

An Application of Bandpass Filters

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Goals for this Discussion:

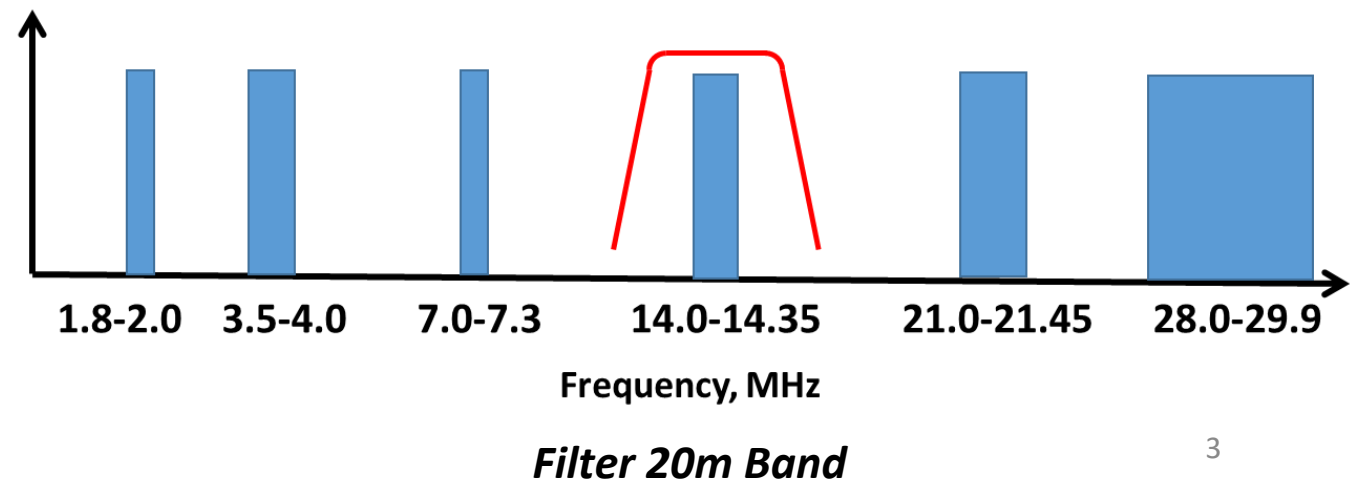
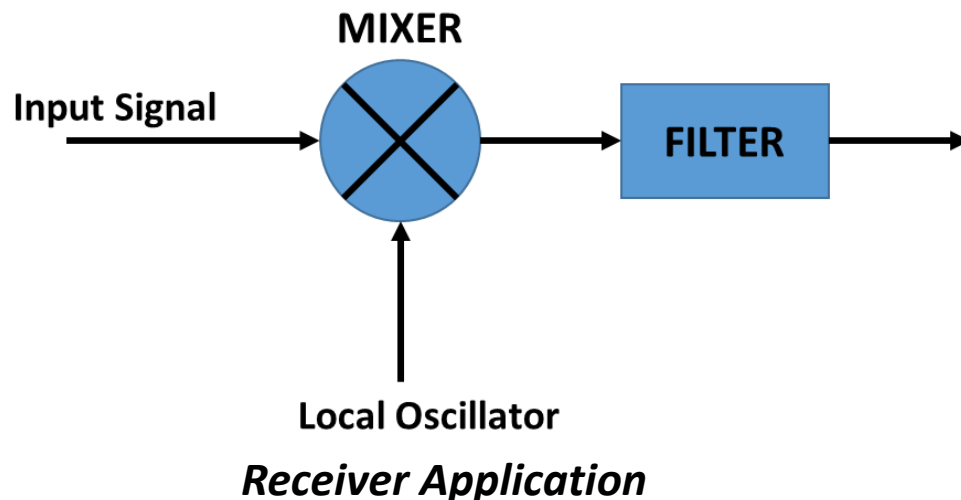
- ☐ Cover some general filter theory
- ☐ Apply this theory to an amateur radio need – SO2R (Single Operator 2 Radios)
- ☐ Conclude in ~ 20 minutes

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

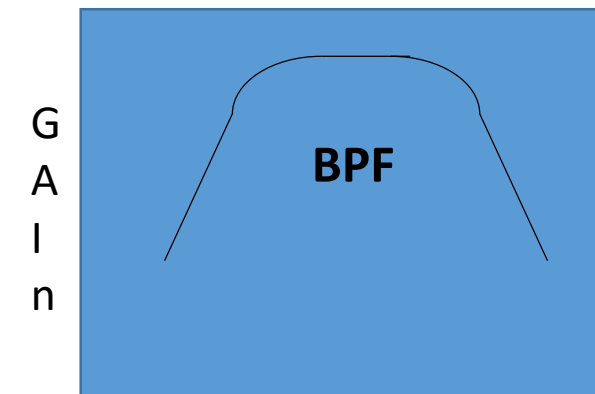
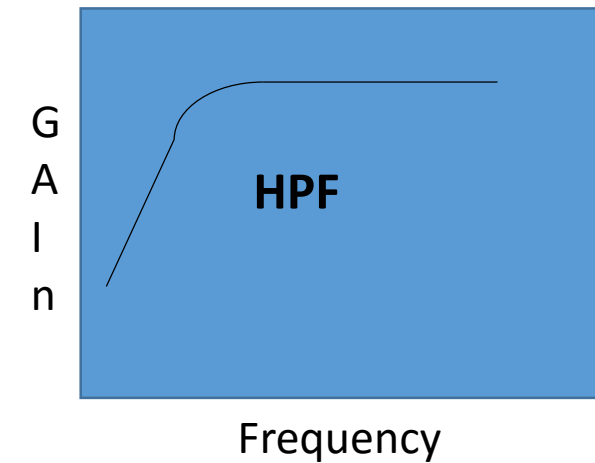
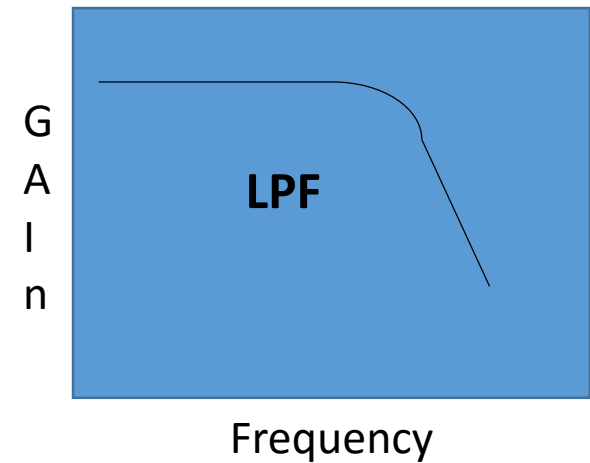
What Do We Need Filters For?

- 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



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

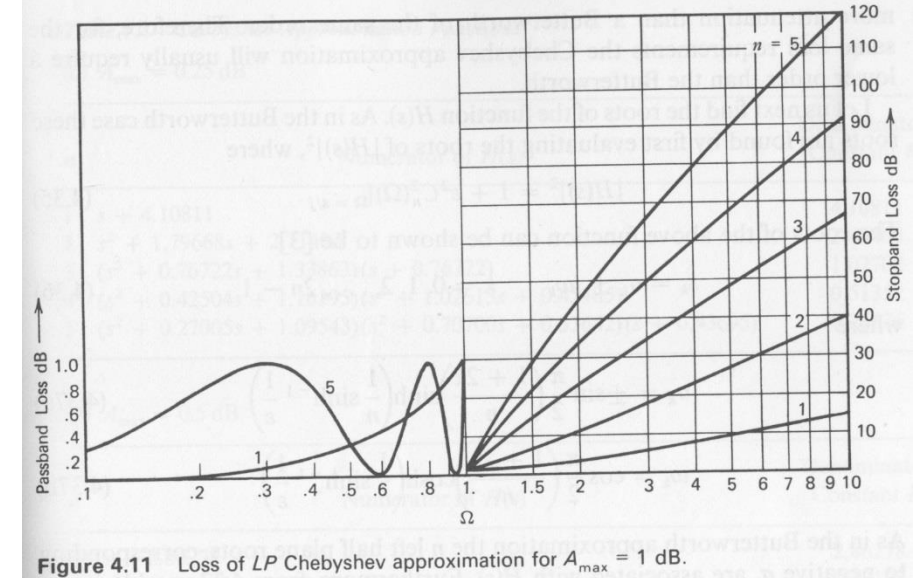
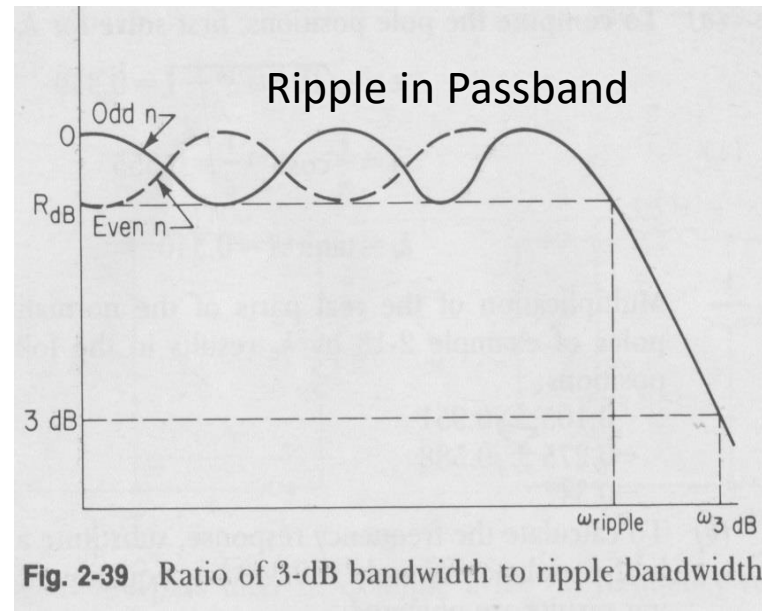
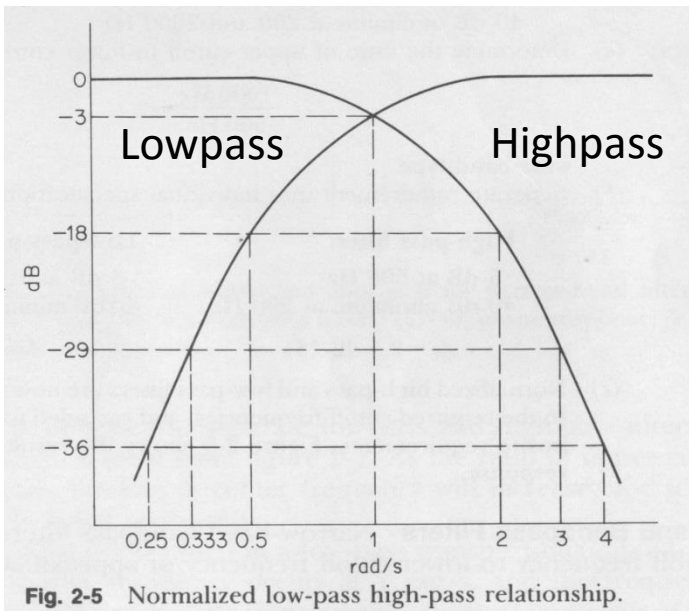
- Different “filter families” offer different characteristics
 - “zero ripple” in the passband (Butterworth)
 - “defined ripple” in the passband (Chebyshev, Elliptic)
 - Shallow or deep “filter skirts”

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

f' is “normalized frequency”

f_c is the LPF or HPF cutoff frequency

Increased Filter Complexity Gives Steeper “Skirts”

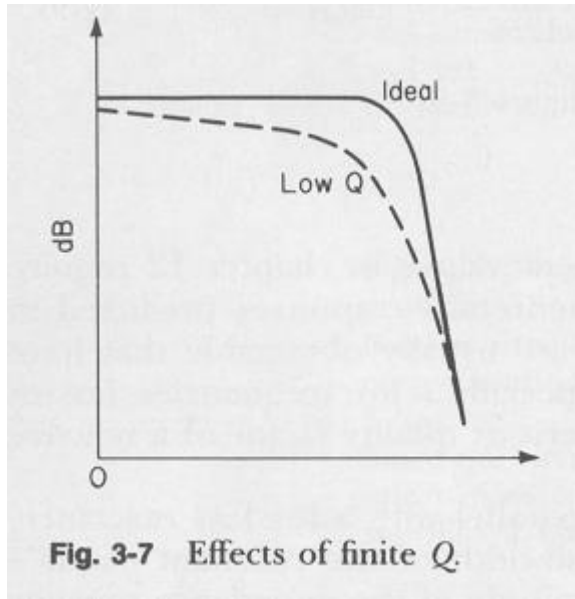


More Filter Considerations - 2

- 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.

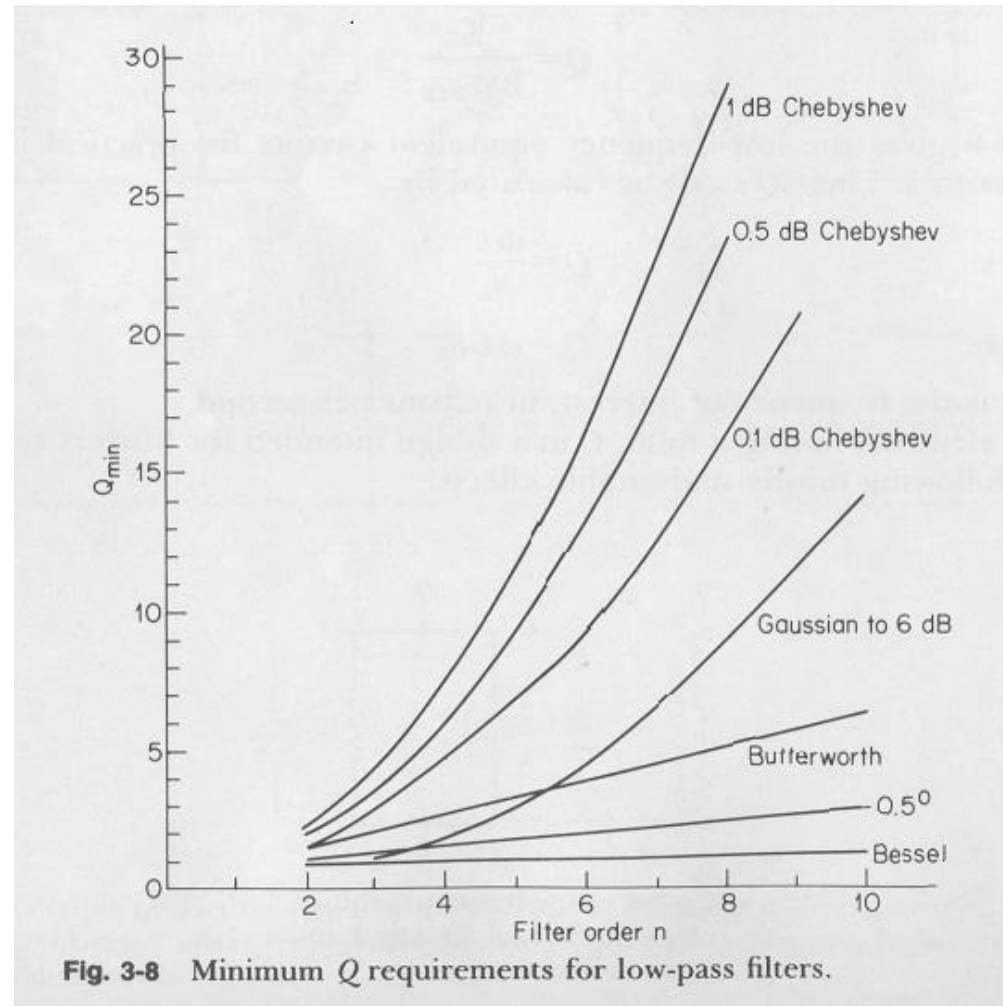
* Minimum “Q” value discussed next page

How Q Enters In



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

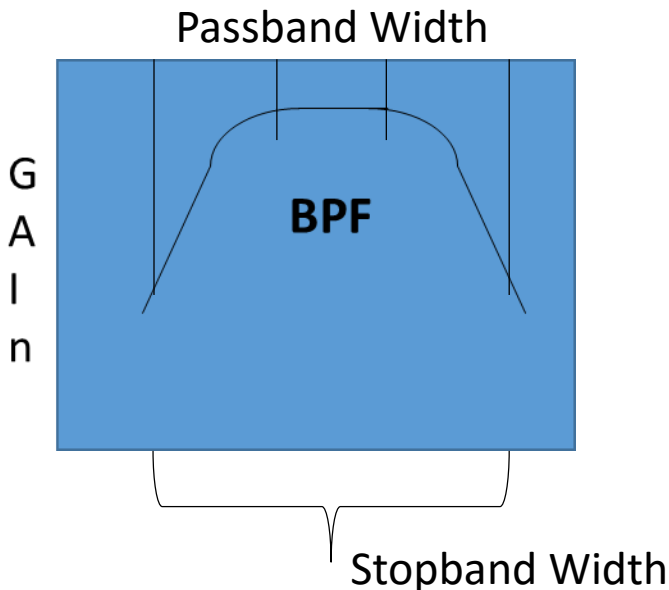
- LPF and HPF were just shown to require a certain minimum Q value for each component
 - Inductors are the “problem” with Qs from 20 to perhaps 200, while capacitors have Q values of 3,000 – 5,000 or more; higher Q is better
- The Q of components in BPF may need to be considerably higher

Minimum Q for BPF is:

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

Punchline: BPFs are more challenging than LPFs or HPFs

FYI With an Input of 1,500 Watts, 0.3 dB loss means **100 Watts** 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

Topology

- ☐ Capacitor-input lowpass
- ☐ Inductor-input lowpass
- ☐ Nodal capacitor-coupled bandpass
- ☐ Nodal inductor-coupled bandpass
- ☐ Shunt-input bandpass
- ☐ Series-input bandpass
- ☐ Mesh capacitor-coupled bandpass
- ☒ Cauer-only bandpass
- ☐ Capacitor-input highpass
- ☐ Inductor-input highpass
- ☐ Series-input bandstop
- ☐ Shunt-input bandstop



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Dimensions

- ☐ cm
- ☒ in

Add title to printout

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Entry assistance

Family

- ☐ Butterworth
- ☐ Chebyshev
- ☒ Cauer
- ☐ Bessel
- ☐ Gaussian
- ☐ Constant-K
- ☐ M-derived

?

See normalized values

- ☐ Manual entry

Cauer even terms.

- ☒ Best selectivity
- ☐ Equal terms.

Cauer BPF topology

- ☒ Normal
- ☐ Zig-zag

Ripple

Bandwidth (Hz) (Fc)

1.5M

Center frequency (Fo)

7M

Order (N) [7 max]

3

Input termination (Rs)

50

Passband ripple (Ap)

0.01995

VSWR: 1.1452 Return: -23.388 dB

LP prototype

Stopband width (Fs)

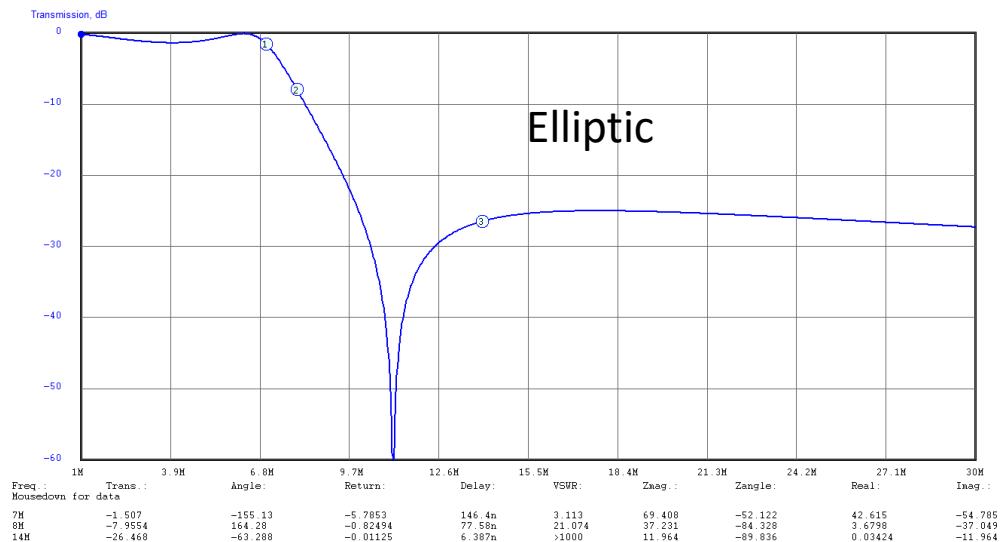
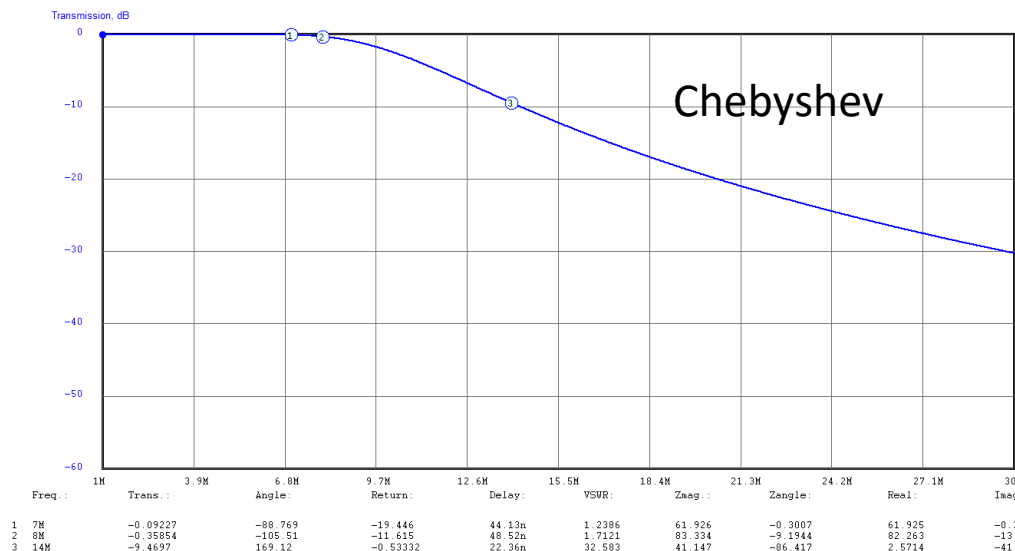
10M

Stopband depth (dB) (As)

50

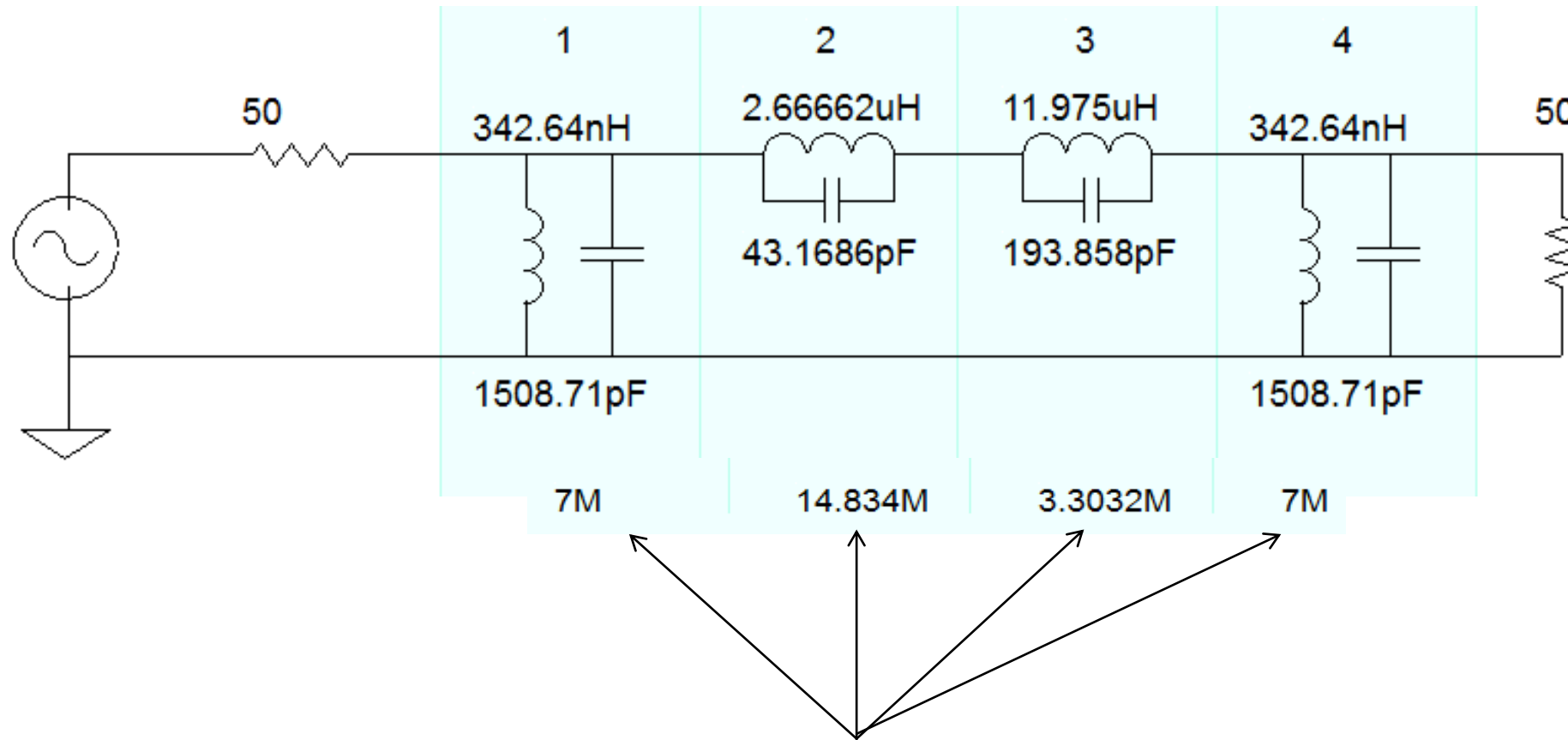
Why an Elliptic Filter Rather Than Chebyshev?

- 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



Elliptic BPF for 7 MHz by ELSIE

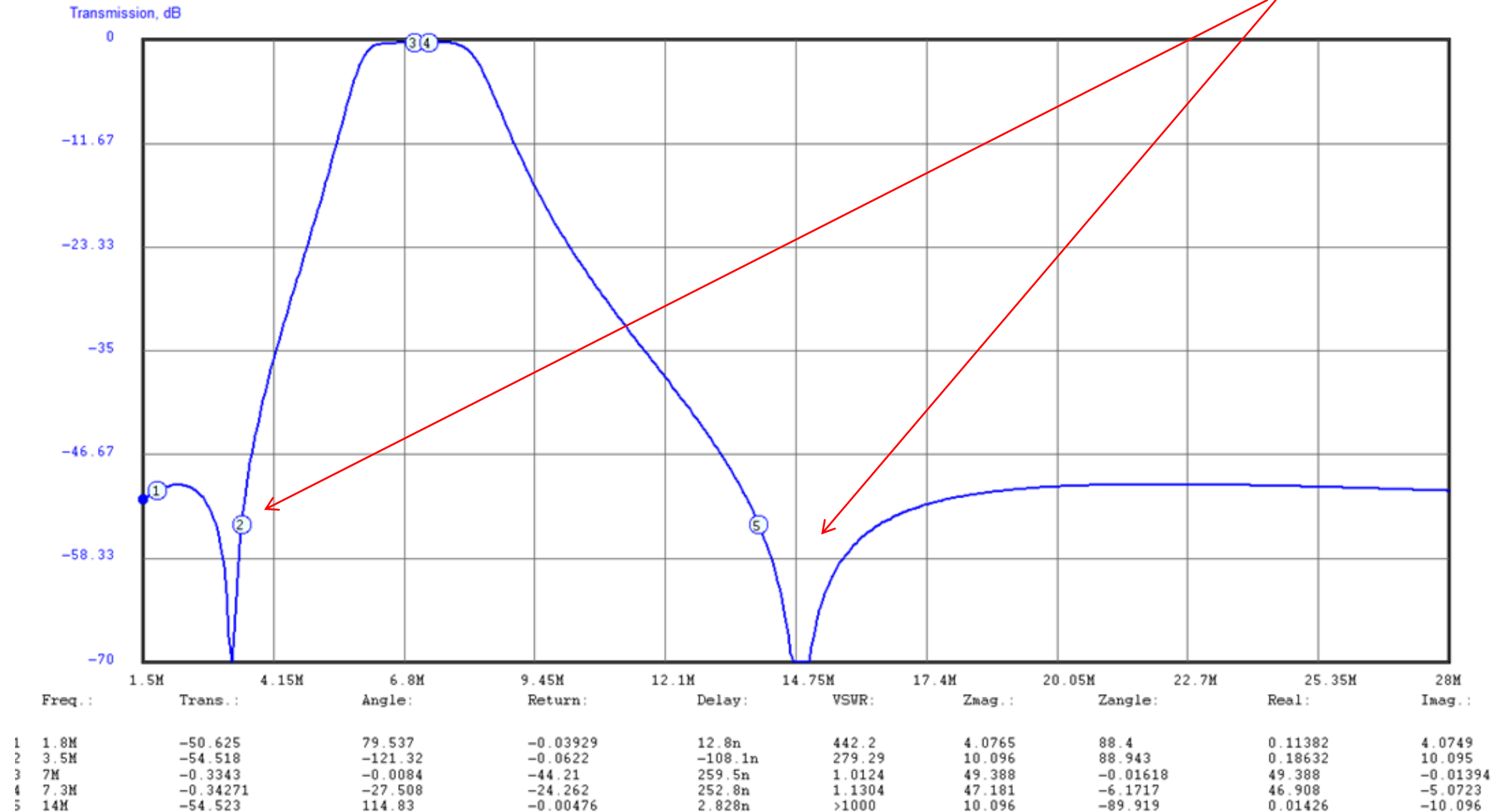
Standard Schematic Output from ELSIE



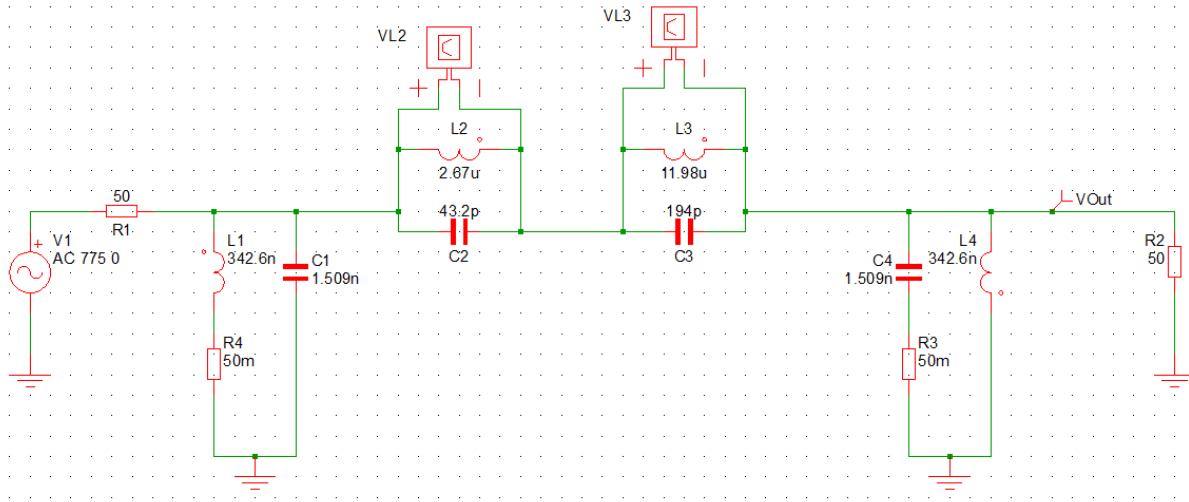
Each LC Section has a specific resonant frequency – Can be very useful in tuning up the filter

Filter Response from ELSIE "Plot"

Some Latitude in Placing These Notches for Greatest Attenuation



SPICE Analysis of ELSIE BPF Design - 1,500 Watts

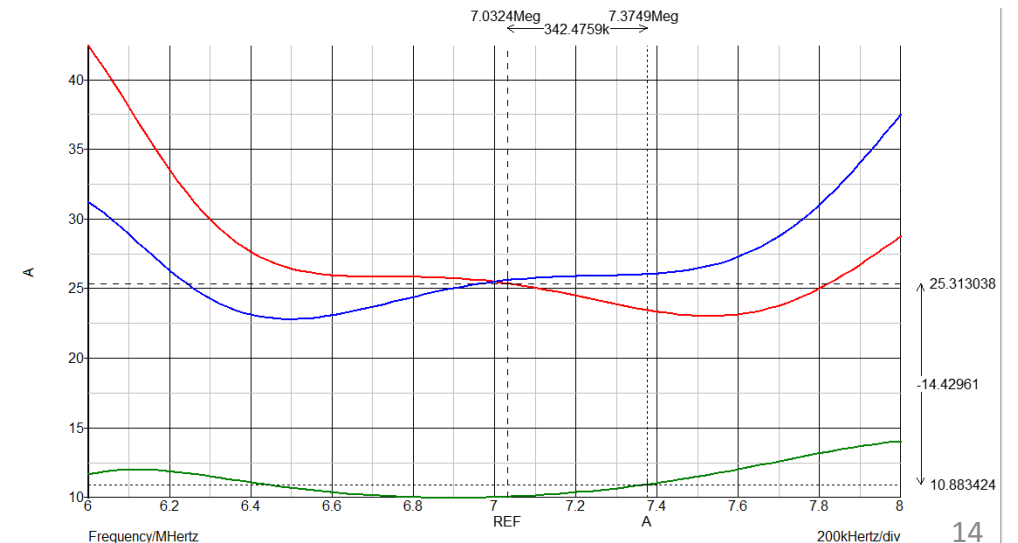
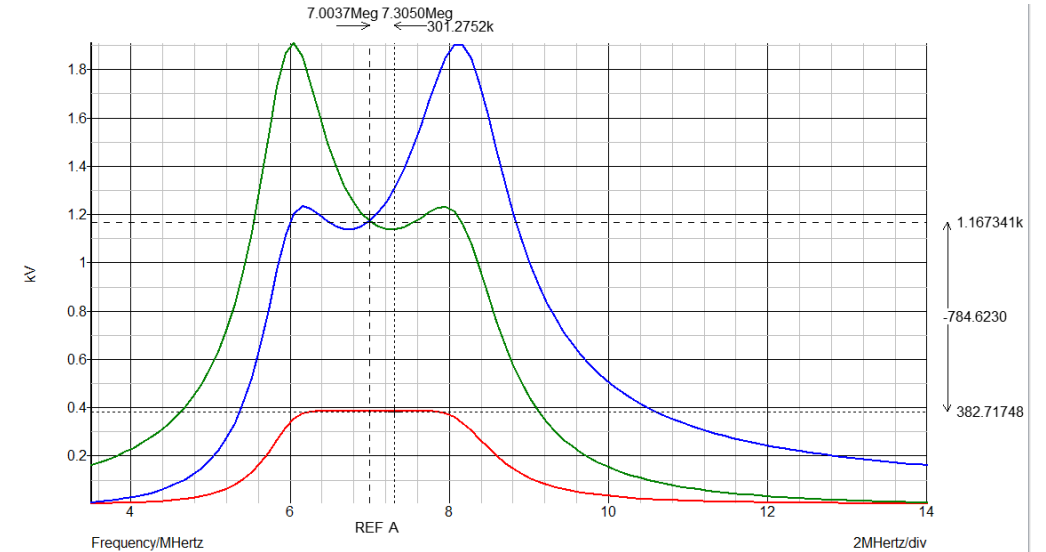


In-band capacitor voltages around 1.3 kV

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

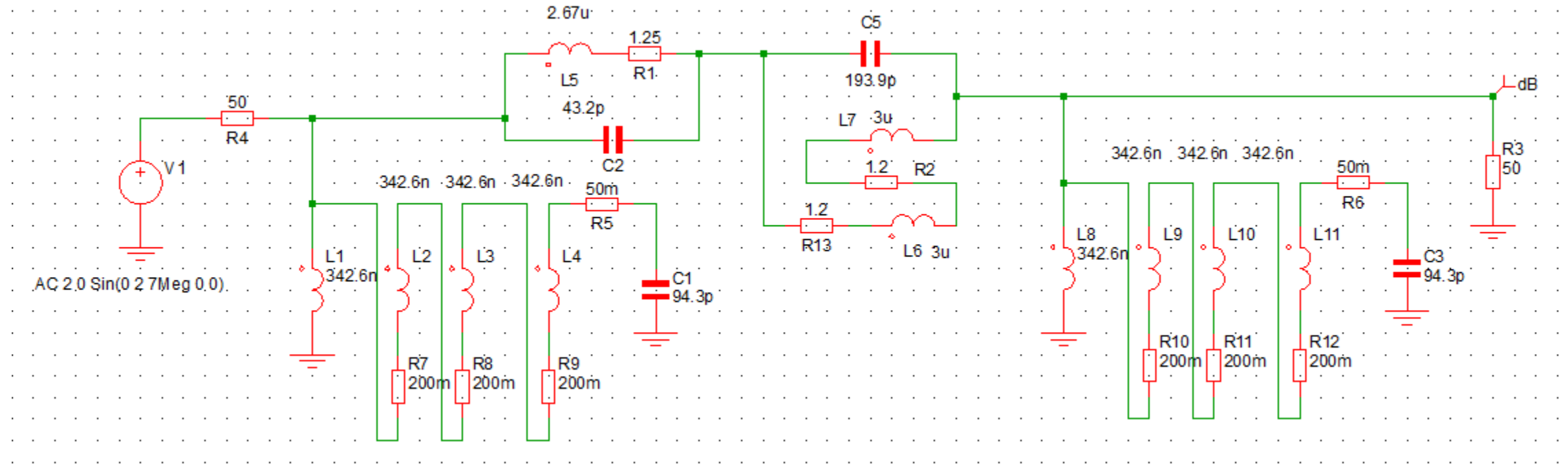
All is not lost – use different impedance levels in the high-current resonators – see Next page



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

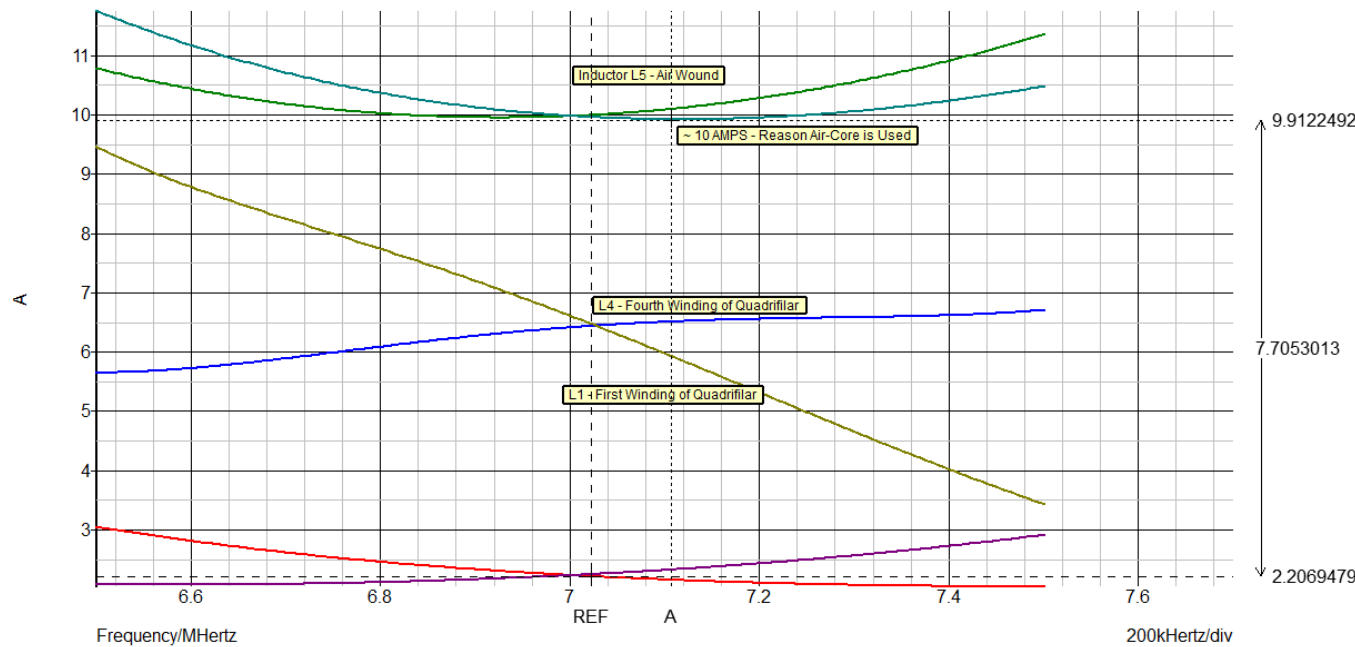
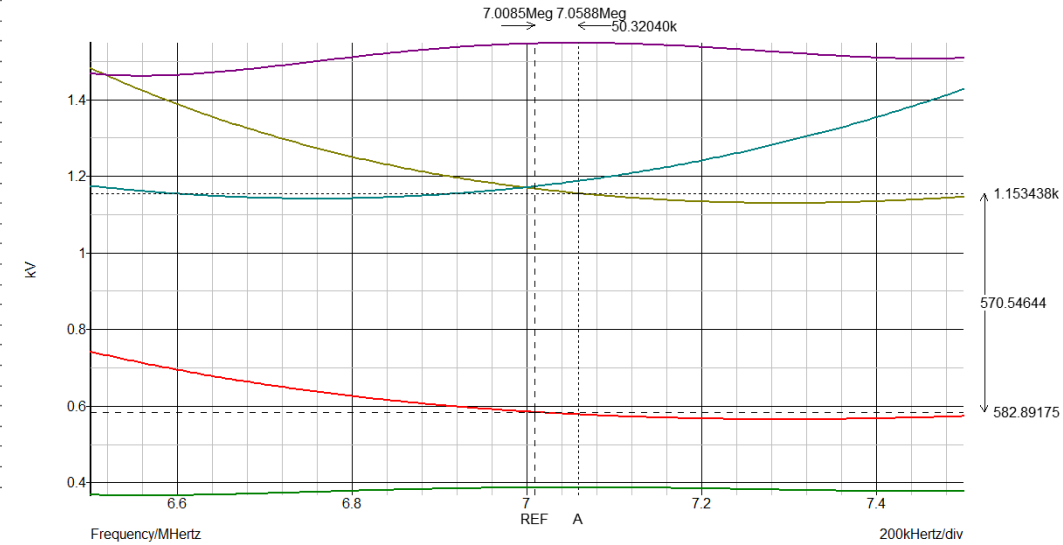
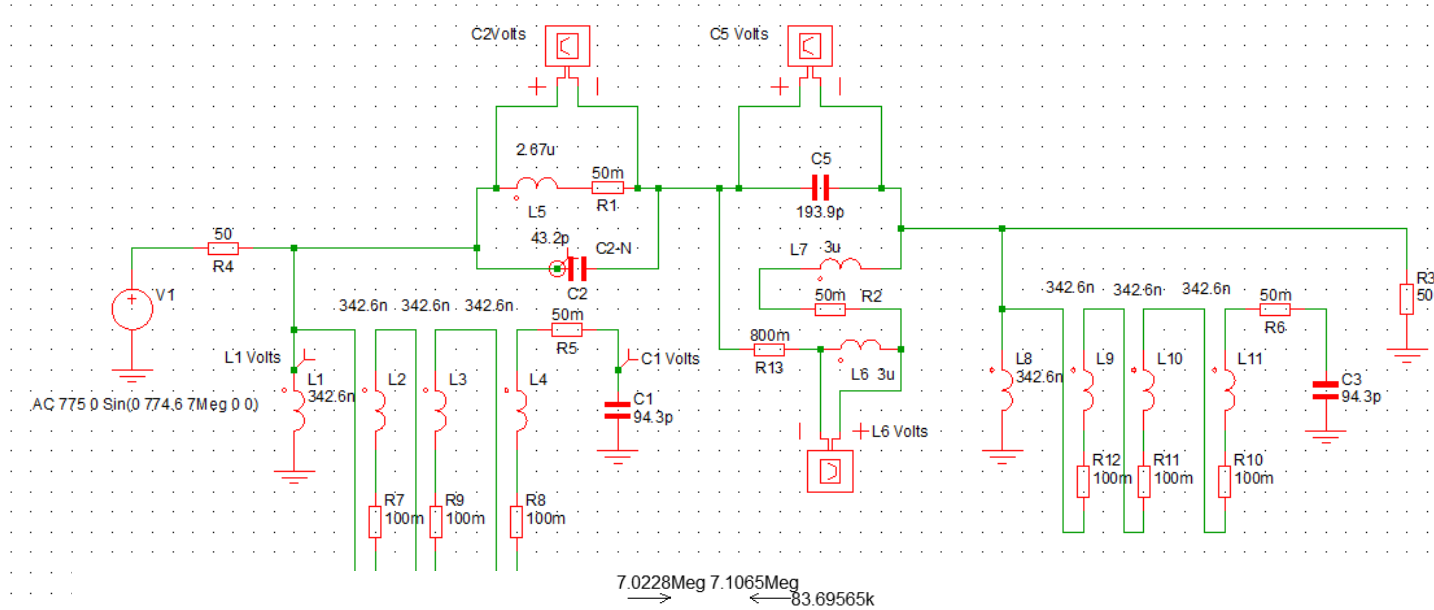


The resistors give the inductors “real-world” values of Q rather than “infinite”, perfect Q

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

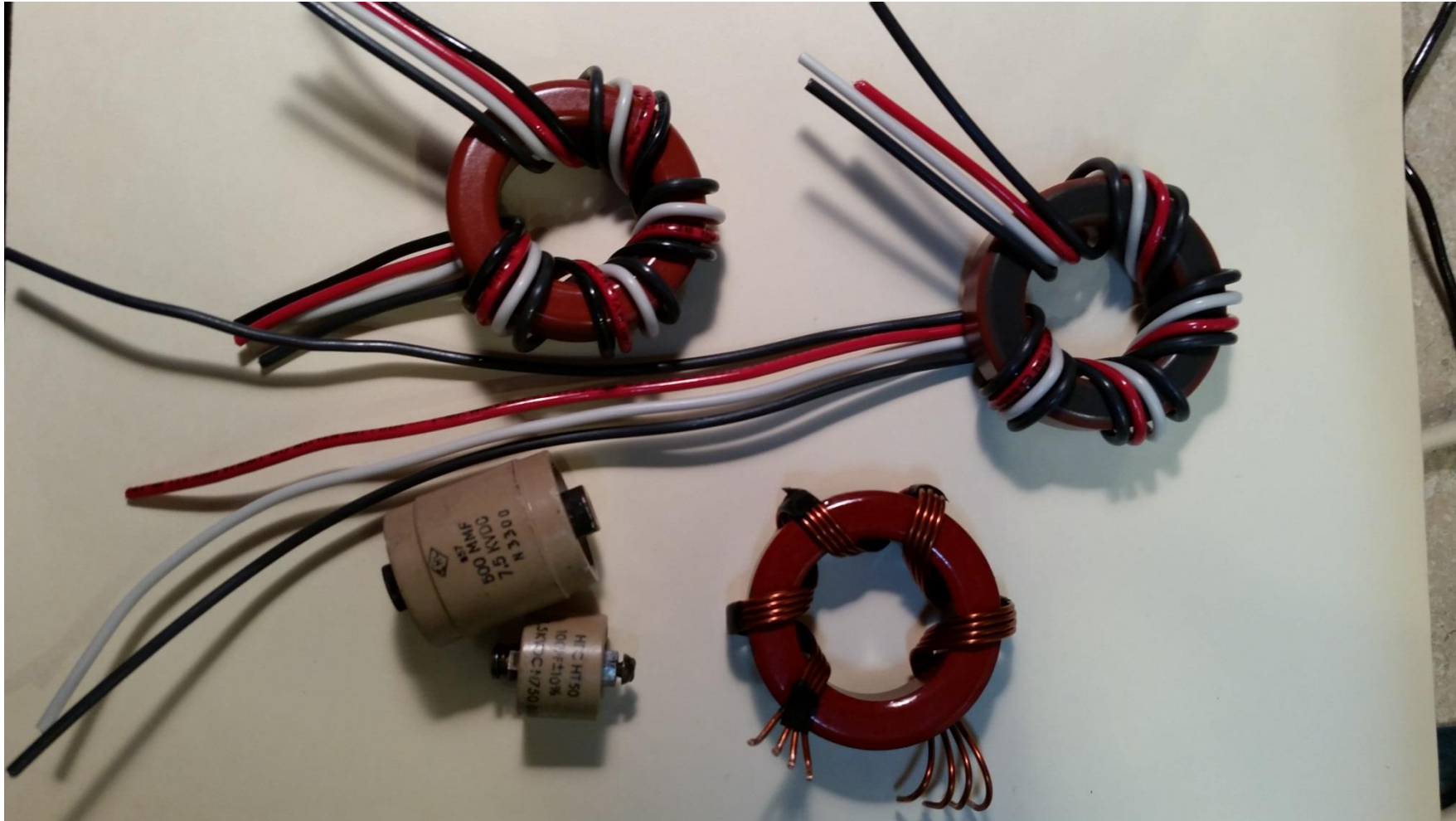
Phase winding details are discussed in Radio Amateur’s Handbook and other places

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

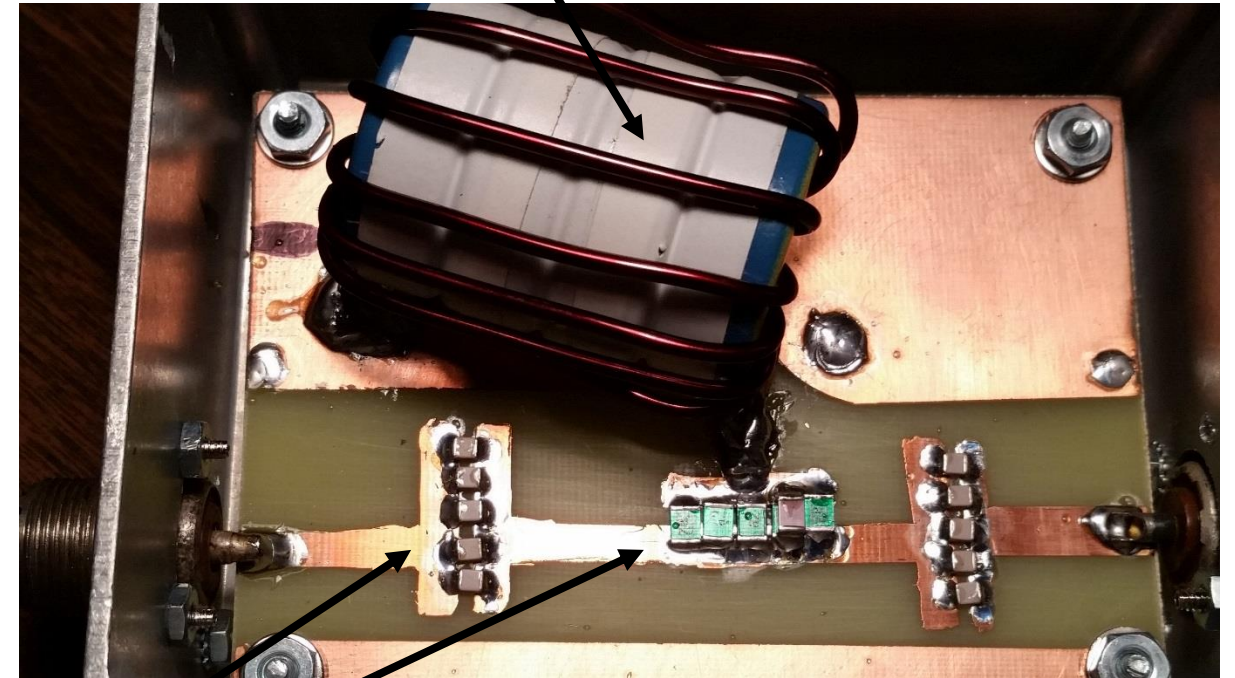


Highpass Filter for 7 MHz



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.

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*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

$$\rho = \frac{VSWR - 1}{VSWR + 1}$$

$$\rho = \sqrt{\frac{\mathcal{E}^2}{1 + \mathcal{E}^2}}$$

$$R_{dB} = -10 \log_{10} (1 + \rho^2)$$

R_{dB} = Return Loss, in dB

\mathcal{E} 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