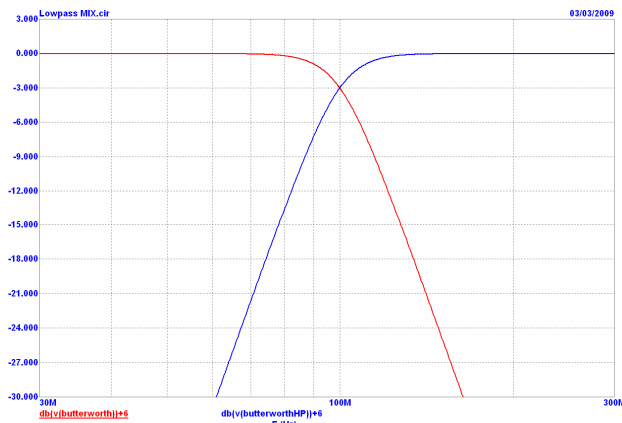


Fig.26

Not all the filter are so easy to transform, if the filter is elliptical you have to transform also the frequencies of the zeros. For example the elliptic filter of fig.5 has a zero in the response at 131 MHz (L58, C61). This frequency must be transformed in the first zero of the high pass, making:

$$F1^{\text{st zero LP}} = F_{\text{cutoff}} / F1^{\text{st zero LP}} = 100/131 = 76.3 \text{ MHz}$$

This will be the resonant frequency of the first zero, all the other will be calculated in the same way.

If you have a SW for filter synthesis, the job will be probably easier, making directly the design of an elliptic high pass filter.

But if you are using the good old data tables on paper, you will have to make this transformation.

High pass filters are less used than Low pass and Band pass. Their use is restricted in

frequency multipliers, low band cutoff in diplexers and broad band pass filters constructed with a low pass and a high pass sections.

### Notch filters:

Starting from the low pass constant K of fig.1 we can design a three resonators notch filter, merely replacing the series elements with parallel resonators, and the shunt elements with series resonators. In fig.27 appears the transformations. Note that  $1\Omega$  series resistors (in red) has been added to the circuit, otherwise the attenuation at resonance will go to infinity.

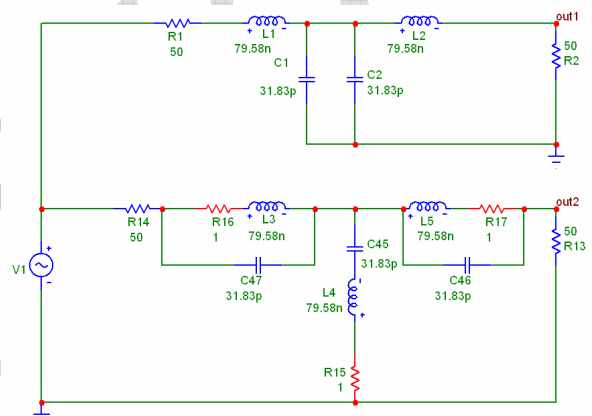


Fig.27

Running a simulation in fig. 28 (blue trace) we can see the deep notch produced by the filter.

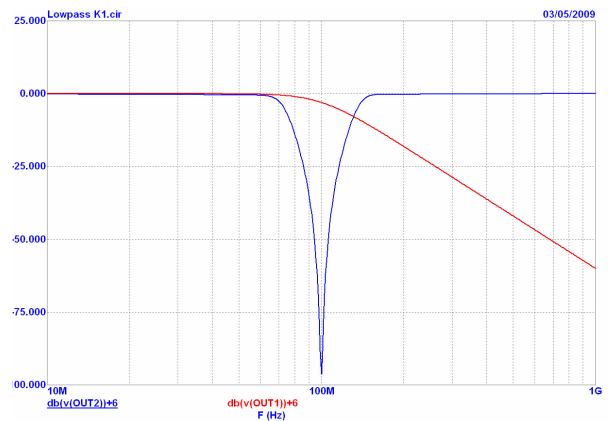


Fig.28

The notch is very deep, but the bandwidth at -25 db, for example is 30 MHz, decreasing to 17 MHz at -40 dB. What can we do if we don't need a -96 db cut at resonance, but instead a wider bandwidth at say -25 dB?

We have two ways to increase the notch bandwidth, the first is to change the resonant frequencies of the two series resonators, the



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other is to change the impedances of the three resonators.

The first possibility is displayed in fig.29 (bottom filter), where the two series resonators has been moved to resonate at 80 and 126 MHz (changing the two parallel capacitors), from the original 100 MHz. The notch is not so deep, but instead three different notches appear at the resonant frequencies.

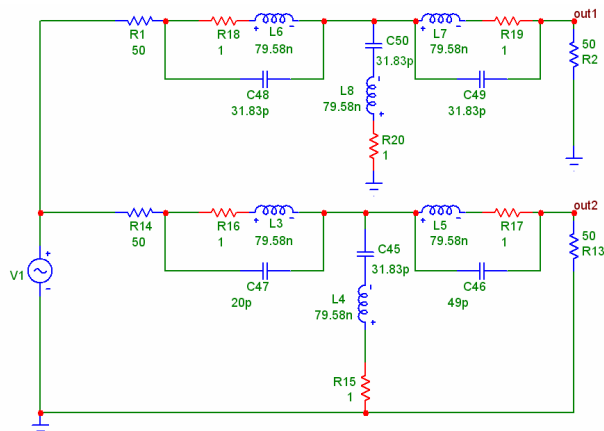


Fig.29

We can see in fig.30 that the -25dB BW increased from 30 MHz to 52 MHz (blue trace).

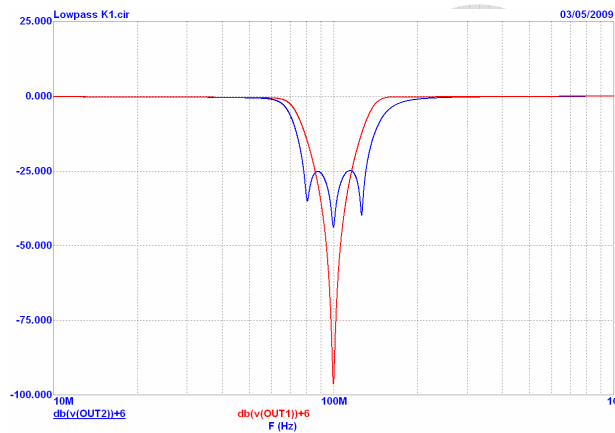


Fig.30

Now we explore the second possibility in fig.31, changing the impedance of the shunt resonator (L4, C45) to 25Ω, doubling the capacitor and halving the inductor values. The two series arms has been changes to 100Ω impedance, doubling the inductors and halving the capacitors values. In fig. 32 we can see the original response (red trace) versus the new one (blue trace). The bandwidth has moved from 30 to 59 MHz.

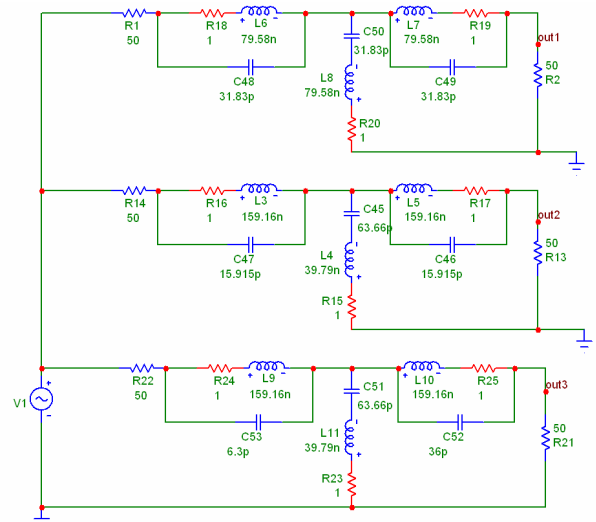


Fig.31

Now we can made the same exercise of change the resonance of the two series arms, from 100 MHz to 66, 6 and 159 MHz, changing the value of the two capacitors C52 and C53 (fig 31 bottom).

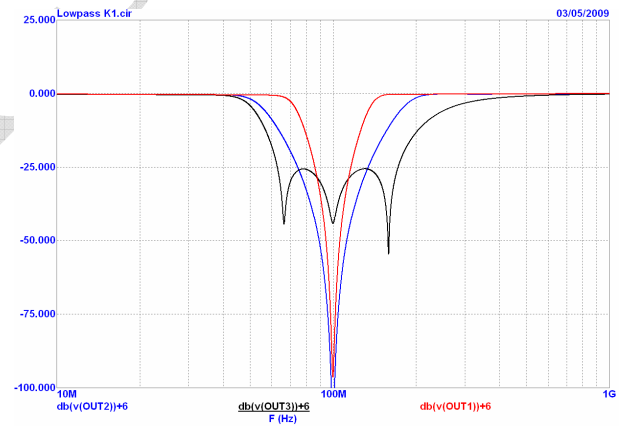


Fig.32

We can see in fig. 32 that the BW has increased from 59 to 109 MHz (black trace).

Parasitic in notch filters weight nearly as in other filters, particularly in the pass band, which extends under and over the stopband.

The deepness of the notch instead mainly depend on the Q of the components.

In Spice simulation it is a good practice to insert loss in components, to avoid notch deep to infinity.

As the notch bandwidth is increased, the steepness of the filter decrease and the loss in pass band increase.

This can be overcome increasing the order of the filter, as the previous cases.

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Next part of this tutorial will treat of active filters.

### Bibliography

- 1) MICROWAVE FILTERS, IMPEDANCE-MATCHING NETWORKS, AND COUPLING STRUCTURES  
G. Matthaei, L.Young, E.M.T. Jones  
1<sup>st</sup> edition 1964 ISBN:0-89006-0991.  
A Historical book, but still actual today
- 2) HANDBOOK OF FILTER SINTHESIS  
Anatol I. Zverev ISBN:0-471-74942-7  
1<sup>st</sup> edition 1967  
A classical book on filter, full of tables for filter design
- 3) FILTERING IN THE TIME AND FREQUENCY DOMAIN A.I.Zverev, H.J. Blinchikoff  
1<sup>st</sup> edition 1976 ISBN: 1-884932-17-7  
Another classical book, perfectly useful today, you couldn't miss it in your library
- 4) INTRODUCTION TO THE THEORY AND DESIGN OF ACTIVE FILTERS  
L.P.Huelsman, P.E.Allen ISBN:0-07-030854-3  
1<sup>st</sup> edition 1980  
Another dated book, but still actual.
- 5) ELECTRONIC FILTER DESIGN HANDBOOK  
A.B.Williams, F.J.Taylor ISBN:0-07-070434-1  
1<sup>st</sup> edition 1981  
A practical book, containing a lot of tables.
- 6) CRYSTAL FILTERS R.G.Kinsman  
1<sup>st</sup> edition 1987 ISBN:0-471-88478-2  
A useful book for the engineers interested in crystal filters design.
- 7) COMPUTER-AIDED CIRCUIT ANALYSIS USING SPICE, W.Banzhaf ISBN:0-13-162579-9  
1<sup>st</sup> edition 1989  
A useful book about Spice simulation
- 8) MICROWAVE CIRCUIT MODELING USING ELECTROMAGNETIC FIELD SIMULATION  
D.G.Swanson, W.J.R.Hoefer  
1<sup>st</sup> edition 2003 ISBN:1-58053-308-6  
A great book on electromagnetic simulation.
- 9) STRIPLINE CIRCUIT DESIGN Harlan Hove, Jr.  
1<sup>st</sup> edition 1974 ISBN:0-89006-020-7  
A good book on stripline circuits and components.