Baseband filter design

- **Baseband filter design**
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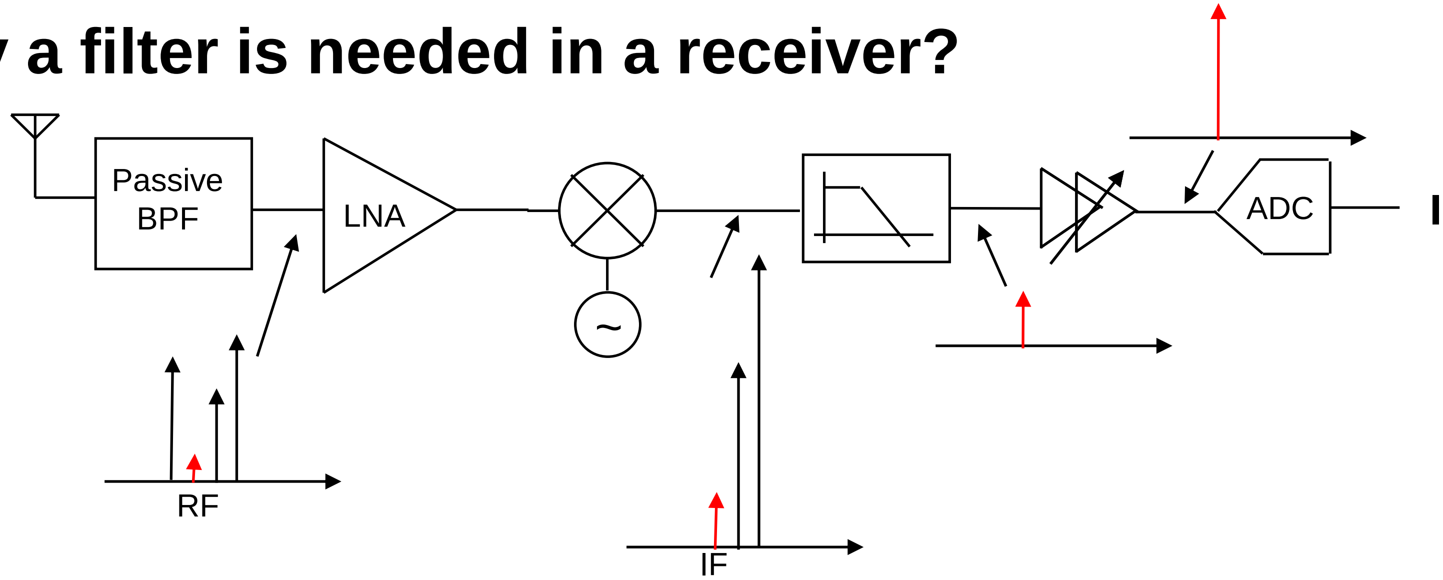
Why a filter is needed in a receiver?

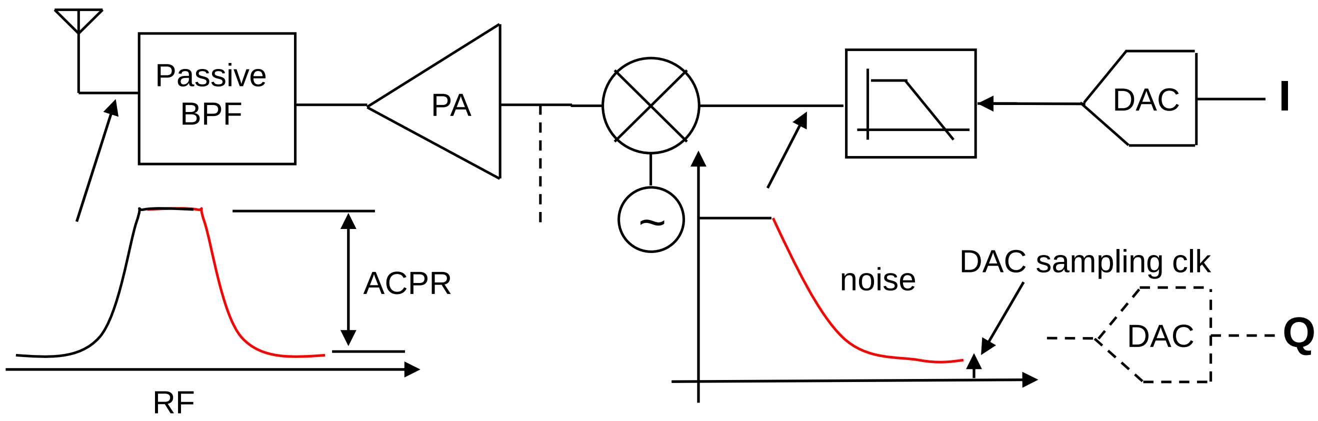


a blocker can be as high as 40~60dB higher than desired signal at ADC input! This means, with no filter, the A/D has to have over 80dB of dynamic range (quantization noise 10dB below desired Rx noise level, which needs to be SNR below desired signal level at ADC input, ADC full-range 3dB higher than blocker level).

The baseband filter helps relax the A/D required dynamic range by attenuating undesired signals before reaching the A/D. Note that the problem is shifted to the filter whose dynamic range requirement becomes high (60dB+SNR in the given example, compression to noise floor). In some systems, it is easier/cheaper to design high dynamic range filters than A/Ds, especially if you have control on the design of both.

It is a tradeoff between filter complexity and ADC design cost.

Why a filter is needed in a transmitter?



The filter acts as a reconstruction filter for the DAC output. Therefore, the rejection of DAC images is an important spec for a Tx BB filter

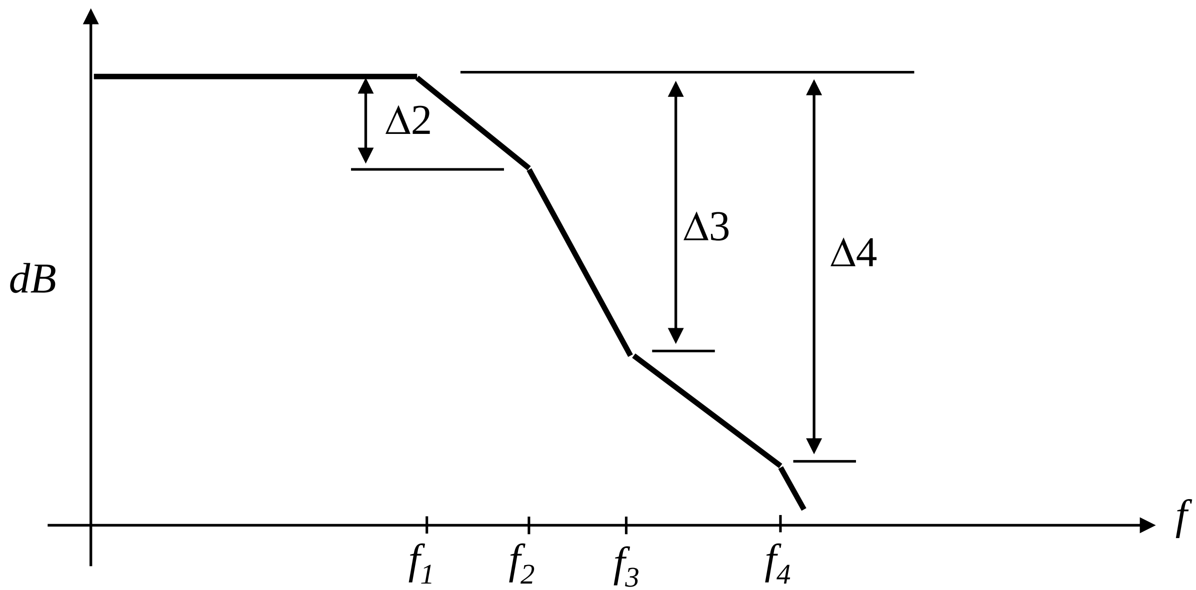
The filter out of band noise, primarily at the adjacent channel frequency, is pretty much a dominant factor in setting the ACPR (Adjacent Channel Power Rejection) at the antenna (FCC regulation and standard specific). Therefore, the out of band filter noise is an important spec.

The filter input swing is usually fixed (0.5~1Vpp typically). THD/OIP3 is also important for EVM and the ACPR

Because the input signal to the filter is well known, the filter tuning accuracy in Tx is a bit relaxed (10% typical).

Important filter specifications:

1. Filter mask:

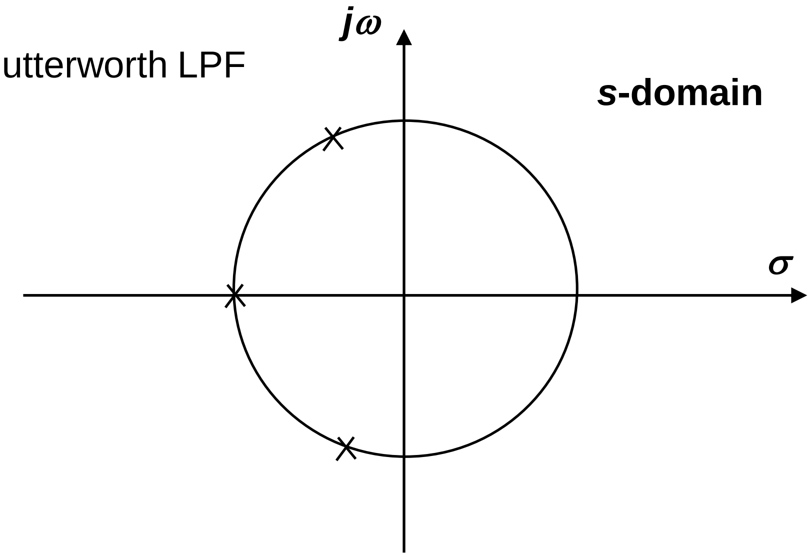


A filter magnitude AC response is composed of a passband and a stopband

A set of rejection requirements at specific frequencies is calculated from system analysis (lecture 4). This set is used to construct the “filter mask”, as shown above.

The filter mask is used as a guide for the selection of the filter function and order, as will be shown later.

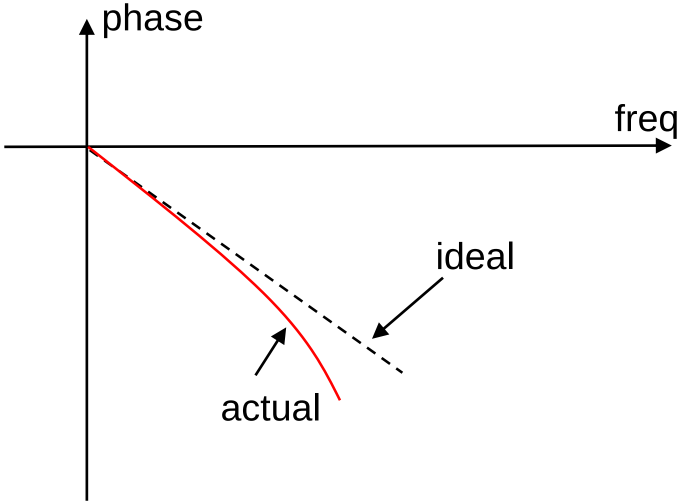
3rd order Butterworth LPF

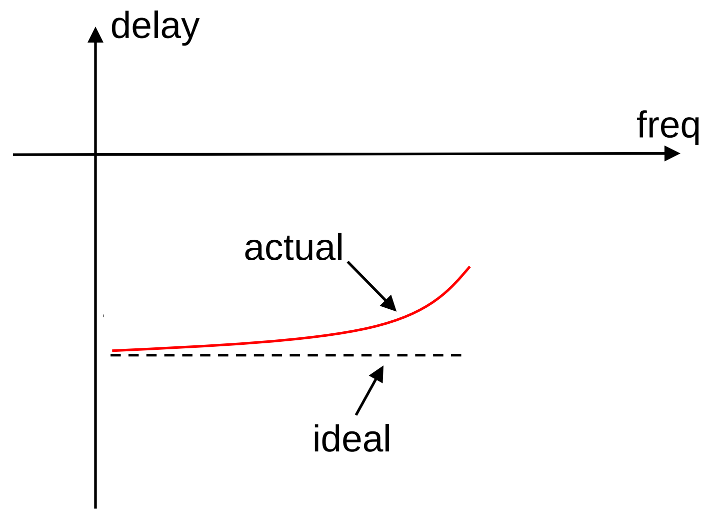


Since a filter is a “frequency selective” device, it relies on “resonance” or sets of poles and zeroes. The way these poles and zeroes are arranged in the s-plane influence the filter response. For example, the above figure presents a “Butterworth” maximally flat response filter.

Sharper stopband rejection generally means higher passband ripple, higher filter Q, and worse group delay ripple. These will be discussed later.

2. Passband group-delay ripple:



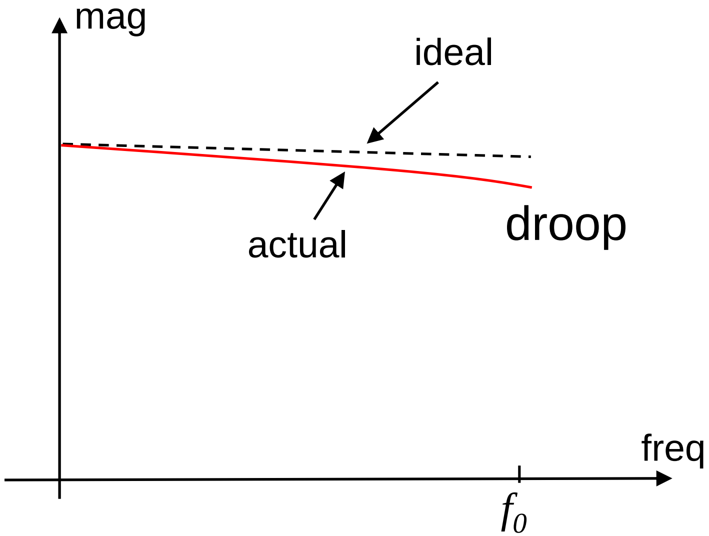


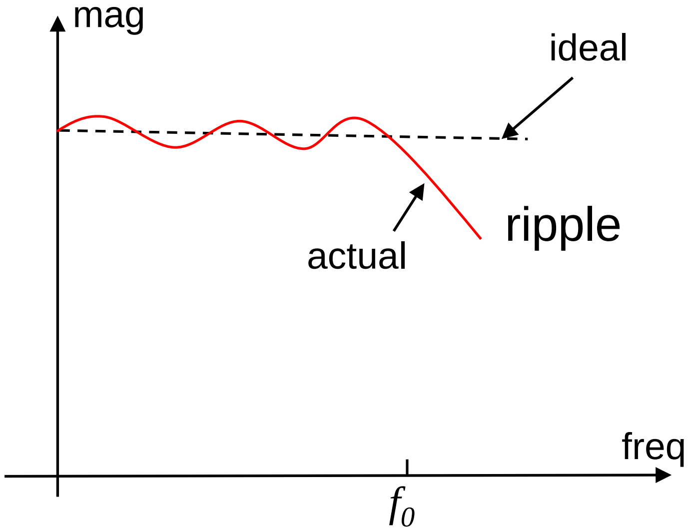
A filter ideally is a linear time invariant system. This means a linear phase and a constant time delay vs. frequency.

Actual filters deviate from the ideal response. This results in phase distortion and intersymbol interference. The maximum acceptable group delay ripple over the desired signal bandwidth depends on the signal modulation. This is one of the important filter specs.

Note: filter group delay can be equalized by digital filters in digital baseband if it has such capability assuming the analog filter characteristics does not change "much" over PVT

3. Passband magnitude ripple/droop:



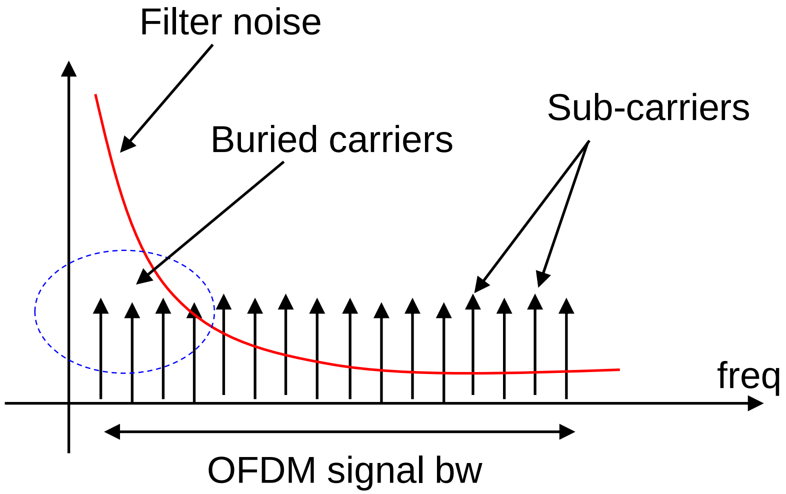


Passband droop or ripple causes signal distortion and degradation of EVM. The passband droop is usually caused by a pole placed at the mixer output that is not part of the filter main transfer function or because of finite VGA bandwidth. The passband ripple happens in some filter functions such as Chebyshev and Elliptic. The sharper the filter attenuation is the higher the passband ripple becomes.

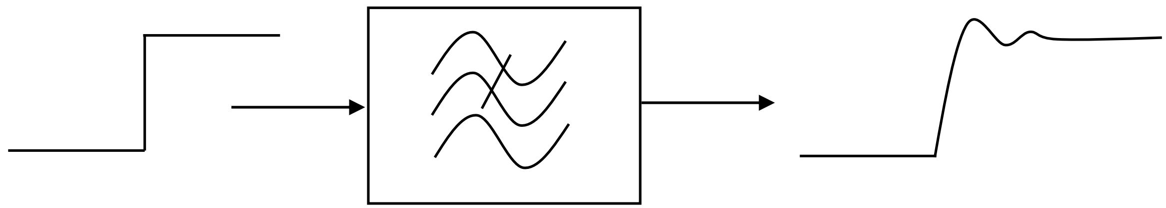
Note: filter passband droop can be equalized by digital filters as well assuming the analog filter characteristics does not change "much" over PVT. Ripple is harder to equalize though

4. Input referred noise

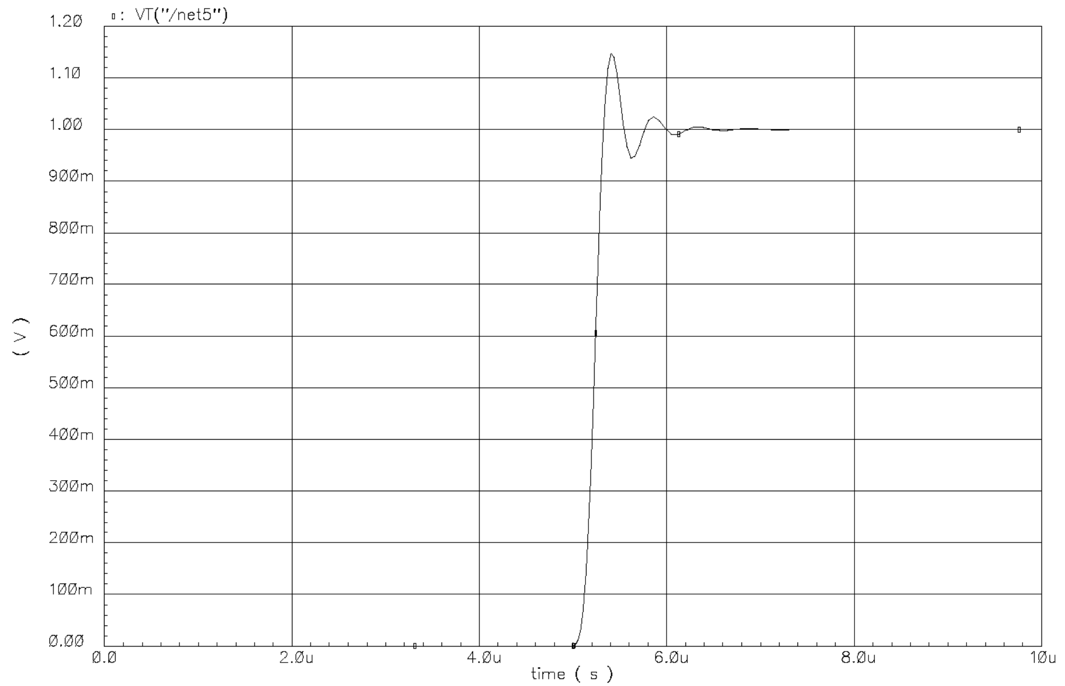
The filter passband noise is important because it can significantly contribute to the overall system NF. Note that both spot noise and integrated noise over signal passband are important. In OFDM modulated signal, spot noise, especially at low-frequency, such as 1/f noise, can wipe out few sub-carriers causing EVM degradation. In broadband none-OFDM signals like WLAN 802.11b, the integrated noise is more meaningful and the 1/f noise has little impact if the overall integrated noise is within spec.



5. Filter step response:



The filter step response is important in TDD systems with OFDM modulation, such as 802.11g/a WLAN. A long-settling step response results in intersymbol interference. Below is an example of 5th Chebyshev II.



6. Linearity

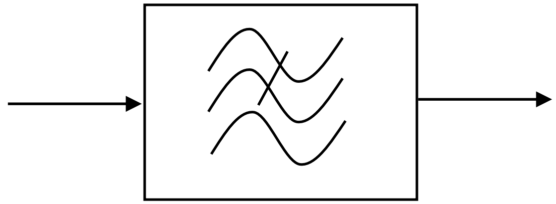
The filter linearity is mainly spec'ed as its IIP3, IIP2 and P1dB compression. The P1dB compression is set to handle the composite maximum possible peak-peak swing at the filter input due to desired signal and unwanted blocker signals. Usually the first stage of the filter sets its linearity since the blocker signals get attenuated as they pass through the filter stages, and so the last stage of the filter suffers the least.

The filter IIP3, is mainly an out of band requirement, setting up two out of band blocker levels coming off the mixer output and find the resulting in-band IM3 level. The first stage of the filter usually sets the entire receiver out of band IIP3 for adjacent-channel blockers. Same applies for IIP2. The in-band IP3 is mainly set by desired EVM

7. Tuning accuracy

Filter tuning accuracy is the variation of the filter corner frequency from the desired value due to PVT expressed in %. In some receivers (such as WCDMA) this can be as tight as 5% if ADC dynamic range is not meant to handle any blockers. Filter tuning will be discussed in detail in subsequent lectures.

Filter s-domain transfer function:

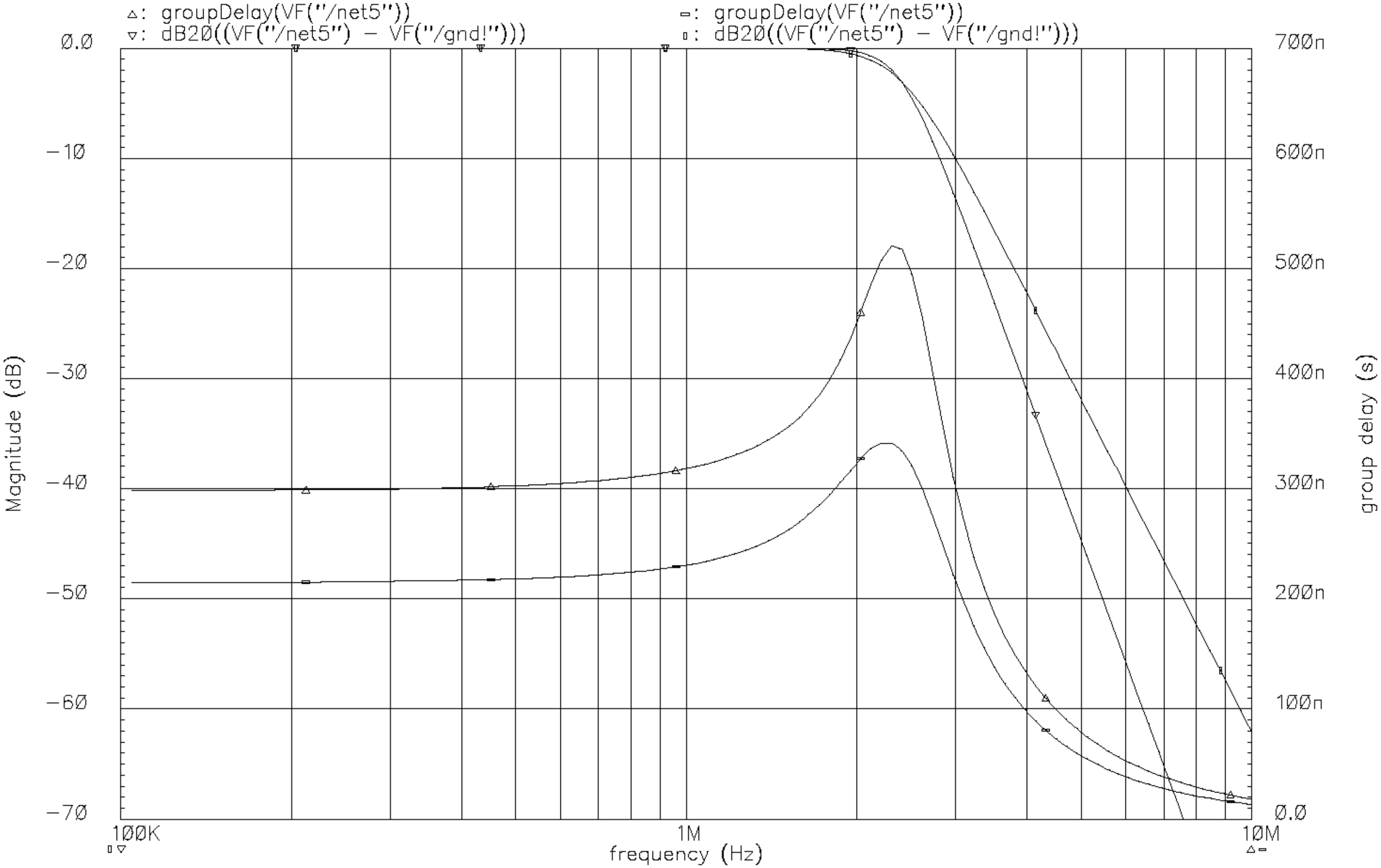
$V_i(s)$  $V_o(s)$

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{a_n s^n + a_{n-1} s^{n-1} + .. + a_1 s + a_0}{b_n s^n + b_{n-1} s^{n-1} + .. + b_1 s + b_0}$$

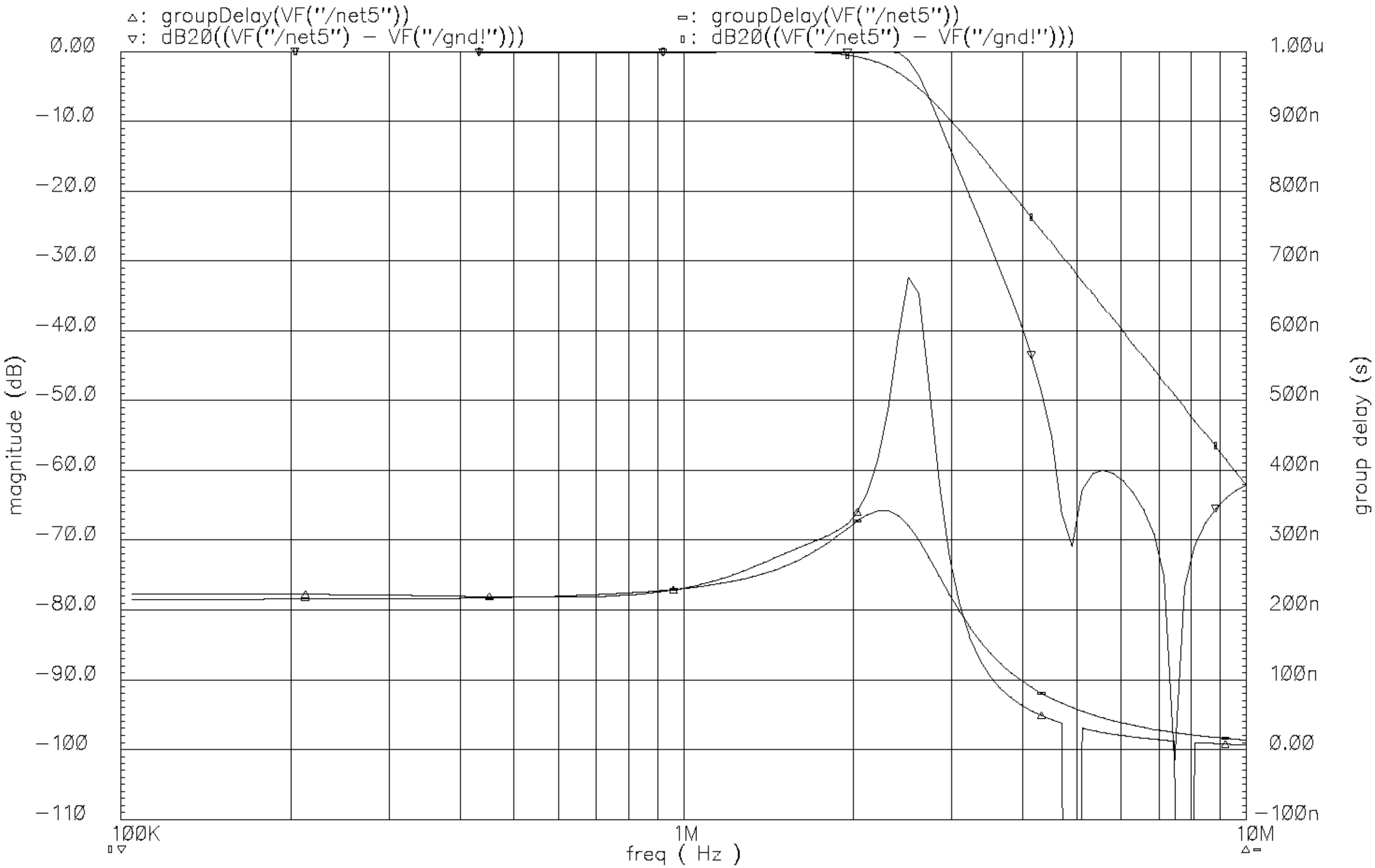
“n” is the filter order. The coefficients “an” and “bn” influence the filter response. For example, if $a_{(1\text{ to }n)} = 0$, the filter is a lowpass. If a_0 alone = 0, the filter is a highpass. If $a_0 = a_n = 0$, the filter is a bandpass.

Common filter functions are: Butterworth, Chebyshev, Chebyshev II (or sometimes called inverse Chebyshev), Elliptic, Bessel (sometimes called equiripple-delay), Hourglass, and Gaussian.

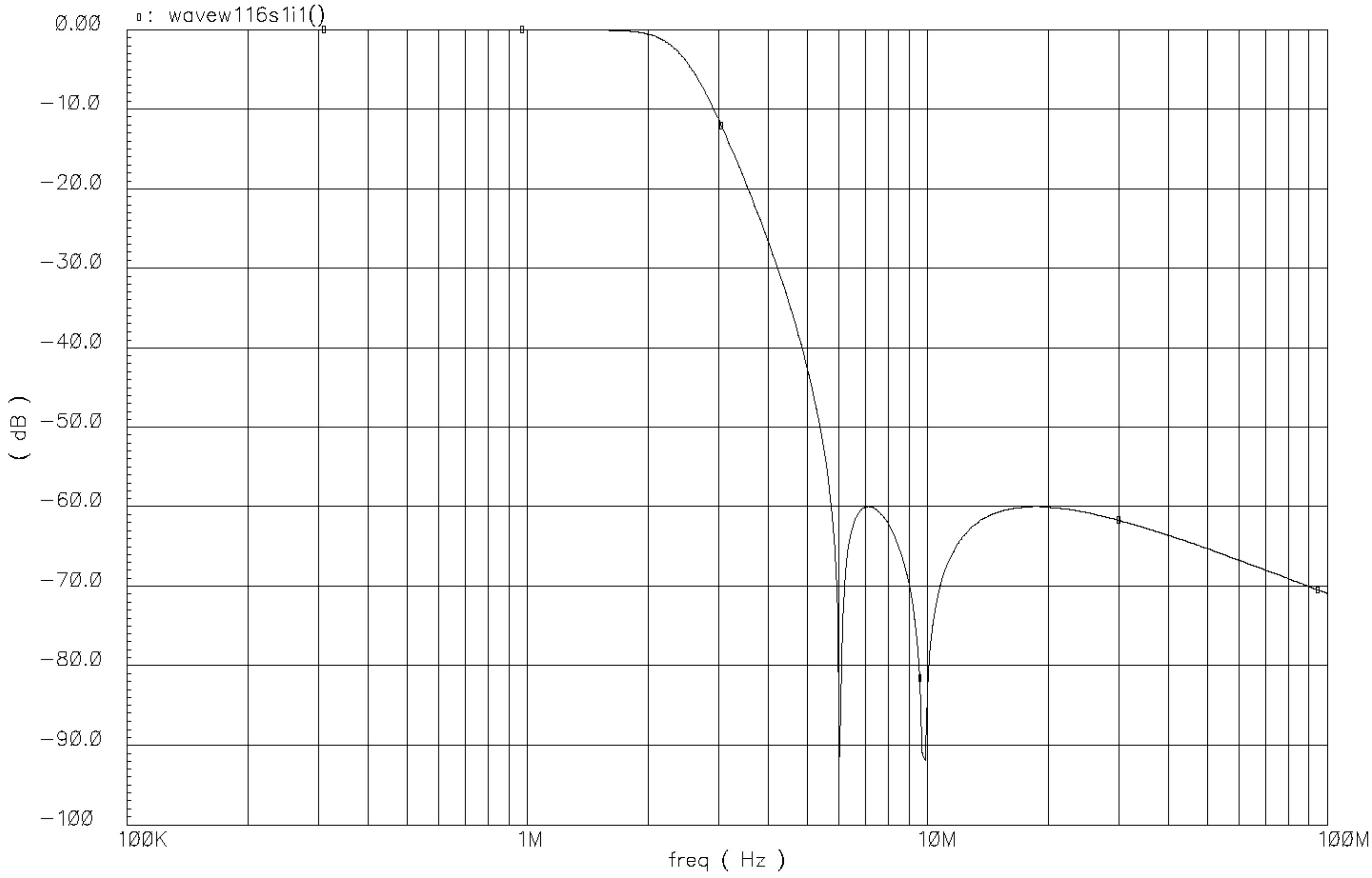
Filter functions differ in trading off stopband roll off for passband ripple, filter Q and group delay. The filter function an order are set to meet the filter rejection mask.



5^{th} order butterworth vs. 7^{th} order. See how the group delay ripple suffers going with higher order filter.



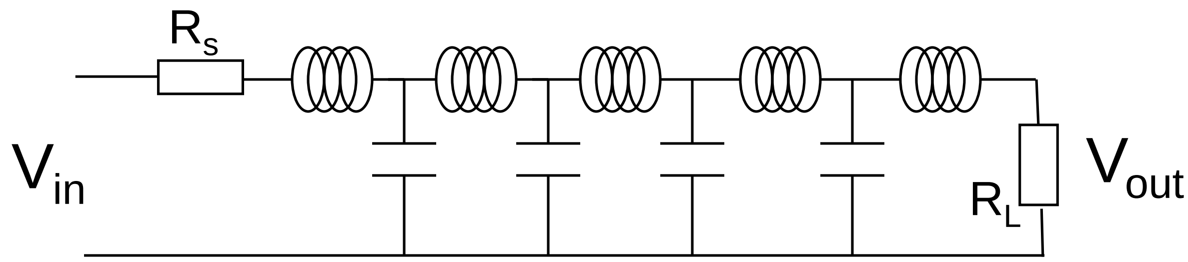
5th order Butterworth vs. 5th order elliptic. Note that 5th order elliptic provides more out of band rejection compared to Butterworth at the expense of worse group delay ripple.



Inverse Chebyshev (also known as Chebyshev II) has good out of band rejection (not as good as elliptic), flat passband, a decent group delay ripple and relatively faster filter step response (compared to Elliptic).

Filter architectures:

- **Ladder:**



Passive low-pass ladder filter

The ladder architecture is to synthesize a filter as a set of series-shunt active networks. The input-out transfer function is the filter’s H(s).

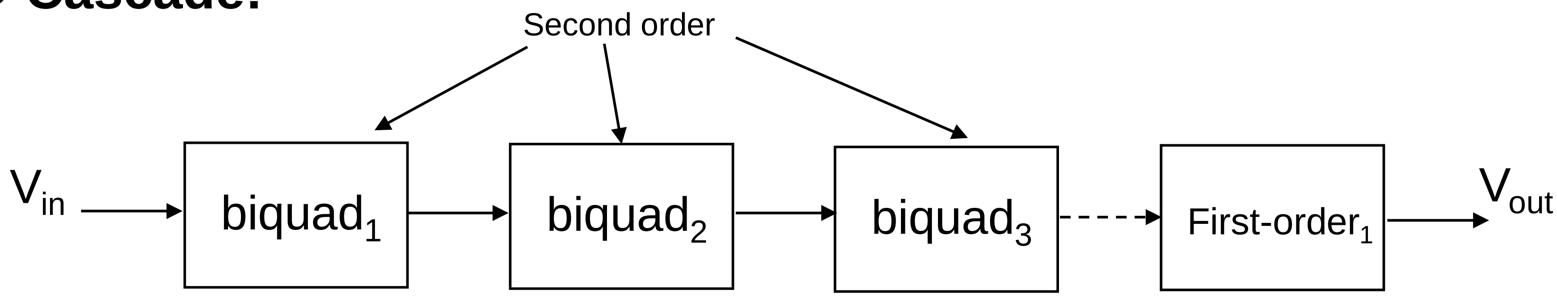
The **advantages** of ladder implementation are:

- lower sensitivity to filter component mismatch (high filter order)
- easy to design and synthesize

The **disadvantages**, however, are:

- cannot rearrange poles/zeroes along the signal path
- cannot realize all functions in s-domain
- sensitivity to termination resistors

- **Cascade:**



The cascade architecture is to synthesize a filter as a chain of second-order networks, biquads. The input-out transfer function is the filter H(s).

The **advantages** of cascade implementation are:

- modularity, easy to design and layout
- can realize any function in s-domain
- easy to rearrange poles and zeroes along the signal path
- insensitive to source and load termination

The **disadvantages**, however, are

- sensitivity to component mismatch

Example:

Let us try to architect the following 5th order elliptic 2.4MHz, 0.2dB passband ripple, 60dB stopband attenuation lowpass filter:

$$H(s)=\frac{1.35e^{5}s^{4}+4.19e^{20}s^{2}+2.72e^{35}}{s^{5}+2.23e^{7}s^{4}+5.45e^{14}s^{3}+6.6e^{21}s^{2}+6.07e^{28}s+2.72e^{35}}$$

1. Filter in ladder architecture:

There are three ways to find the ladder components of the above transfer function:

I. Mathematically through long division

II. Using filter tables published in filter cookbooks.

III. Using filter CAD tools

II. using filter tables in filter cookbooks:

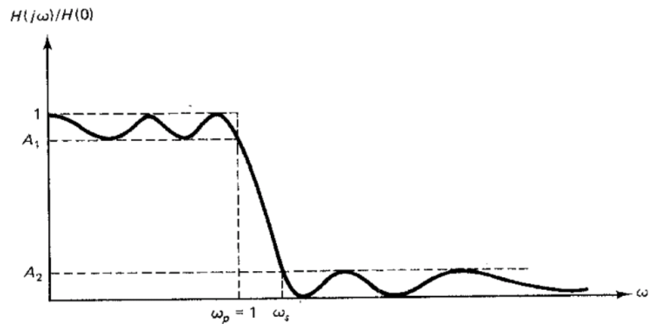


TABLE III-3c FOURTH-ORDER ELLIPTIC FUNCTION PARAMETERS*

$$H(s) = \frac{H(s^2 + a_1)(s^2 + a_2)}{(s^2 + b_{11}s + b_{10})(s^2 + b_{21}s + b_{20})}$$

A_1 \ ω_s	1.05	1.075	1.1	1.15	1.20	1.25	1.3
0.99	1.24184	1.36998	1.43445	1.48461	1.49416	1.48971	1.48067
	1.76639	1.64271	1.52732	1.35343	1.23106	1.14128	1.07349
	1.15362	1.22234	1.29092	1.42978	1.57242	1.71971	1.87203
	0.073511	0.104589	0.132384	0.179552	0.218090	0.250180	0.277321
	1.09961	1.12737	1.14901	1.18196	1.20610	1.22469	1.23958
	3.31266	3.85083	4.34993	5.29789	6.22434	7.15325	8.09589
	0.503140	0.389504	0.309376	0.209067	0.150187	0.112478	0.086921
0.97	1.11694	1.15719	1.17084	1.17132	1.16143	1.14961	1.13807
	1.17034	1.05721	0.974214	0.860463	0.785950	0.733037	0.693369
	1.15363	1.22235	1.29093	1.42979	1.57244	1.71971	1.87203
	0.082382	0.109829	0.132841	0.169869	0.198774	0.222152	0.241517
	1.06041	1.07297	1.08228	1.09550	1.10463	1.11140	1.11664
	3.31252	3.85097	4.34995	5.29782	6.22442	7.15325	8.09588
	0.315149	0.233744	0.182127	0.120698	0.086036	0.064240	0.049553
0.95	1.00616	1.02456	1.02740	1.01897	1.00707	0.994981	0.983063
	0.949099	0.853237	0.785841	0.695368	0.637238	0.595833	0.563827
	1.15362	1.22235	1.29090	1.42980	1.57240	1.71971	1.87203
	0.081657	0.106240	0.126428	0.158254	0.182889	0.202523	0.218409
	1.04043	1.04722	1.05200	1.05833	1.06243	1.06526	1.06699
	3.31238	3.85097	4.34973	5.29772	6.22421	7.15328	8.09613
	0.245492	0.180326	0.139862	0.092248	0.065716	0.049015	0.037702

III. using filter CAD tools:

There are several CAD tools available in the market that have filter support. Some examples are:

- Keysight ADS
- FilterSolution (https://www.nuhertz.com/)*. The package costs $3,900 with a network license. There is a 30-day free trial version
- Matlab

• The tool in general is straightforward to use. Set the filter function, order, guaranteed rejection, bandwidth …etc., and the software calculates the ladder components and displays the AC response.

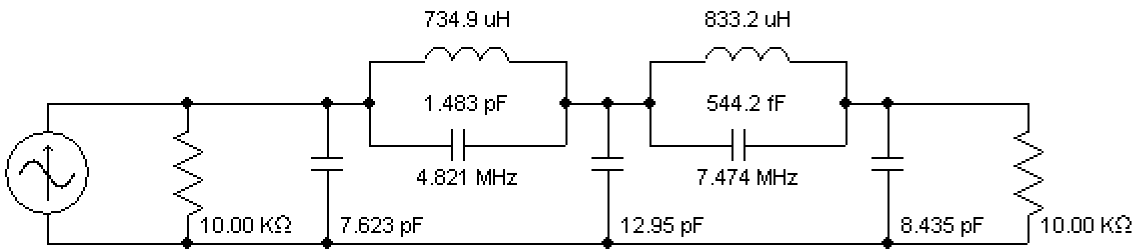
• In this example, the FilterSolution tool is used and the following implementation is obtained:

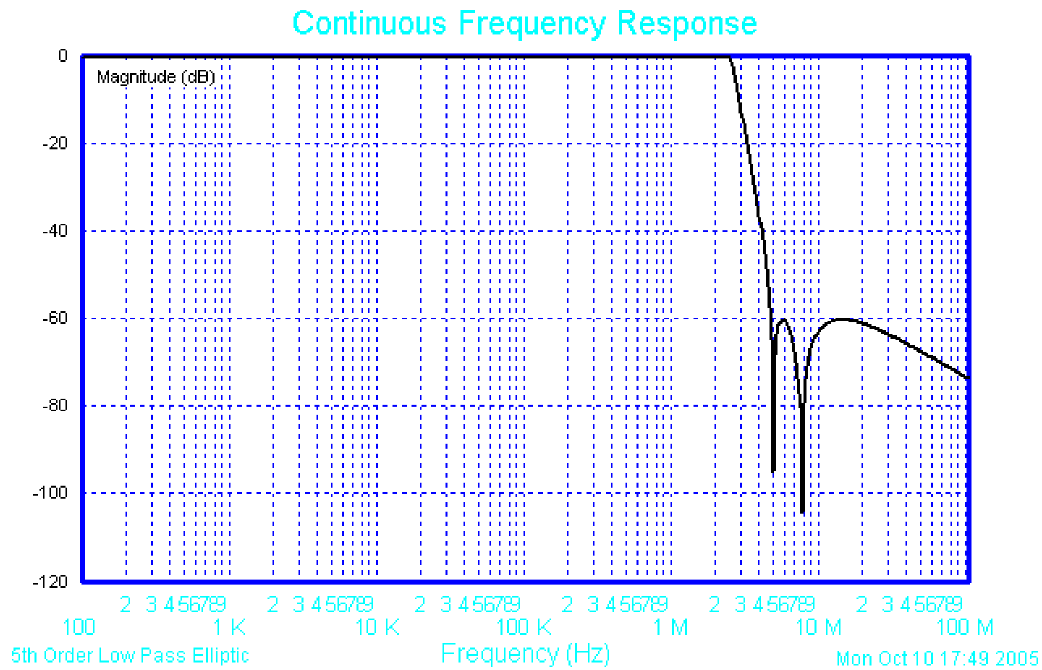
* The instructor of this class has no affiliation with NuHertz Inc.

5th Order Low Pass Elliptic

Pass Band Frequency = 2.400 MHz
Pass Band Ripple = 200.0 mdB

Stop Band Ratio = 1.924
Stop Band Frequency = 4.618 MHz
Stop Band Attenuation = 60.00 dB



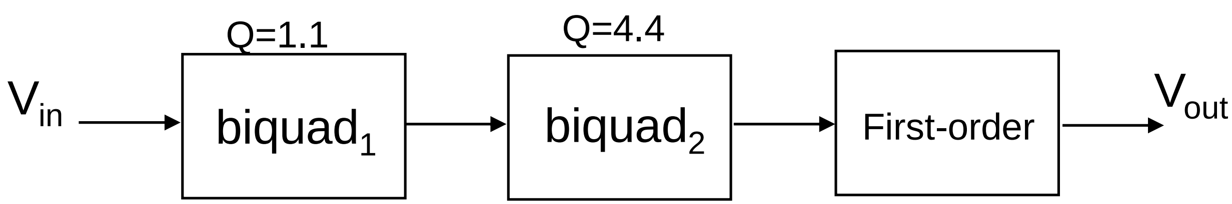


2. Filter as cascade architecture

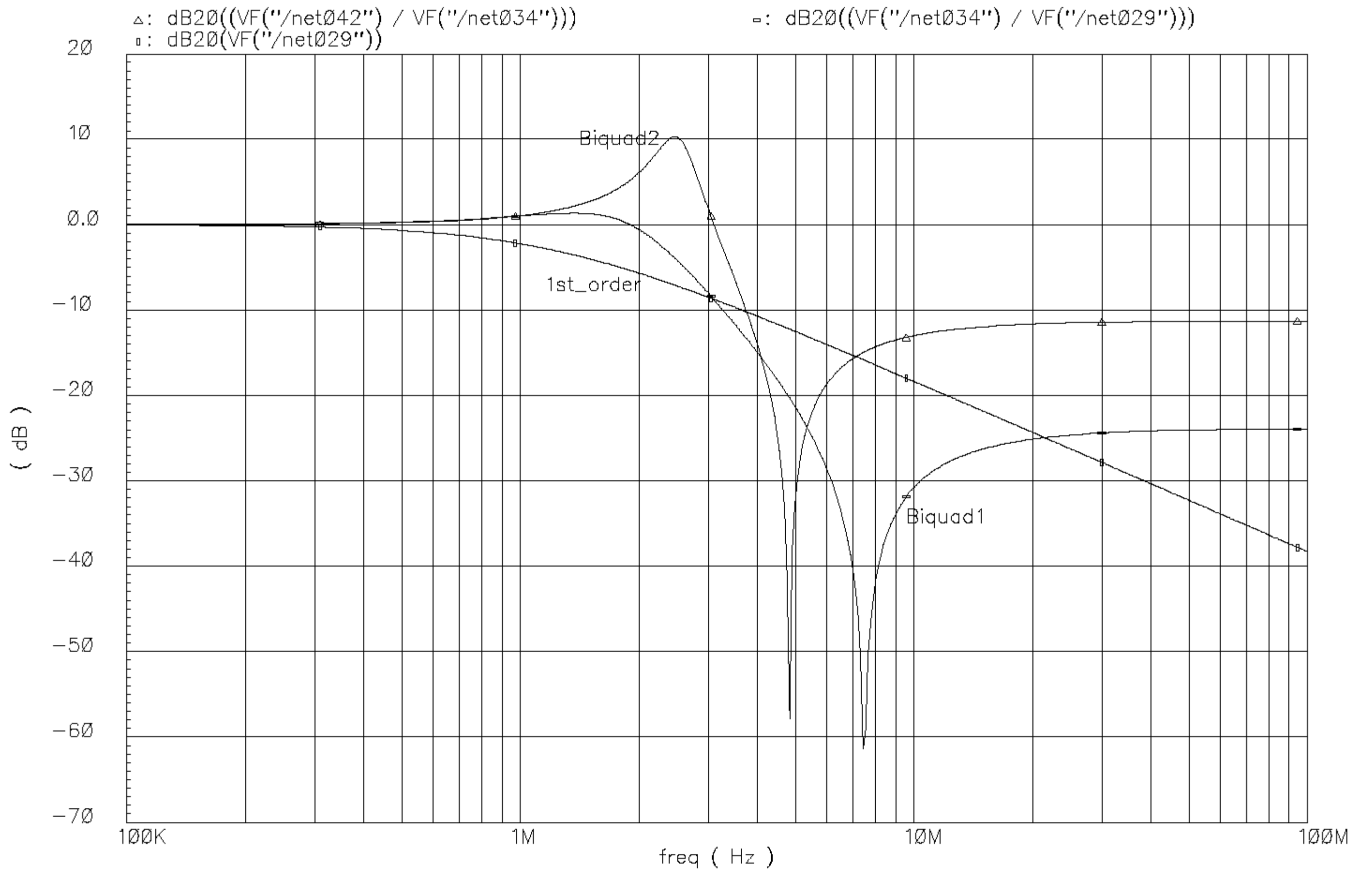
The filter transfer function can be broken into sets of biquads and first order stages as follows:

$$H(s) = \frac{1.35e^{5}s^{4} + 4.19e^{20}s^{2} + 2.72e^{35}}{s^{5} + 2.23e^{7}s^{4} + 5.45e^{14}s^{3} + 6.6e^{21}s^{2} + 6.07e^{28}s + 2.72e^{35}}$$

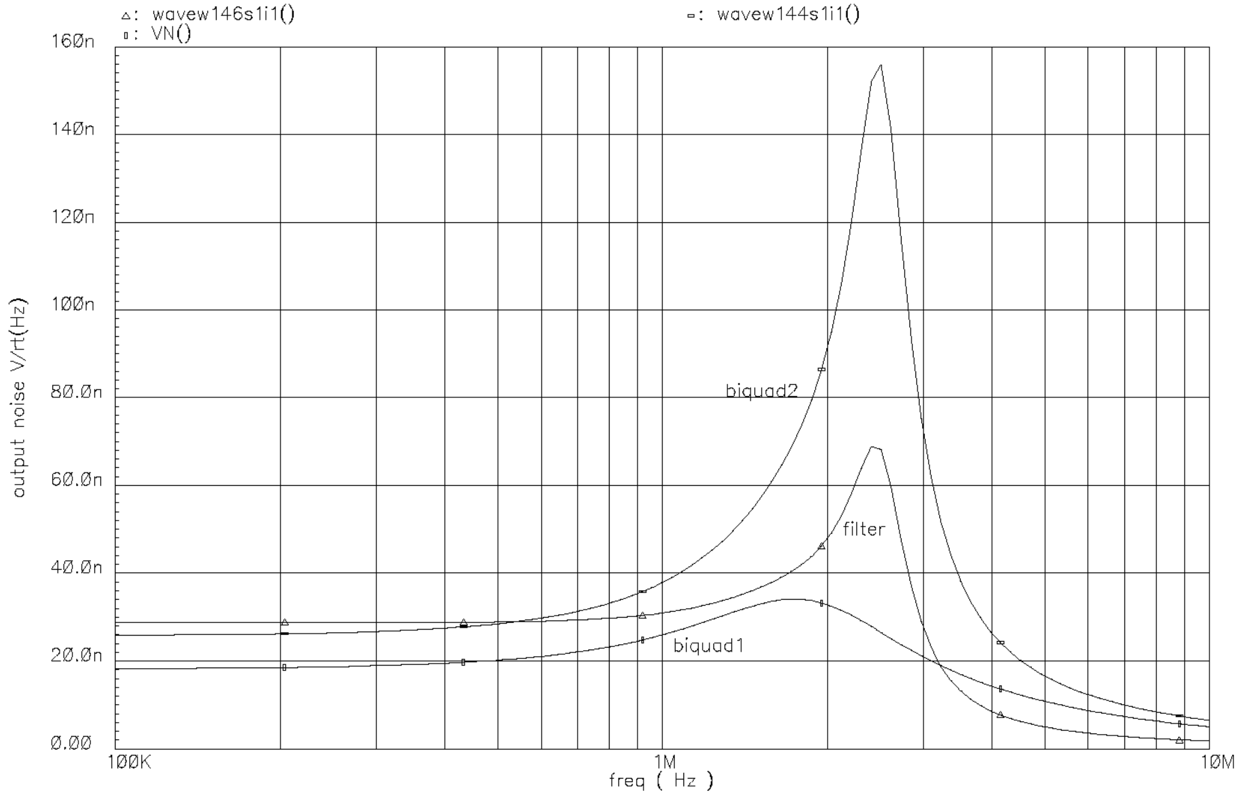
$$= \left(\frac{s^{2} + 2.2e^{15}}{s^{2} + 1.1e^{7}s + 1.42e^{14}}\right)\left(\frac{s^{2} + 9.17e^{14}}{s^{2} + 3.58e^{6}s + 2.5e^{14}}\right)\left(\frac{1.34e^{5}}{s + 7.65e^{6}}\right)$$



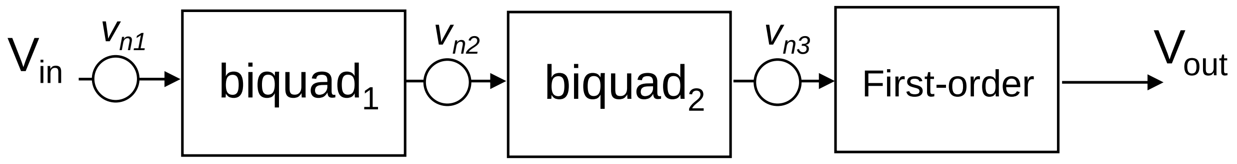
The order of the stages does not matter as far as the transfer function is concerned. However, rearranging the cascade affects the filter dynamic range as well as out of band noise density. This is one of main advantages of cascade topology over ladder.



The above plot shows the input/output response of each block in the cascade. Biquad2 has peaking, and so it will "amplify" any close-in blocer if placed first in the cascade. Therefore, it makes sense to place the first-order block first in the cascade followed by biquad1 then biquad2 to obtain best filter dynamic range.



The above plot shows the input/output noise of the filter at its biquad stages. It is evident that the noise of the filter does not follow the filter AC response since the noise is distributed and generated in each stage. In transmitter, placing biquad 2 last is bad because of its large out of band noise. Having biquad 2 followed by biquad 1 and then the first order stage last offers best out of band noise, which is important for transmit baseband filters (for good ACPR)



v_{n1}, v_{n2} and v_{n3} represent the equivalent input noise of biquad$_1$, biquad$_2$ and the first-order network, respectively. The noise generated by biquad$_1$ get shaped partially by biquad$_1$ itself and fully by biquad$_2$ and the first-order network. The noise generated by biquad$_2$, however, gets shaped partially by biquad$_2$ and only fully by the first-order network. Therefore, the output noise density of the filter vs. frequency does not fall as sharp as the filter AC response itself, rather it follows almost a 20dB/decade slope or even less. The arrangement of the cascade affects the output noise shape and could result in noise peaking around the 3dB corner.

References:

[1] R. Schaumann, K. Laker, M. Ghaussi, *Design of Analog Filters, Passive, Active RC, and Switched Capacitor*, Prentice Hall, 1990, ISBN: 0-13-200288-4

[2] R. Schaumann, V. Valkensenburg, *Design of Analog Filters*, Oxford Univ. Press, 2001, ISBN:0-19-511877-4