An Application of Bandpass Filters

Jeff Crawford - KØZR

October 15, 2016

Goals for this Discussion:

- ❑ Cover some general filter theory
- ❑ Apply this theory to an amateur radio need – SO2R (Single Operator 2 Radios)
- ❑ Conclude in ~ 20 minutes

Topics to be covered

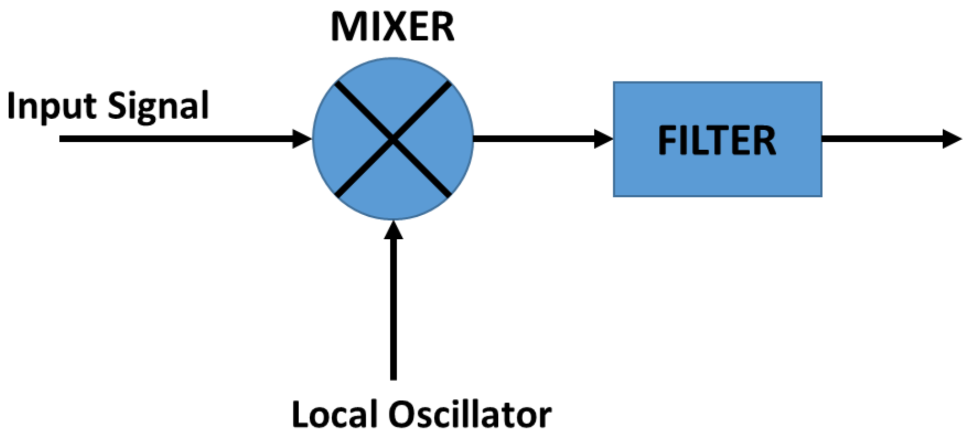
- Why we need filters?
- Introduction to some common filter terminology
- Brief comparison of filter “families”
- Free software and recommended references to help with the design process
- ELSIE design of a 40m (7 MHz) bandpass filter
- Design modification to reduce critical RF currents
- Simulation results – frequency response and voltage/current requirements
- Example 7 MHz HPF

What Do We Need Filters For?

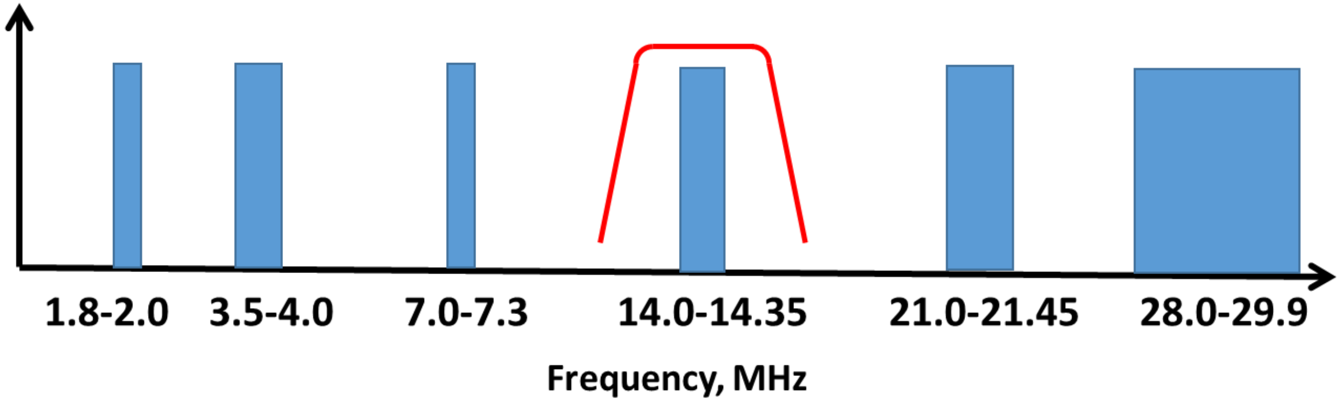
- Filters are an absolute necessity to separate desired signals from undesired signals
  - Radio transmitters and receivers would not be possible without them

- Filters are found at the input of each “frequency band” { 3.5, 7, 14 MHz, etc} in a receiver and are also used to achieve the final desired bandwidth of 2.7 kHz for SSB-voice or ~ 600 Hz for CW (code) (Filters occur in transmitters too ☺)

- Good filters in receivers do influence the cost of the radio significantly. In higher-end radios there are multiple filters used to select different bandwidths



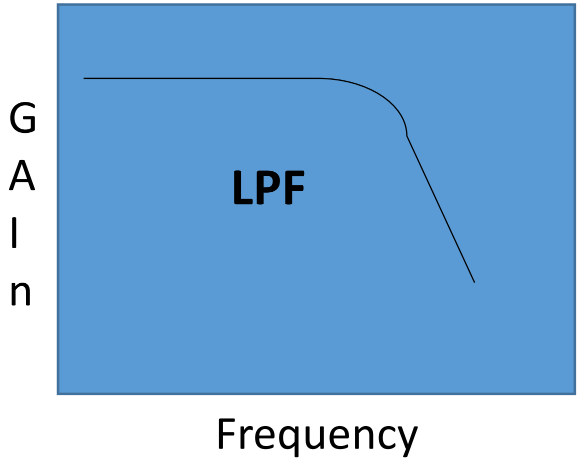
Receiver Application

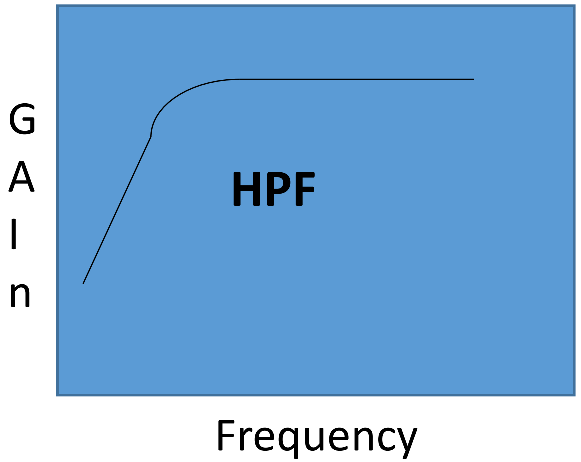


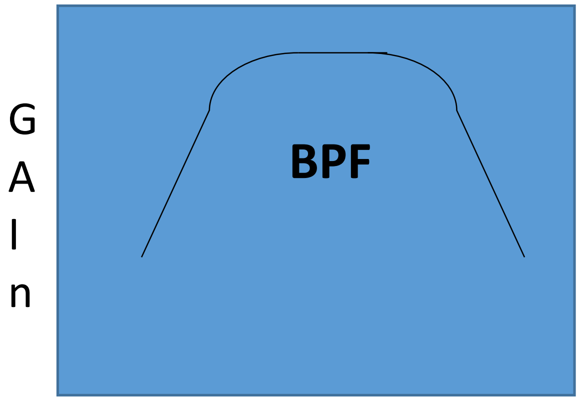
Filter 20m Band

Common Filter Terminology

- Lowpass Filters – pass all frequencies up to a specific frequency
- Highpass Filters – pass all frequencies above a specific frequency
- Bandpass Filters – pass a range of frequencies
- Bandreject Filters – reject a range of frequencies







Filter Families

- Different “filter families” offer different characteristics
  - “zero ripple” in the passband (Butterworth)
  - “defined ripple” in the passband (Chebyshev, Elliptic)
  - Shallow or deep “filter skirts”

$$f' = \frac{f}{f_c}$$

f’ is “normalized frequency” f_c is the LPF or HPF cutoff frequency

Increased Filter Complexity Gives Steeper “Skirts”

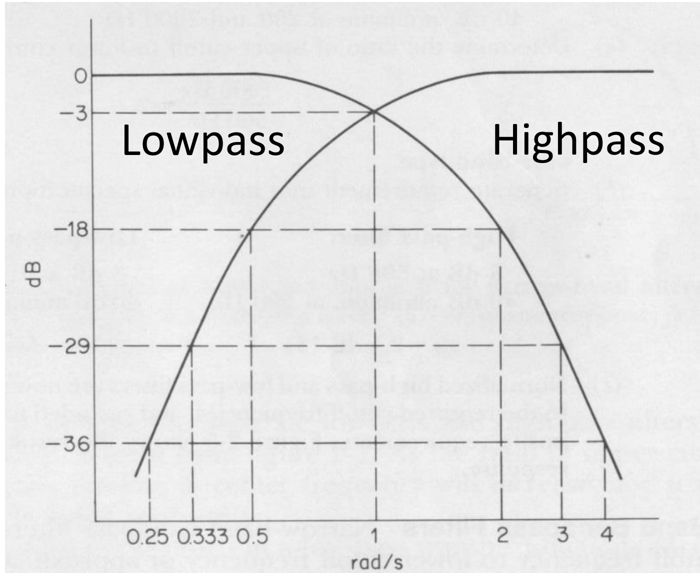


Fig. 2-5 Normalized low-pass high-pass relationship.

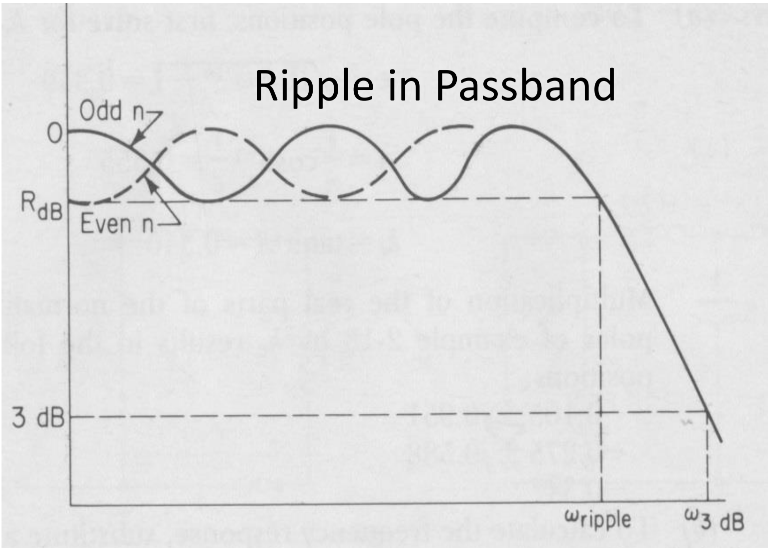


Fig. 2-39 Ratio of 3-dB bandwidth to ripple bandwidth.

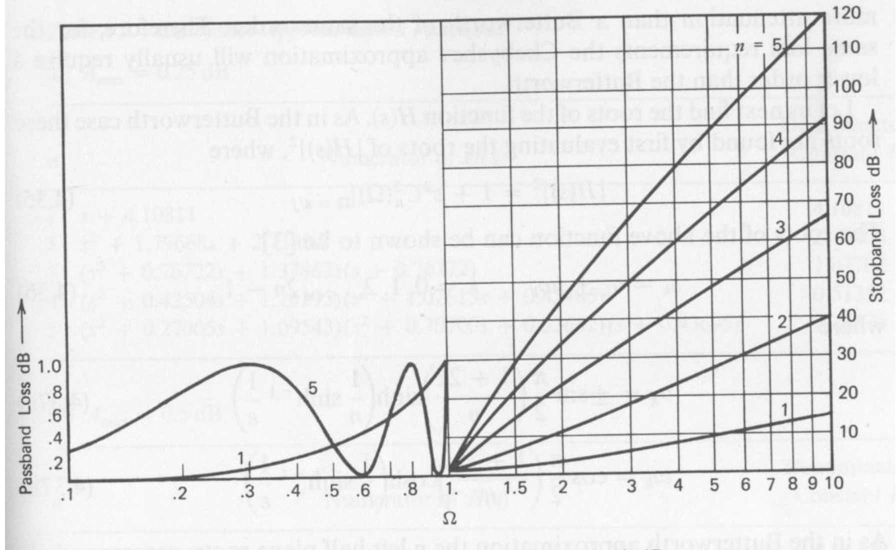


Figure 4.11 Loss of *LP* Chebyshev approximation for A_{max} = 1 dB.

More Filter Considerations - 2

- The larger the ripple factor, the steeper the filter skirts can be, but with
  - Increased insertion loss
  - Increased VSWR in the passband
- Each component in a filter has an associated “Q-Value” or quality factor
  - Q-values greater than a “minimum*” are required to achieve a desired filter response
    - Inductors with series resistance limit their “Q”
    - Capacitors with parallel resistance limit their “Q”
  - If your inductors have less than the “minimum Q”, the passband loss increases, and the “corner” of the filter prematurely rounds off.

* Minimum “Q” value discussed next page

How Q Enters In

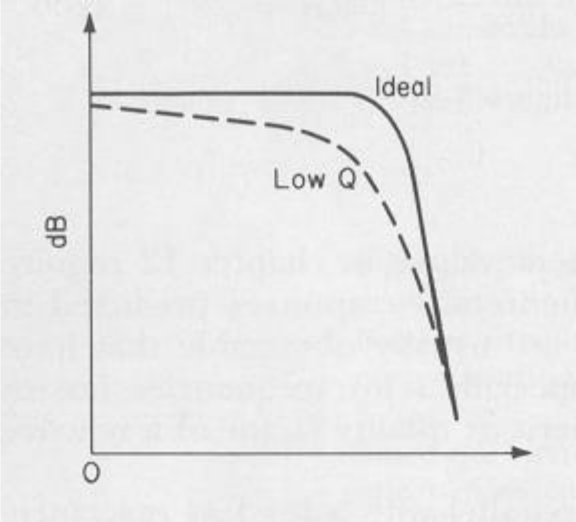


Fig. 3-7 Effects of finite *Q*.

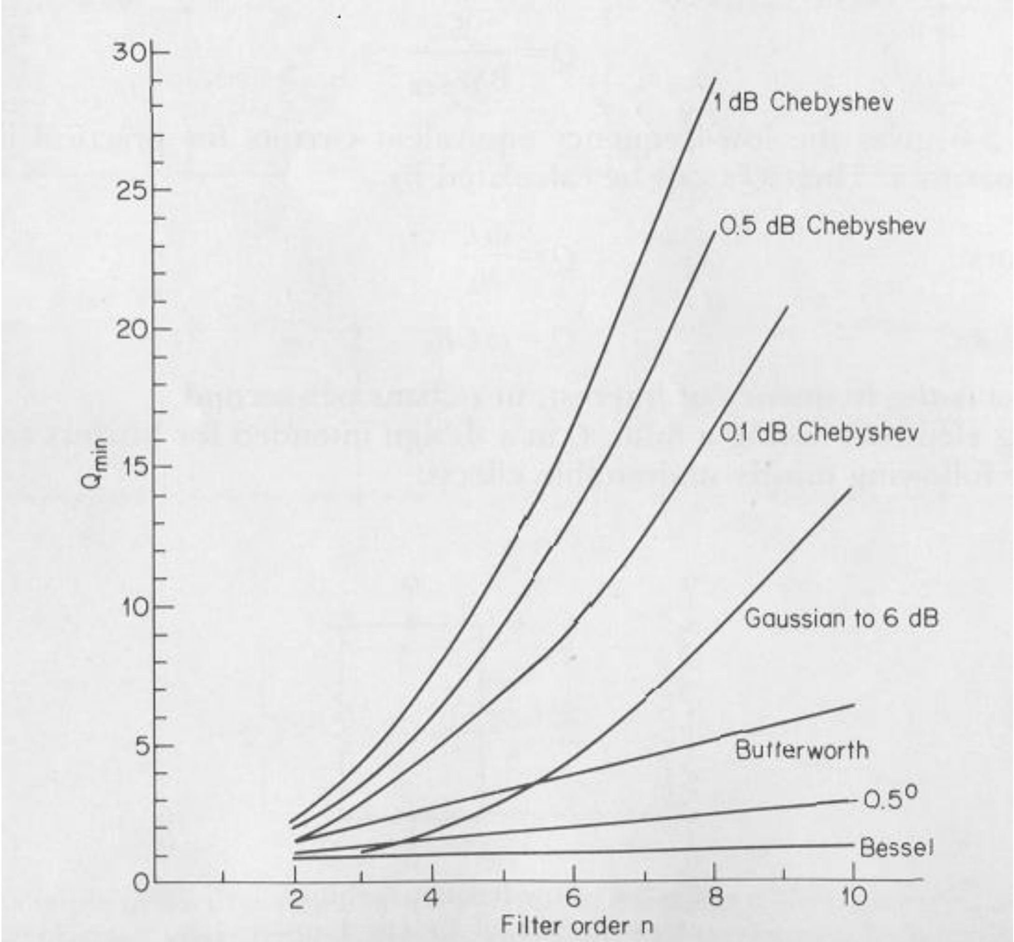


Fig. 3-8 Minimum *Q* requirements for low-pass filters.

As Filter Order increases, so does the minimum required Q value

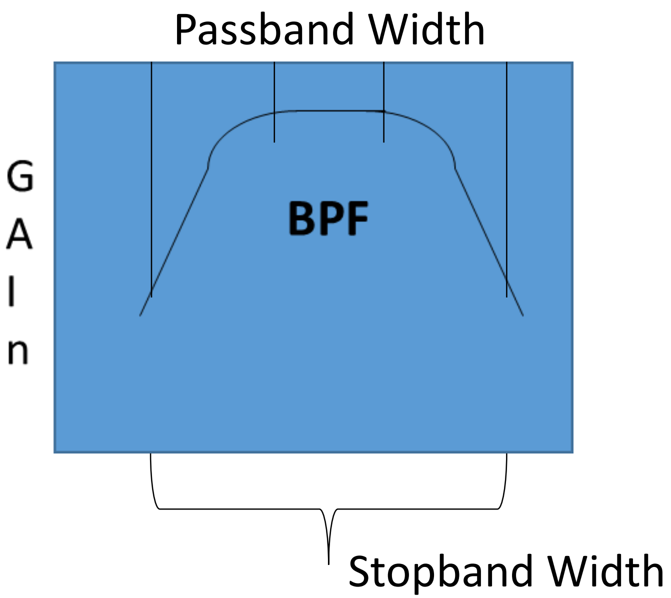
As filter ripple increases, so too the minimum Q's required increase

$$f' = \frac{f}{f_c}$$

f' is "normalized frequency" f_c is the LPF or HPF cutoff frequency

Filter Considerations - 4

- LPF and HPF were just shown to require a certain minimum Q value for each component
  - Inductors are the “problem” with Qs from 20 to perhaps 200, while capacitors have Q values of 3,000 – 5,000 or more; higher Q is better
- The Q of components in BPF may need to be considerably higher



Minimum Q for BPF is:

$$Q_{\min} = Q_{\min,LPF} \times Q_{BP} \;\; where \quad Q_{BP} = \frac{Stopband}{Passband}$$

Punchline: BPFs are more challenging than LPFs or HPFs

FYI With an Input of 1,500 Watts, 0.3 dB loss means **<u>100 Watts</u>** is dissipated
In the filter

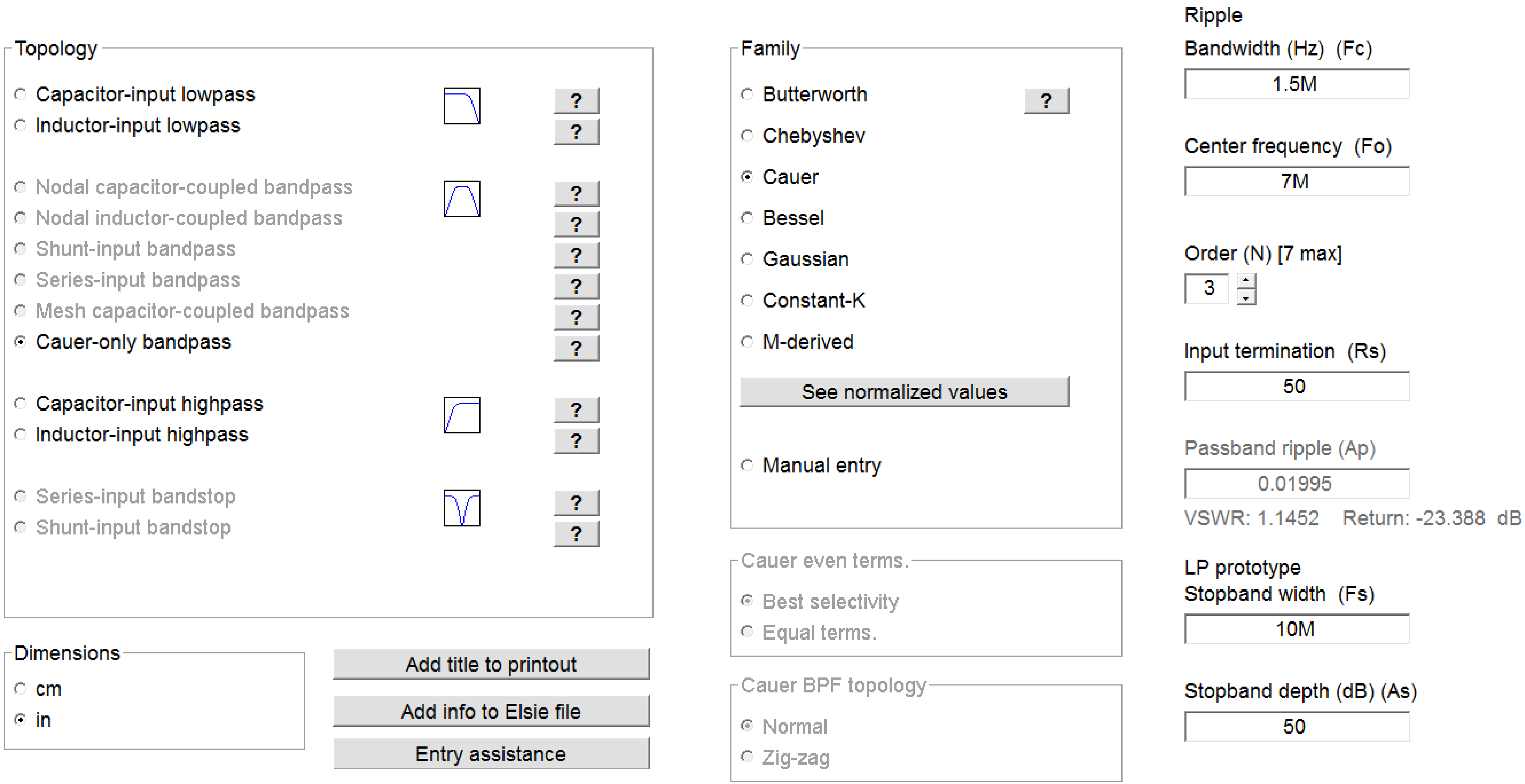
Resources for Filter Work

- ELSIE – “free” filter design software on the web, up to 7th order filters
- LTSpice – “free” circuit simulator to analyze your filters (and other circuits)
- ORCAD Lite – “free” SPICE analysis software
- MicroCap
- DXZone – Filter design
- DesignSpark PCB for PCB layout (not limited to 3” x 4” like many other programs)

References:

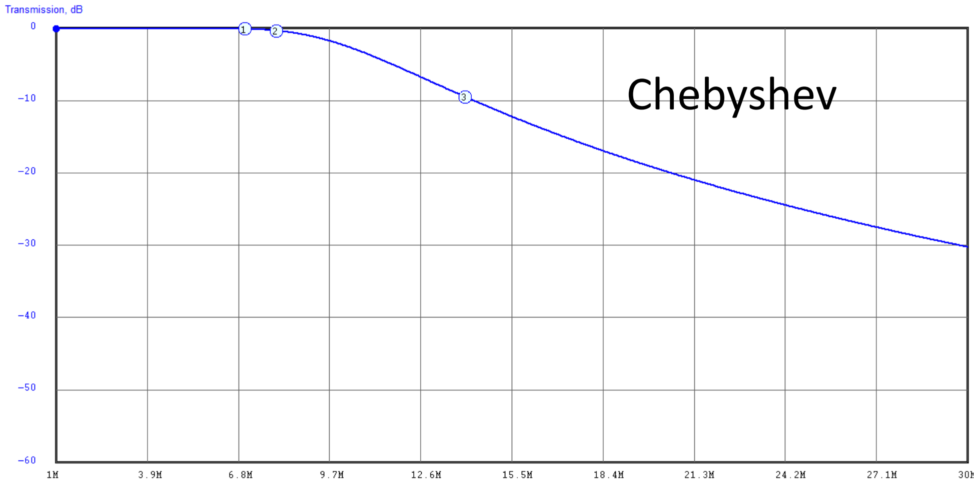
- Electronic Filter Design Handbook, Arthur B. Williams, McGraw-Hill
- Principles of Active Network Synthesis and Design, Gobind Daryanani, John Wiley
- Electrical Filters, Donald White, Don White Consultants

Design Our Filter in ELSIE – 40m BPF

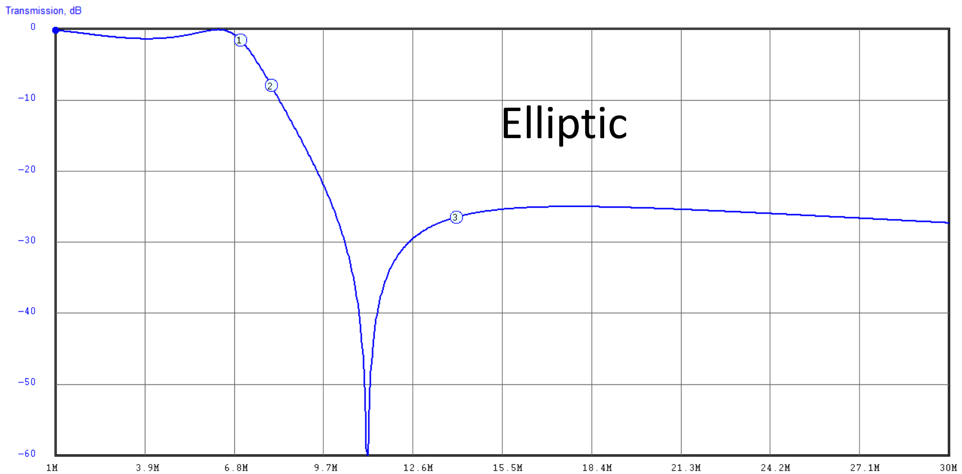


Why an Elliptic Filter Rather Than Chebyshev?

- Elliptic filters have ripple in both the passband and stopband
  - Chebyshev filters have ripple only in their passband
- Proper design of an elliptic can:
  - ❑ Develop steeper skirts than the same order Chebyshev filter
  - ❑ Allows selective placement of large attenuation “poles” at critical frequencies below and above the Passband
  - ❑ Obtain required attenuation everywhere across the passband, not just at frequencies farther removed from the passband



	Freq.:	Trans.:	Angle:	Return:	Delay:	VSWR:	Zmag.:	Zangle:	Real:	Imag.:
1	7M	-0.09227	-88.769	-19.446	44.13n	1.2386	61.926	-0.3007	61.925	-0.325
2	8M	-0.35854	-105.51	-11.615	48.52n	1.7121	83.334	-9.1944	82.263	-13.315
3	14M	-9.4697	169.12	-0.53332	22.36n	32.583	41.147	-86.417	2.5714	-41.067

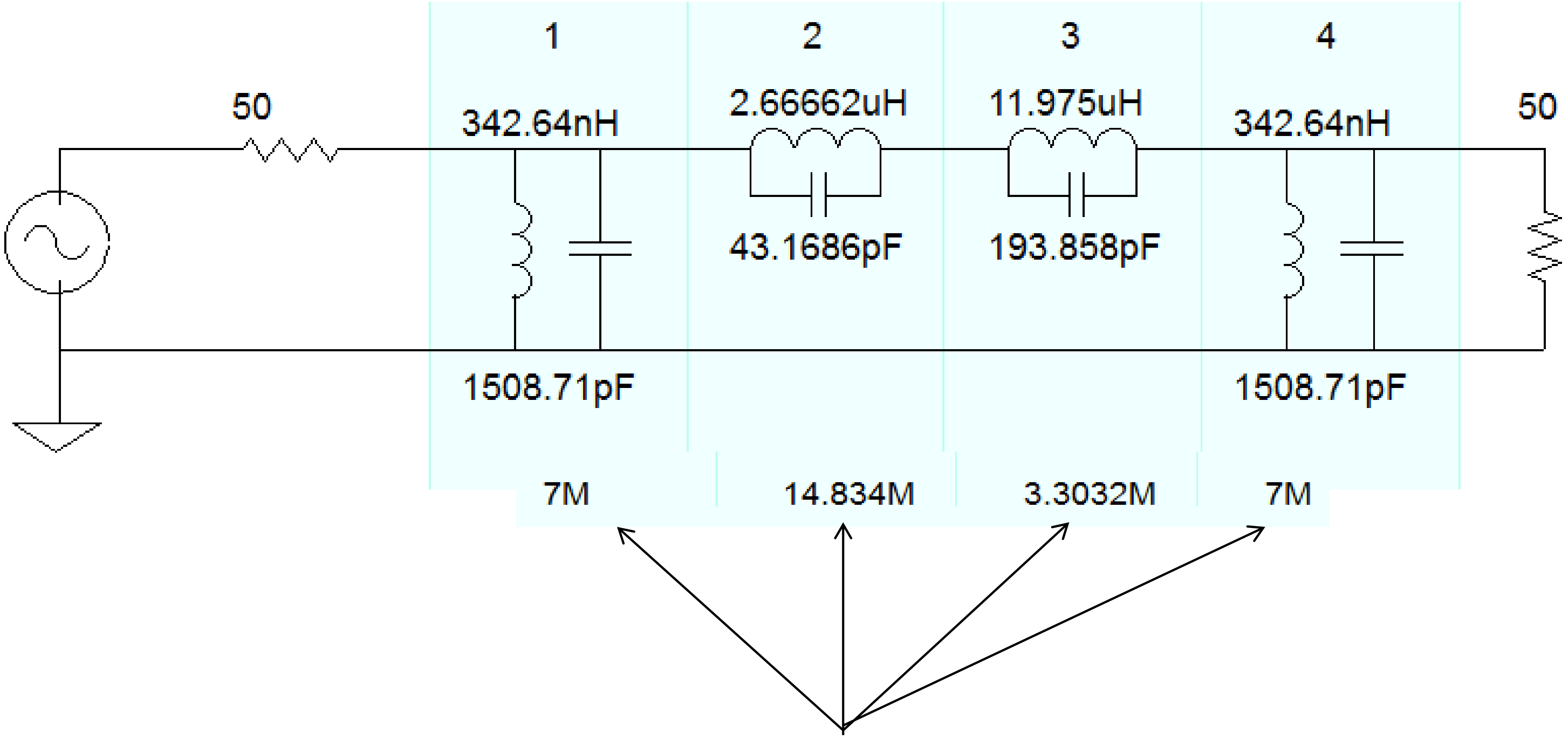


Mousedown for data

Freq.:	Trans.:	Angle:	Return:	Delay:	VSWR:	Zmag.:	Zangle:	Real:	Imag.:
7M	-1.507	-155.13	-5.7853	146.4n	3.113	69.408	-52.122	42.615	-54.785
8M	-7.9554	164.28	-0.82494	77.58n	21.074	37.231	-84.328	3.6798	-37.049
14M	-26.468	-63.288	-0.01125	6.387n	>1000	11.964	-89.836	0.03424	-11.964

Elliptic BPF for 7 MHz by ELSIE

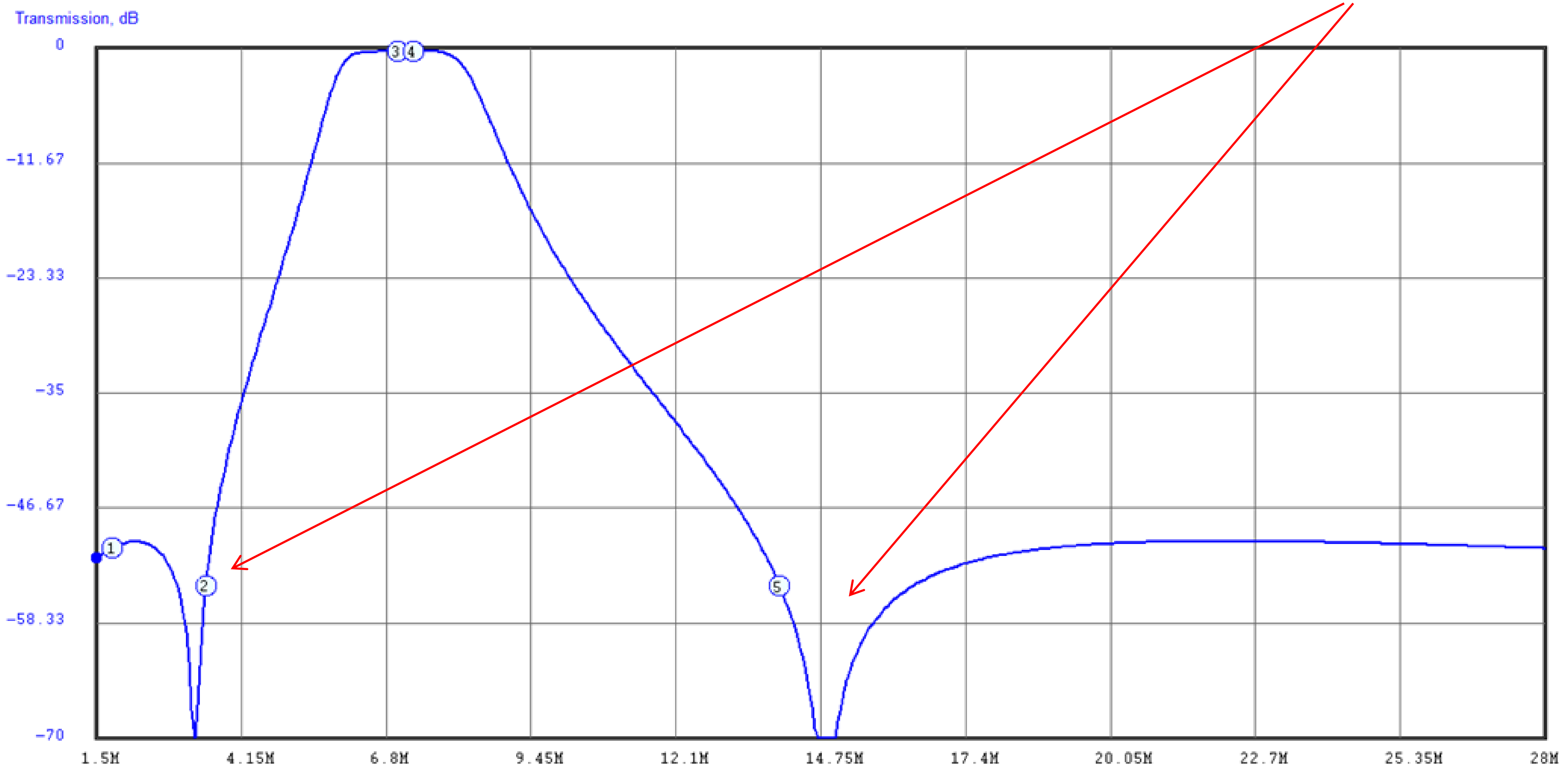
Standard Schematic Output from ELSIE



Each LC Section has a specific resonant frequency – Can be very useful in tuning up the filter

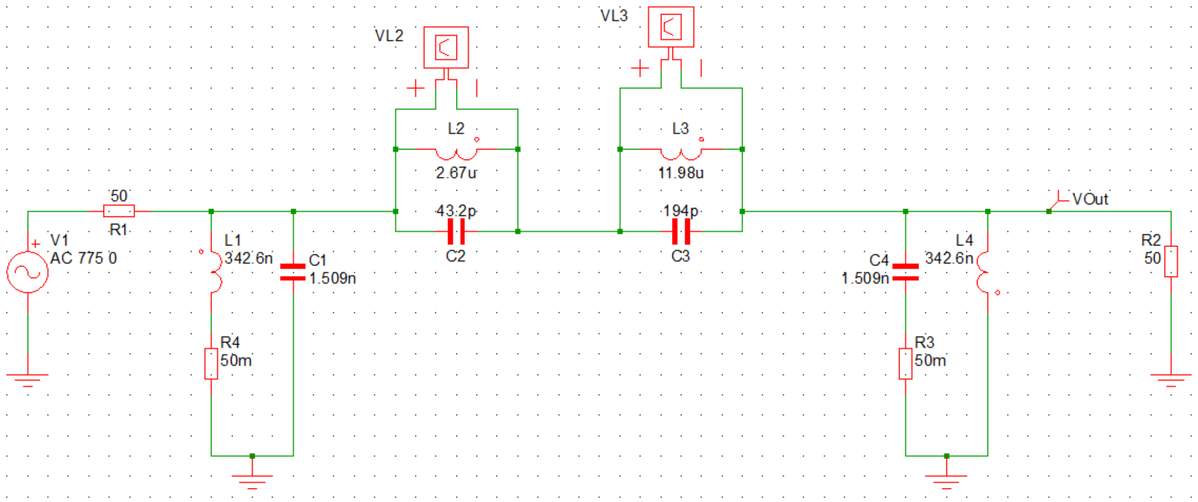
Filter Response from ELSIE “Plot”

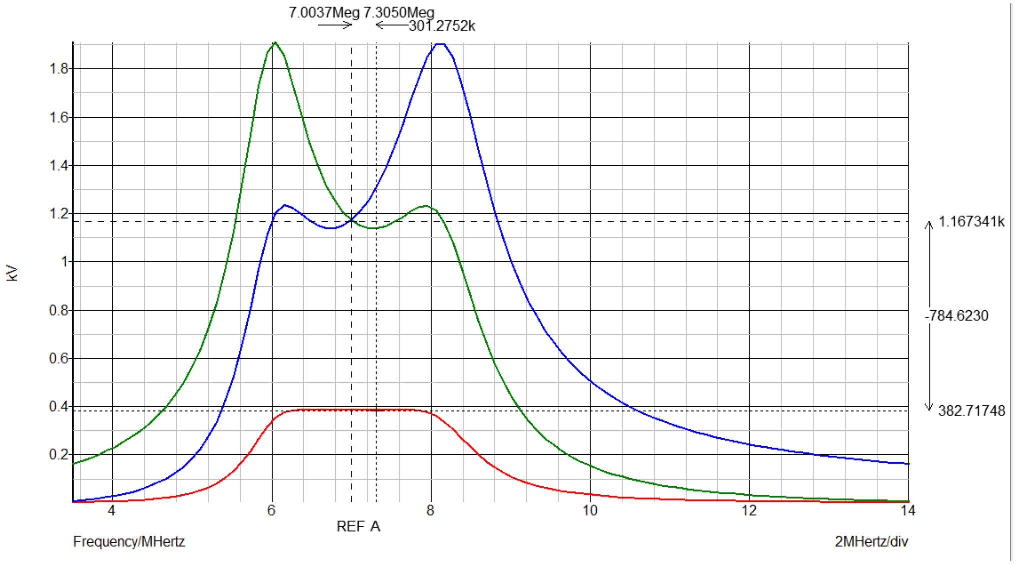
Some Latitude in Placing These Notches for Greatest Attenuation



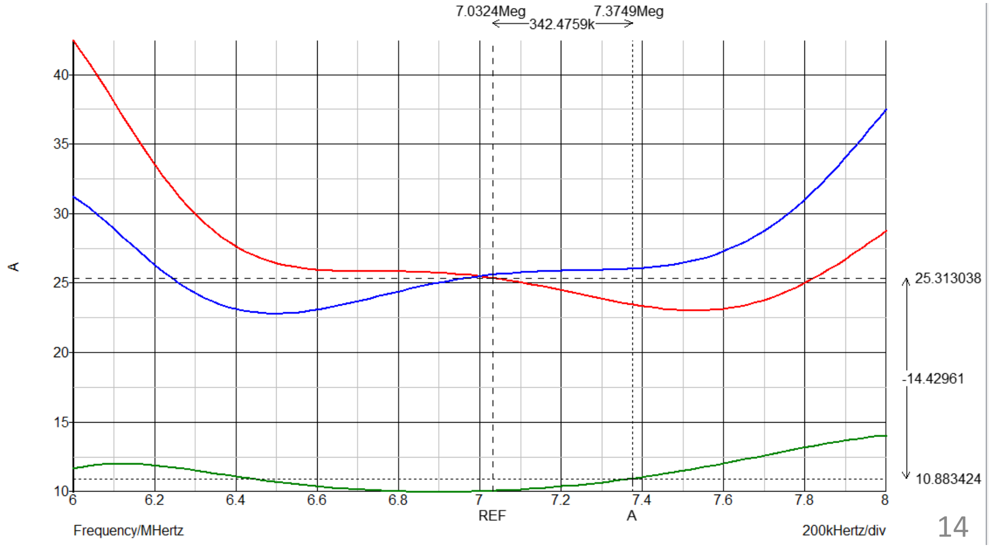
	Freq.:	Trans.:	Angle:	Return:	Delay:	VSWR:	Zmag.:	Zangle:	Real:	Imag.:
1	1.8M	-50.625	79.537	-0.03929	12.8n	442.2	4.0765	88.4	0.11382	4.0749
2	3.5M	-54.518	-121.32	-0.0622	-108.1n	279.29	10.096	88.943	0.18632	10.095
3	7M	-0.3343	-0.0084	-44.21	259.5n	1.0124	49.388	-0.01618	49.388	-0.01394
4	7.3M	-0.34271	-27.508	-24.262	252.8n	1.1304	47.181	-6.1717	46.908	-5.0723
5	14M	-54.523	114.83	-0.00476	2.828n	>1000	10.096	-89.919	0.01426	-10.096

SPICE Analysis of ELSIE BPF Design - 1,500 Watts





In-band capacitor voltages around 1.3 kV
In-band capacitor and inductor currents ~ **25 AMPS**



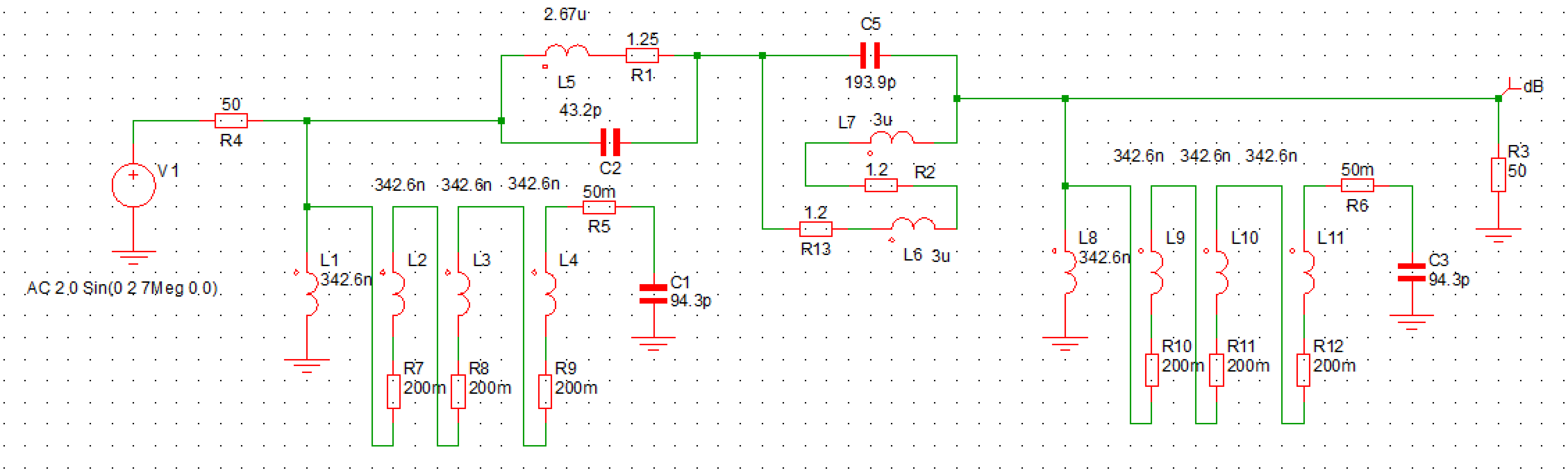
This design works in ELSIE, but at the 1.5 KW level it is close to “unbuildable” without expending serious $’s for the required parts

All is not lost – use different impedance levels in the high-current resonators – see Next page

A 16:1 Impedance Step-Up in First and Last Resonator Provides Current Reduction

- In 3 of the 4 cases where inductors are needed in my design, powdered iron toroids are used
  - Toroids are “self-shielding”, thus relatively insensitive to other nearby components and aluminum/steel box walls
  - Use of single winding, air-core inductors become prohibitively large in the real estate required. (This can be done, but capacitors complicate things)
  - Instead of using a single-winding on the first and last coils, use of quadrifilar windings (four wires together) reduces the aforementioned 25 amps to 25/4 = 6.25 amps
- A source of good quality, low-cost, high-voltage capacitors is hard to find. When using air-core inductors, “door knob” capacitors are generally used - $20 each, or other high quality capacitors
  - These are expensive
    - Multiple capacitors must be used in parallel to achieve “current sharing”
  - I use MLCCs – multi-layer ceramic chip capacitors, which are very small and MUCH less expensive

Modified ELSIE Design

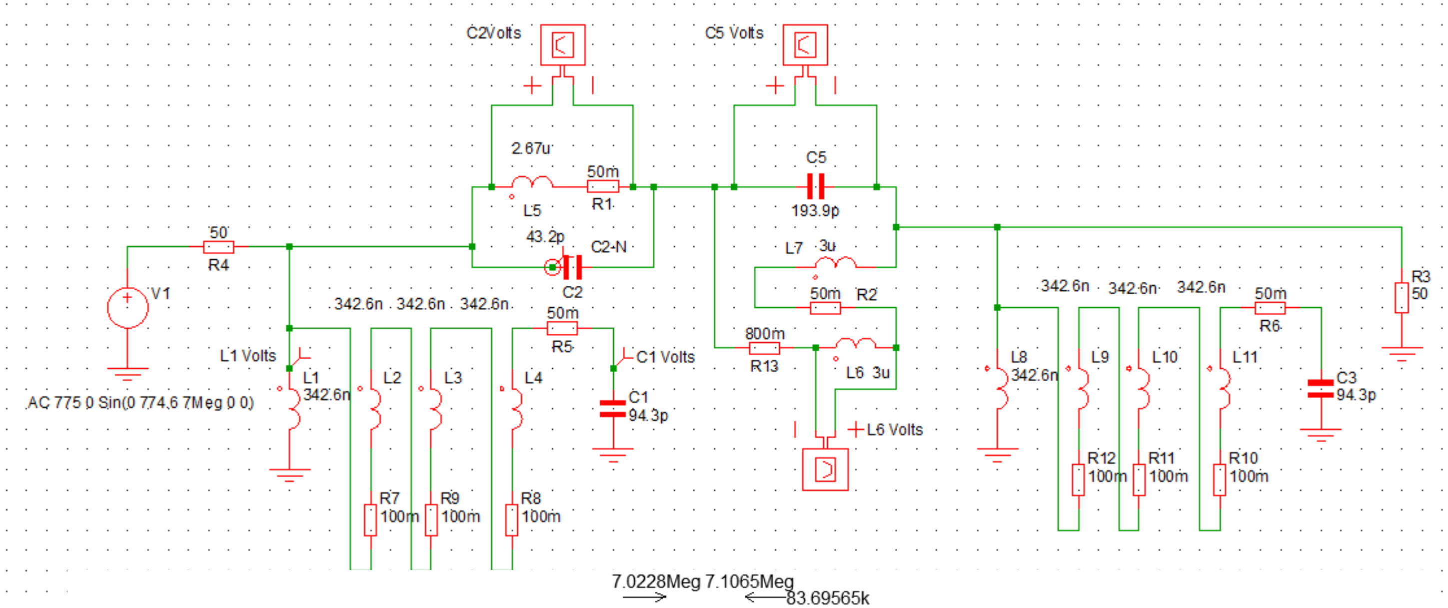


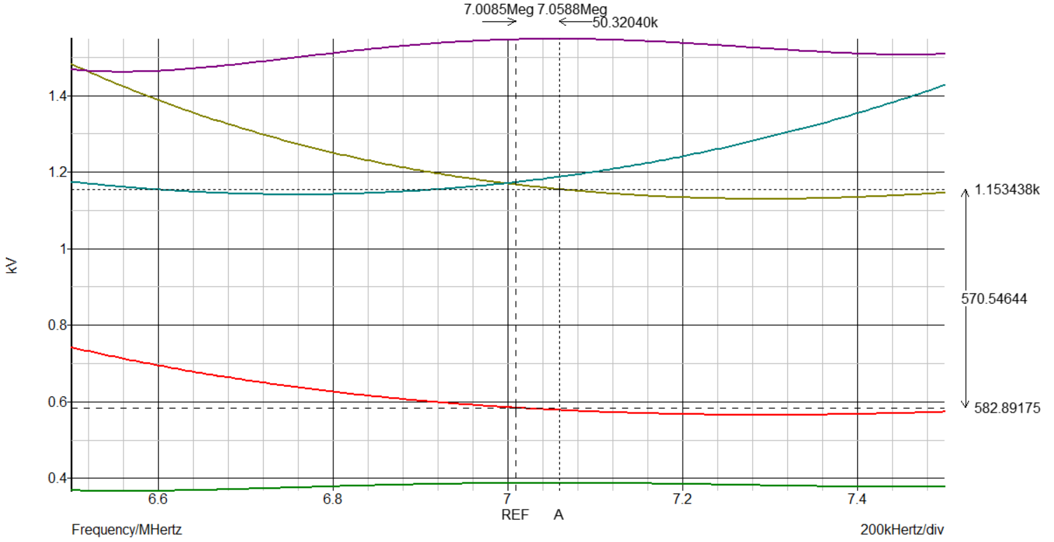
The resistors give the inductors "real-world" values of Q rather than "infinite", perfect Q

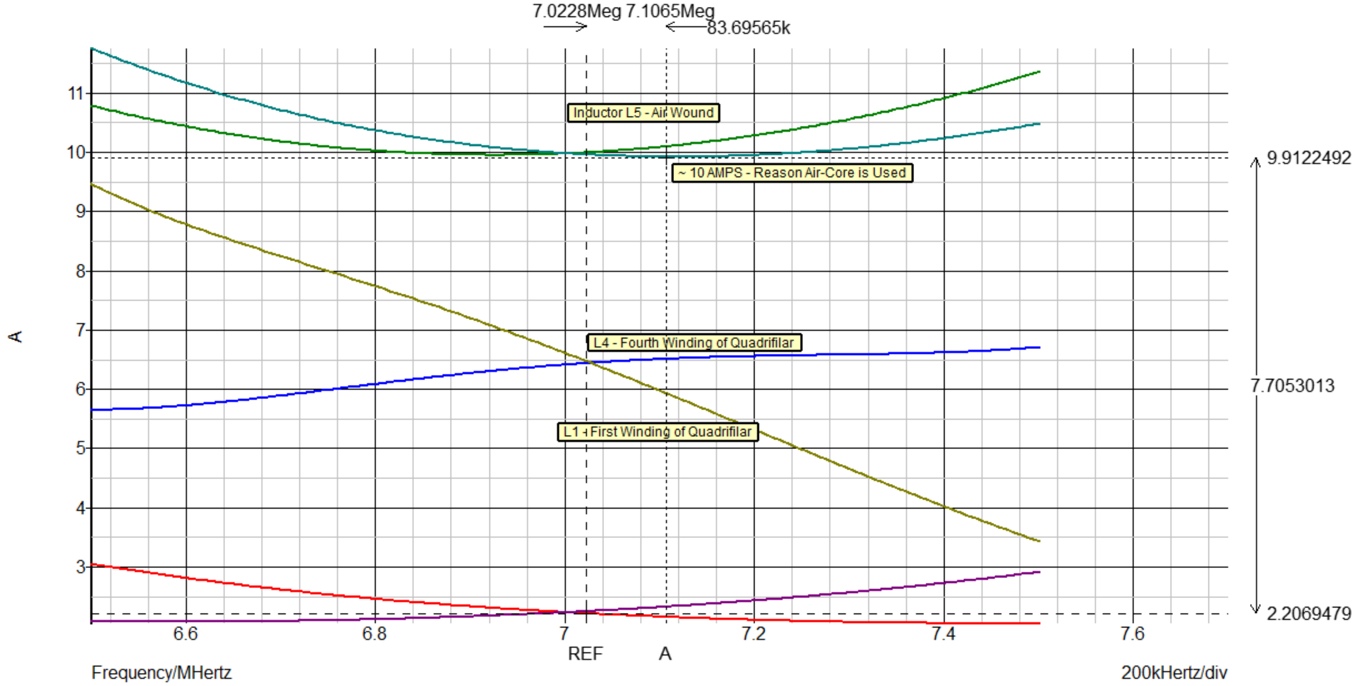
The "dots" on the inductors indicate phasing of the windings – critically important

Phase winding details are discussed in Radio Amateur's Handbook and other places

Modified Design Voltages and Currents



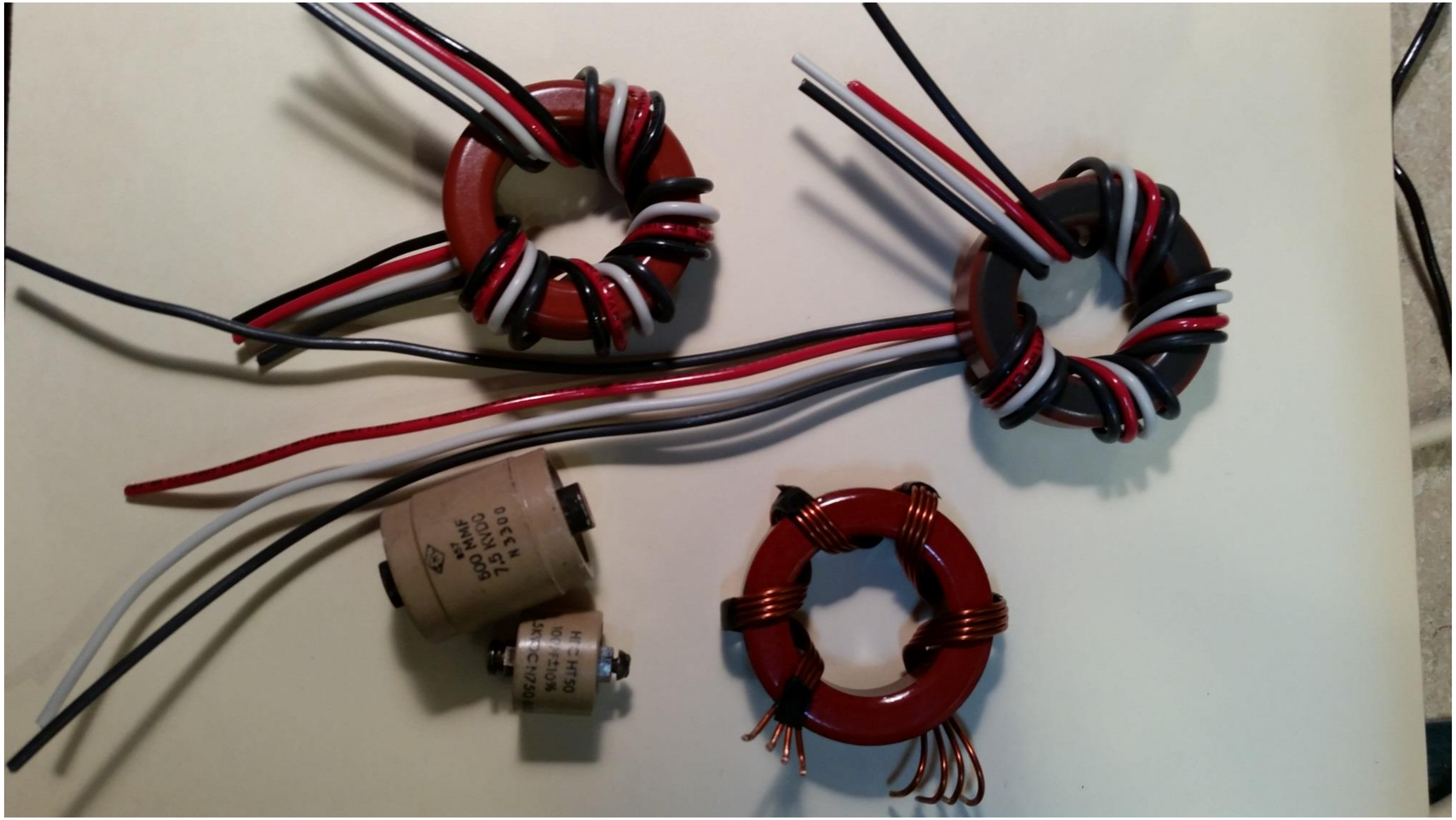




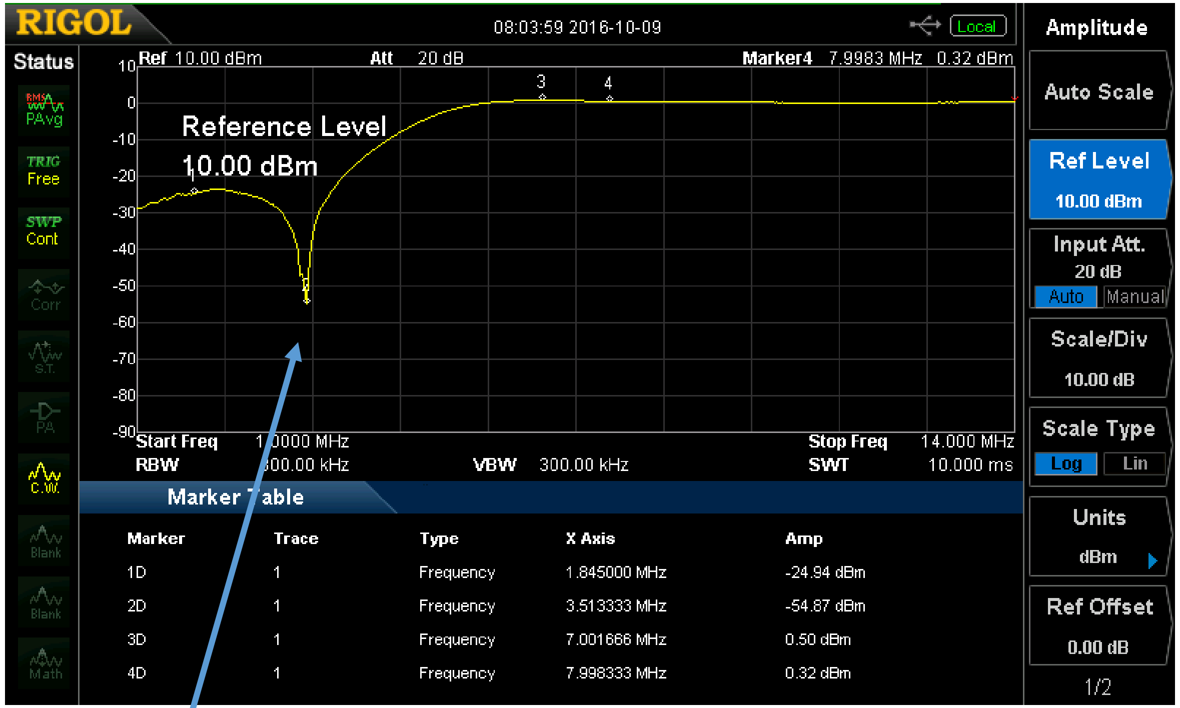
- Capacitor voltages still ~ 1.5 kV
- First and Last inductors ~ 6 Amps rather than 25
- Air Core inductor, L5, has ~ 10 Amps

  Cannot use toroid due to saturation

Quadrifilar Toroids and “Door Knob” Capacitors

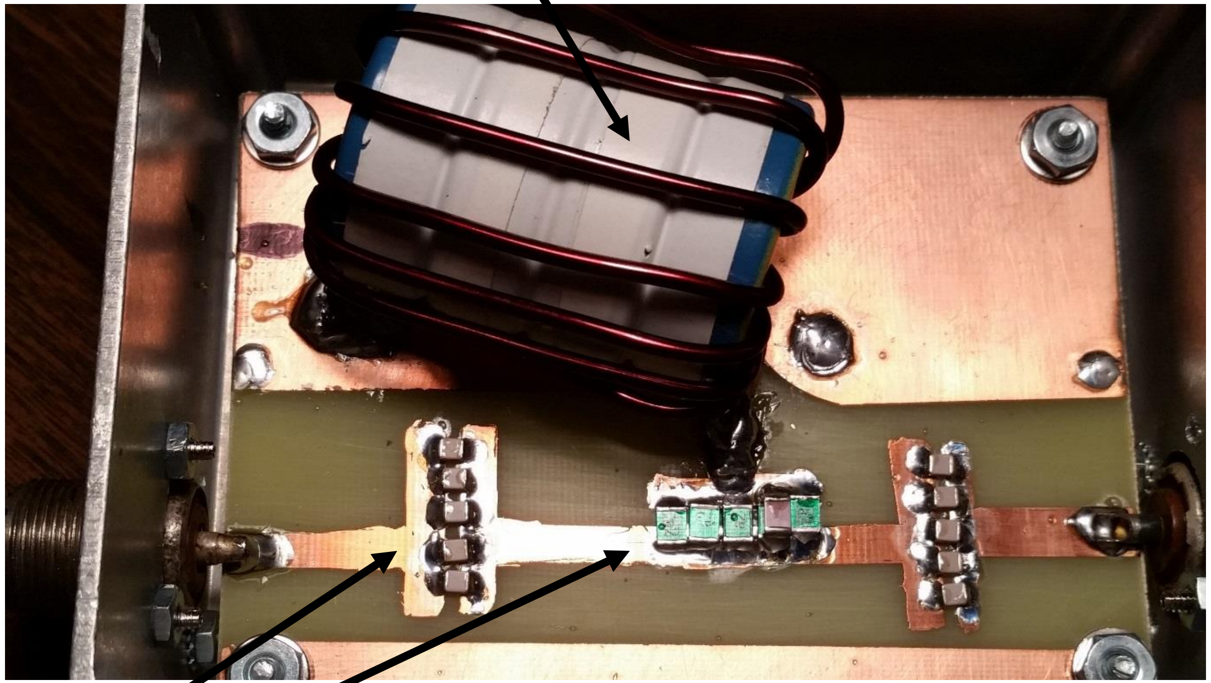


Highpass Filter for 7 MHz



Deepest “notch” at 3.5 MHz

Four stacked cores to decrease core saturation concerns



Multiple, paralleled MLCCs for current-sharing

Summary

- High voltages and currents occur in even a 100 Watt filter, much less a 1.5 KW filter
- The nature of self-shielding in toroids makes the design more compact with less interaction from one resonator to the next
  - Must carefully monitor core saturation*
    - When this occurs, use a larger diameter core or “stack” 2 or 3 cores together
    - In my case I elected to use a single, air-wound inductor for the one inductor
- Here we have considered only frequency response and out-of-band attenuation
  - In true “communications” applications, other factors such as group delay and linear phase must be factored in
- Most filters we use are “Odd order”. Even-order filters have a different output impedance than their input, creating another VSWR challenge
- With the advent of inexpensive capacitance meters as well as other Z meters, such a project is doable without expensive test equipment. Once you “get close”, a LARG member with a network or impedance analyzer can get you across the finish line if needed.

kzerozr@gmail.com

*Manner in which core saturation is calculated is found at Amidon Associates web site

Backup

Other Filter Considerations

- The “order of the filter” indicates how many components, sometimes called “resonators”, are used
  - The higher the filter order, the sharper the possible filter response
  - The more complex the filter, the more difficult to build and “tune”
  - Generally, increasing insertion loss occurs as filter order increases
- Ripple in the passband is directly related to the minimum VSWR possible with a filter

$$\rho = \frac{VSWR-1}{VSWR+1} \qquad \rho = \sqrt{\frac{\varepsilon^2}{1+\varepsilon^2}} \qquad R_{dB} = -10\log_{10}\left(1+\rho^2\right)$$

R_{dB} = Return Loss, in dB

ε is the ripple factor in Chebyshev filters

$$f' = \frac{f}{f_c}$$

f’ is “normalized frequency” f_c is the LPF or HPF cutoff frequency