6-Meter Filter with Harmonic Suppression

Paul Wade W1GHZ ©2015

w1ghz@arrl.net

I have developed an allergy to high voltage, so I have decided to switch to solid-state power amplifiers. For six meters, I had acquired an old MRI amplifier that I was modifying. It is rated for 2000 watts peak power, and I had seen 1200 watts output key down. Then I shorted something, and damaged the control circuitry.

While waiting for replacement parts, I started thinking about a filter for the output – the amplifier covers roughly 10 to 80 MHz, so it probably can generate strong harmonics. I particularly wanted to suppress the second harmonic, right in the middle of the FM band. The third harmonic, at 150 MHz, could also clobber my wife's EMT handy-talky and pager. Since I had a few days, I started to make a filter, using what I had on hand.

You probably aren't going to copy this filter – you might already have one, or maybe don't need one. So I am going to describe the process: the design, adjusting the design to available parts, construction, and tuning. Perhaps you might learn something to help with your next project, including some things that the books don't tell you.

Design

The first step in any design is to define the requirements. The basic requirement is to pass 50 MHz with low loss and reject frequencies out of band, particularly harmonics of 50 MHz, and to handle high power, up to1500 watts. Frequencies other than harmonics are better filtered out before the amplifier, at low power level, so that we don't waste power amplifying them and generating more spurs.

Today, the next step is to search on the internet. W7GJ[1] has a good 6-Meter web page showing some good options for low-pass filters. One by K1WHS has good performance, and another by N6CA[2] has good performance and terminates the harmonics as well. Another choice is a stub filter, with a good description provided by G4SWX[3]; I think stubs would be a great choice for two meters and up, but the stubs are a bit long at six meters.

Since my goal was to do it with parts on hand if possible, so that I could get it done before starting something else, none of these choices fit the bill. The next step is to play with software and try some alternatives. For filters, I use **Ansoft Designer SV** (Student Version), which used to be free but is no longer available. Fortunately, it may still be found on the internet[4,5]. It includes a "Filter Wizard" which is useful for quickly finding a starting point. Then you can fiddle the component values to your satisfaction.

The basic filter circuit is the one used by all the above low-pass filters:

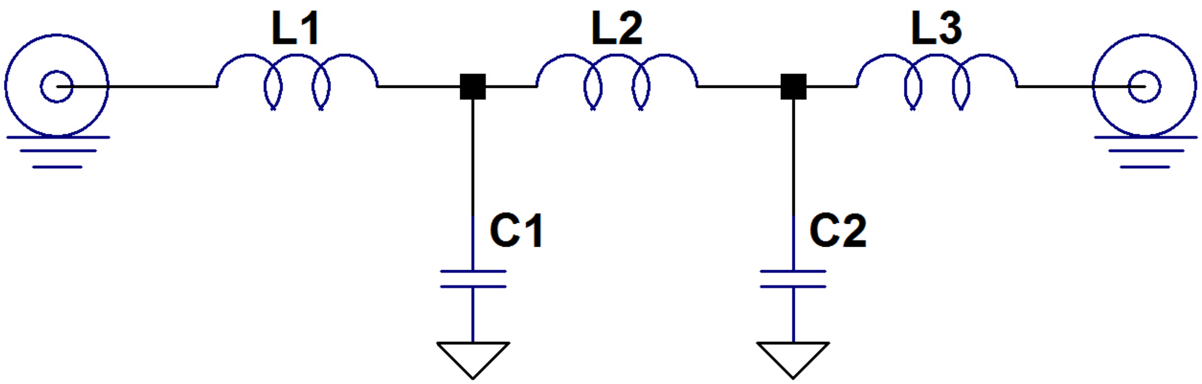


Figure 1 – Schematic of Generic Low-pass Filter

Inductor and capacitor values are chosen for the desired response characteristics: a Butterworth, or maximally-flat, response is very smooth, while a Chebyshev response has a sharper cutoff but has ripples in the passband.

I have a 6-meter filter made by K1DPP (SK), shown in Figure 2, which appears to have been designed for something close to a Butterworth response. The measured performance in Figure 3 is very similar to the Butterworth response calculated by the Filter Wizard in **Ansoft Designer SV**. This filter is not very good at harmonic reduction, since the second harmonic, at 100 MHz, is only about 14 dB down.

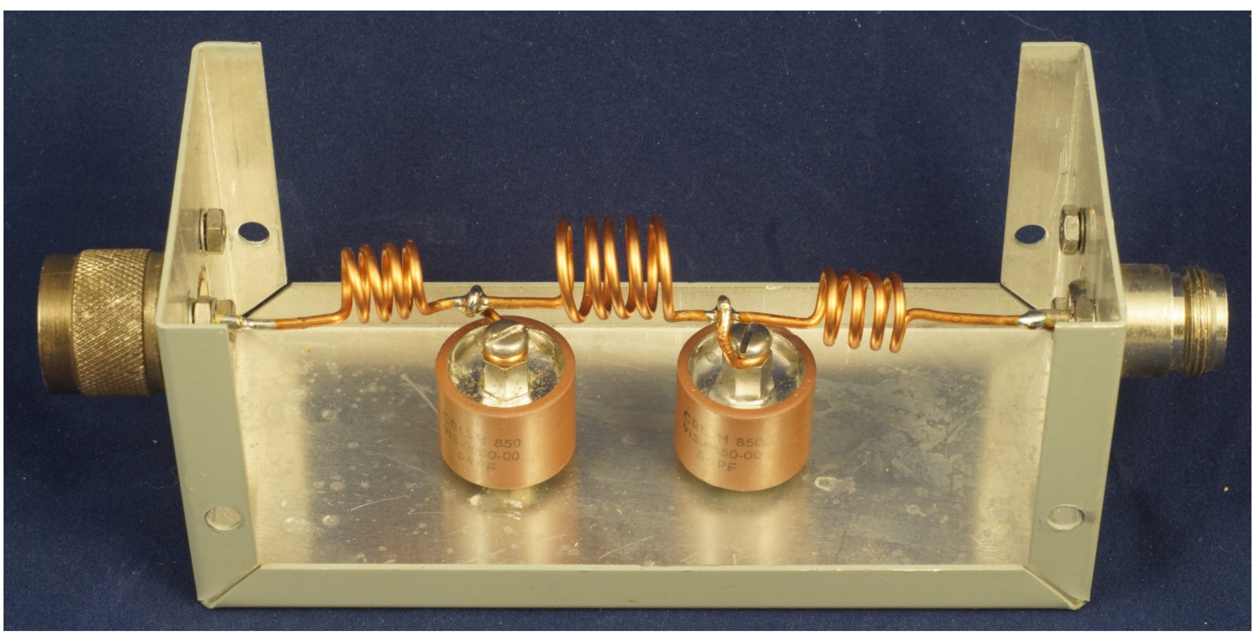


Figure 2 – 6 Meter Low-pass Filter made by K1DPP

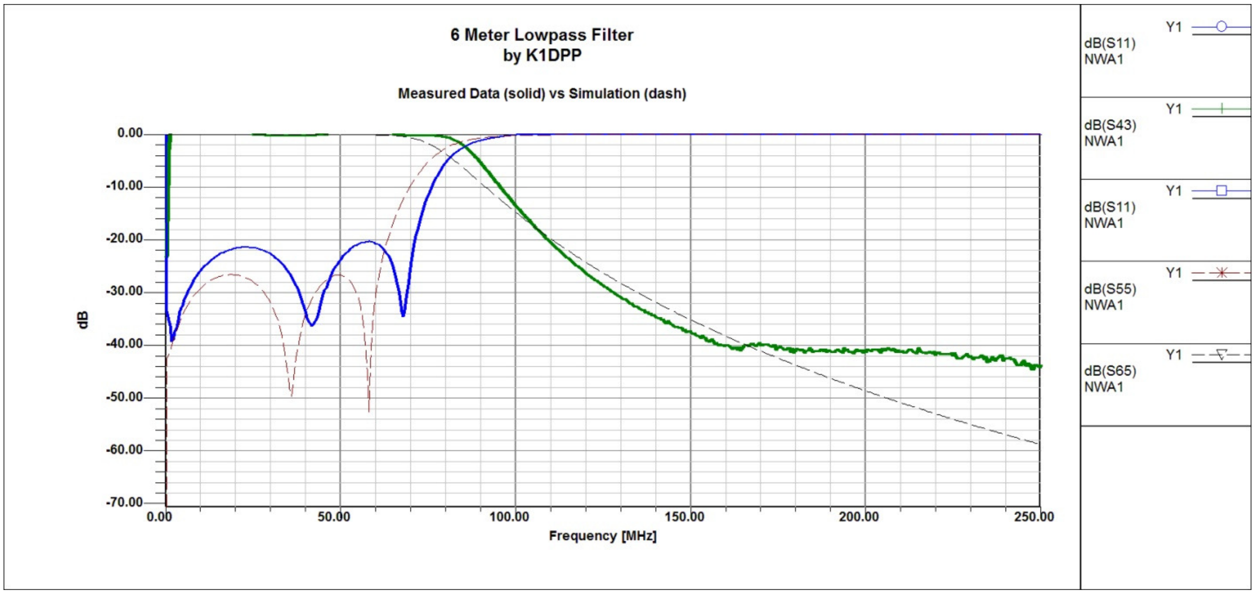


Figure 3 – Measured data and simulated response of filter in Figure 2

The K1WHS low-pass filter is shown in Figure 4 (photo courtesy of W7GJ website). This filter adds some shielding between the coils, to reduce coupling and leakthrough. Dave gives inductor physical dimensions rather than inductance, so I used inductances suggested by YU7EF for simulation, shown in Figure 5. This is pretty clearly a Chebyshev response, with almost 2 dB of ripple in the passband, and a steeper cutoff, so the second harmonic is about 32 dB down and higher harmonics more than 50 dB down. The component values, Figure 6, have been tweaked for low loss and excellent return loss at 50 MHz – that's what counts.

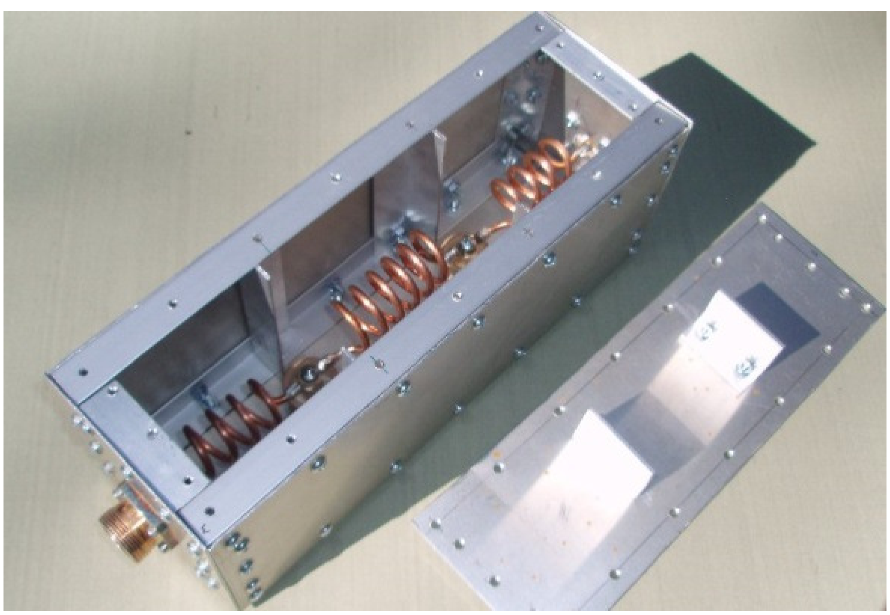
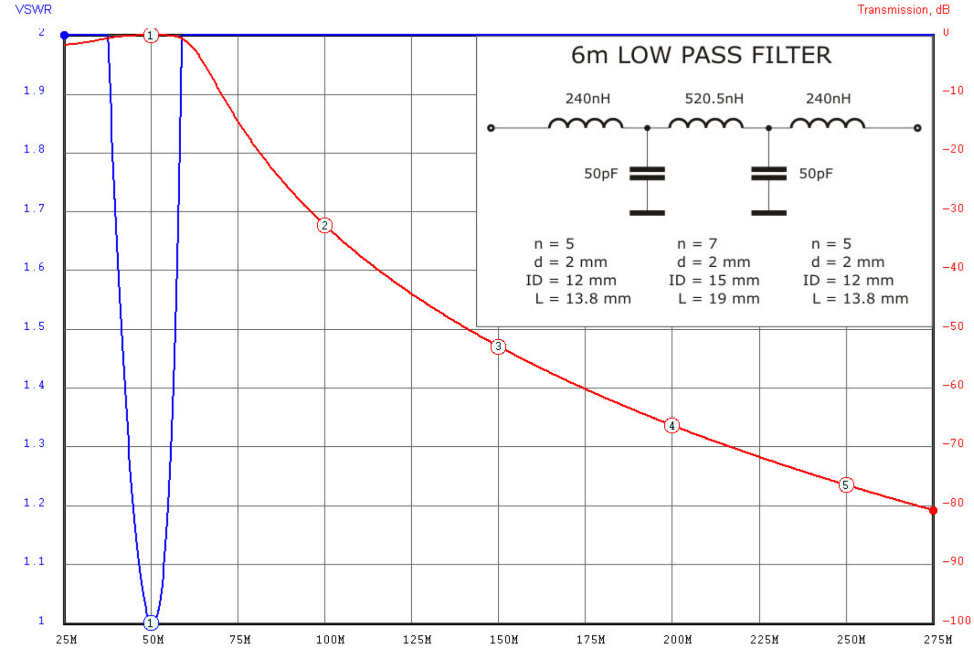


Figure 4 – 6 Meter Low-pass Filter made by K1WHS



	Freq.:	Trans.:	Angle:	Return:	Delay:	VSWR:	Zmag.:	Zangle:	Real:	Imag.:
1	50M	0.0000	153.53	-61.397	16.33n	1.0017	49.962	-0.08734	49.962	-0.07616
2	100M	-32.239	-43.007	-0.00259	2.002n	>1000	115.01	89.977	0.04699	115.01
3	150M	-52.847	-62.452	-0.00002	604.3p	>1000	203.96	90	0.00114	203.96
4	200M	-66.28	-70.117	0.0000	302.9p	>1000	285.27	90	0.00012	285.27
5	250M	-76.389	-74.36	0.0000	184.2p	>1000	364.05	90	0.0000	364.05

Figure 5 – Response of YU7EF version of K1WHS filter in Figure 4

The performance of this filter would probably be adequate, but I didn't have the appropriate capacitors on hand. I only had three of the nice doorknob ceramic capacitors: one each of 25, 40, and 50 pf. Returning to the Filter Wizard, I tried a filter version called "Chebyshev Type 1," which adds an inductor in series with each capacitor. I fiddled the component values until I got a decent response with available capacitors, the 25 and 50 pf. The circuit is shown in Figure 6, with the measured and simulated response in Figure 7. The response is tuned for enhanced harmonic suppression, with the second and third harmonics more than 60 dB down.

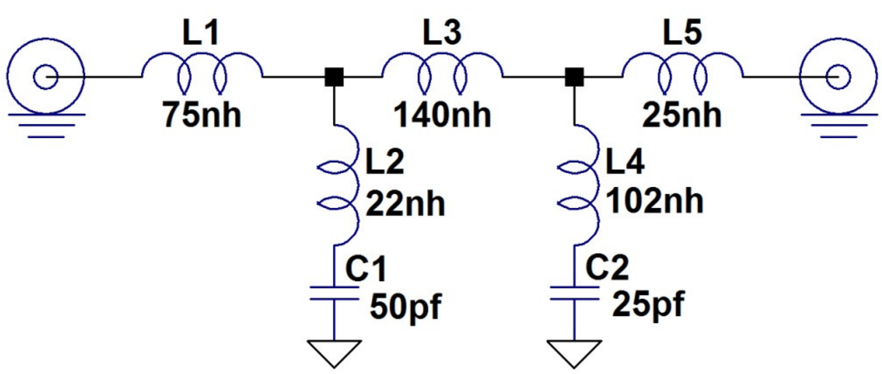


Figure 6 – Schematic diagram of W1GHZ 6-meter filter with harmonic suppression

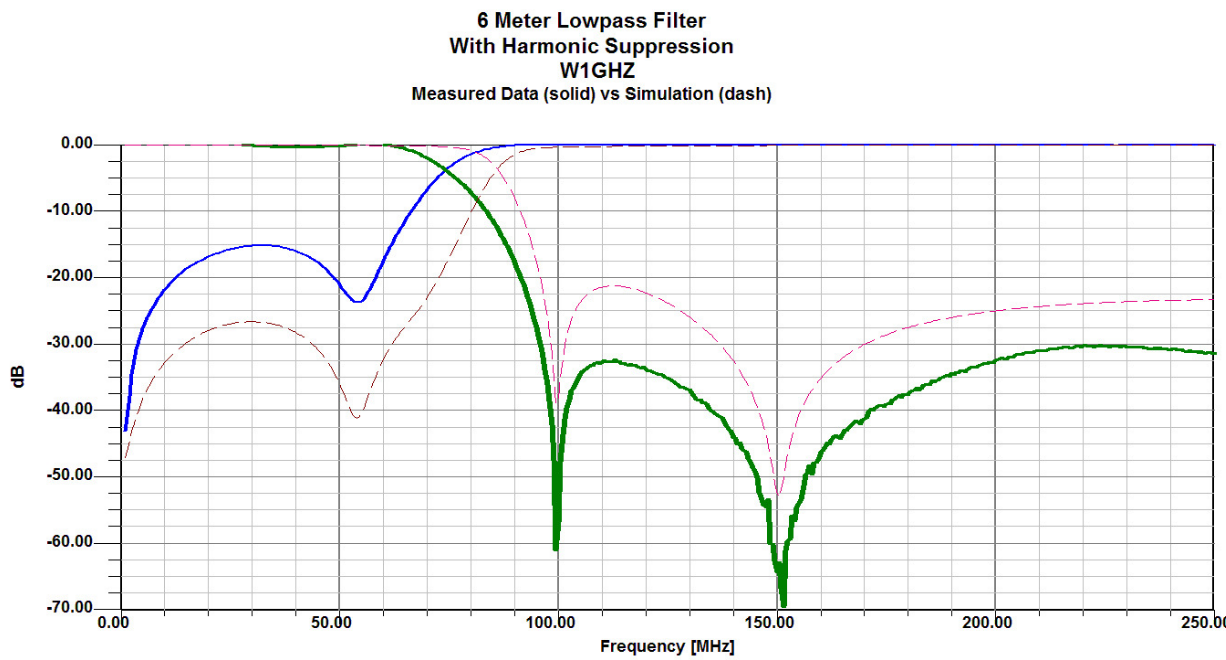


Figure 7 – Measured data and simulation of W1GHZ 6-meter filter with harmonic suppression

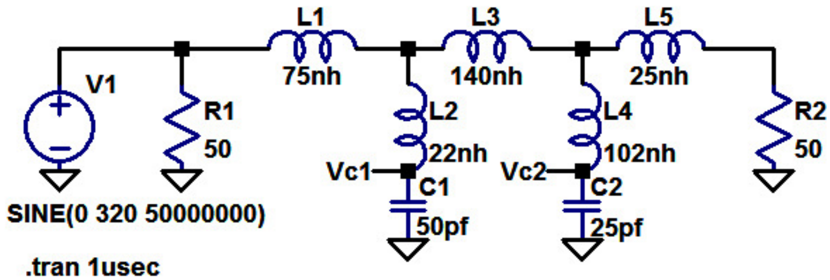
Understanding the Circuit

Adding the inductors L2 and L4 in series with the shunt capacitors in Figure 6 creates series-resonant circuits, similar to the stub filters, providing deep nulls at 100 and 150 MHz. The inductance values are manually changed and perforance simulated in the **Ansoft Designer SV** software for best performance. Keeping notes on the changes show that L2 is tuned to resonate with C1 at 100 MHz, while L4 is tuned to resonate with C2 at 150 MHz. The other inductances are then tuned for best Return Loss or VSWR, with L5 tuned last to provide the dip in Return Loss at 50 MHz. If I had different capacitors available, similar performance could be achieved using different inductances – I did try the 40 pf capacitor, but the combination shown seemed to give best results.

It might also be possible to add a third null at the third harmonic, 200 MHz, if a smaller capacitance were available. A coax stub might be small enough at this frequency, and the software can easily include coax or other transmission lines in the circuit, so you can play with them as well.

Power Handling

A quick calculation with Ohm's Law shows that 1 Kilowatt at 50 ohms is about 320 volts peak and about 4.5 amps peak. We can simulate voltages and currents in each component by analyzing the circuit from Figure 6 using the free **LTspice** software[6] to show that the current in the capacitors is about 6 amps peak and the capacitor voltage is about 400 volts peak – Figure 8 shows the waveforms for C1. The voltage and current in the capacitor are 90° out of phase, so the current is zero when the voltage is maximum and vice-versa. Thus the power is purely reactive and no power is dissipated in a perfect capacitor. But if the capacitor is not capable of handling the current, it will act as a fuse and fail.



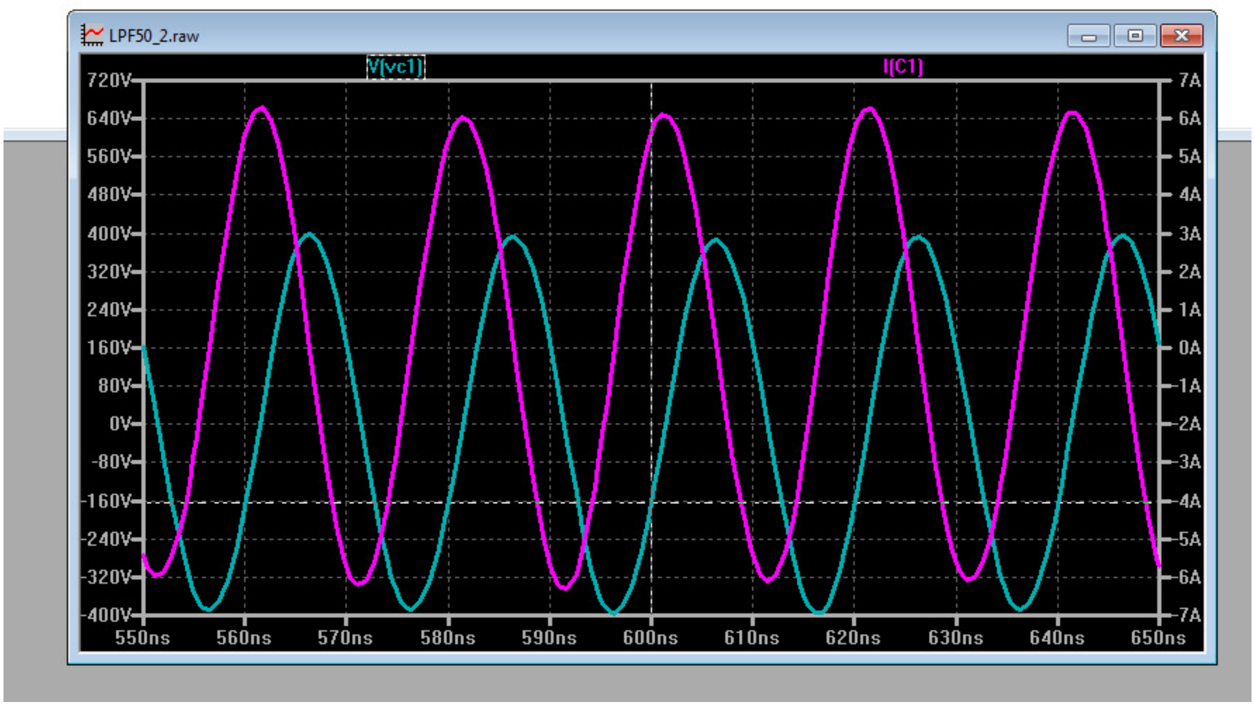


Figure 8 – Voltage and Current in Capacitor C1 at 1 Kilowatt power

We can also add harmonics – Figure 9 shows an **LTspice** simulation with both second and third harmonics 20 dB down. The output power and current are unchanged, but the peak capacitor current is about 7 amps with the harmonics. And if we simulate the current with an open circuit output, no antenna, or a short circuit, the peak current increases to about 10 amps, and the peak voltage to about 700 volts. At legal limit power, the voltages and currents are 22% higher, or over 12 amps.

The ceramic doorknob capacitors are rated 5 KV or more, so the voltages are not a problem. However, the current ratings are just barely enough – the smaller HT50/850 series are rated for 7 to 10 amps at 30 MHz, depending on capacitance. The larger HT57/857 series are rated for 10 to 13 amps, so they should be fine. Fortunately, the caps I had were all the 857 size, capable of handling 1.5 KW in this circuit.

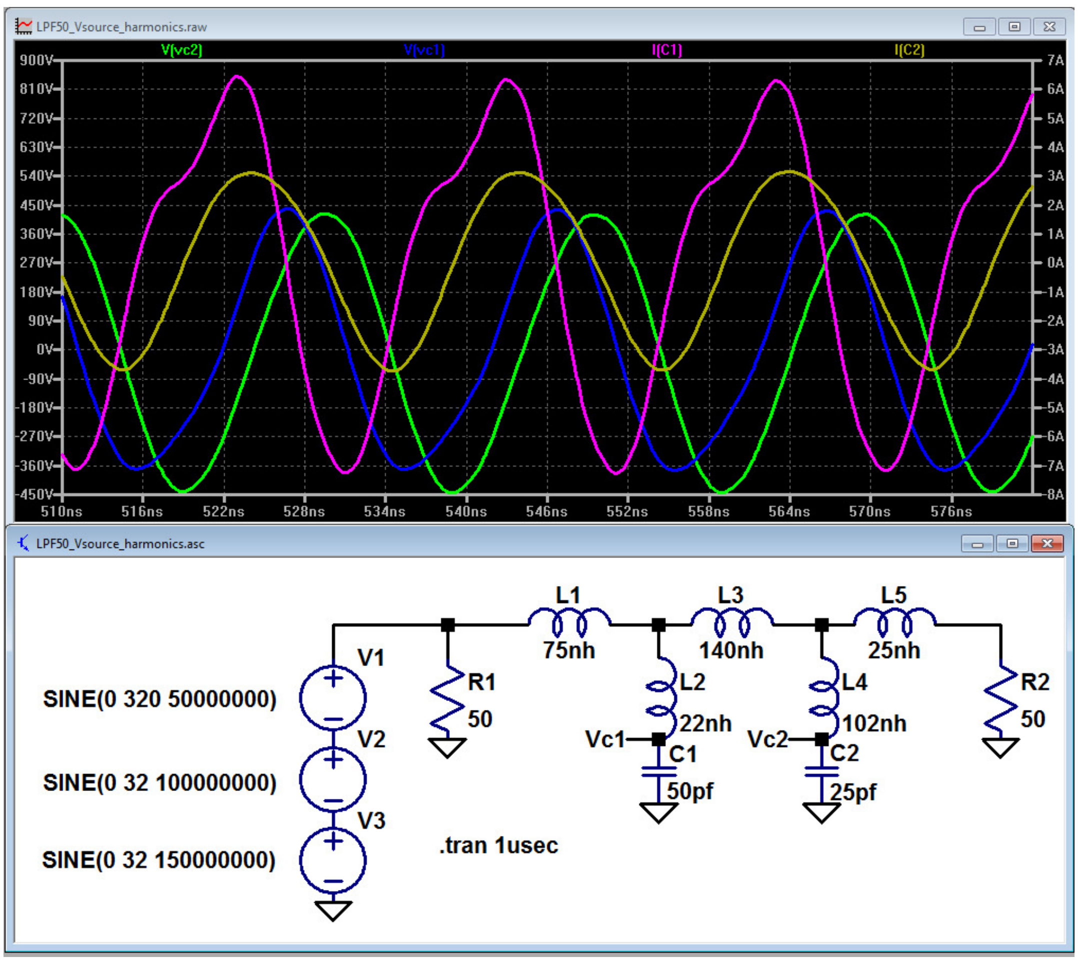


Figure 9 – Voltages and currents in capacitors at 1 KW with harmonics 20 dB down

Inductors

For the inductors, I used scrap ends of #12 AWG copper wire from wiring my house, which should be adequate for peak current 10 Amps. I wound coils on a piece of ½ inch drill rod, so the coils are ½ inch inner diameter – this felt like a reasonable size to provide good Q.

I measured coil inductance with my old “grid-dip” meter, as shown in Figure 10; the 50 year old meter is actually transistorized. The coils were resonated with a 100 pf mica capacitor, so that resonant frequencies were in the 30 to 70 MHz range. For the single-turn inductor, needed for the 22 nh inductance, the mica capacitor leads would add too much inductance, so I soldered a chip capacitor between the ends of the coil. The resonance technique has two advantages: measurements are made near the operating frequency, and it provides a feel for the spacing required to reduce coupling between coils, especially when the coils are inline like Figure 2.

If you don’t have a grid-dip meter, a similar technique could be used with a network analyzer or antenna analyzer – couple a coil loosely to the resonant circuit and look for the frequency where the response shows a dip or other discontinuity.

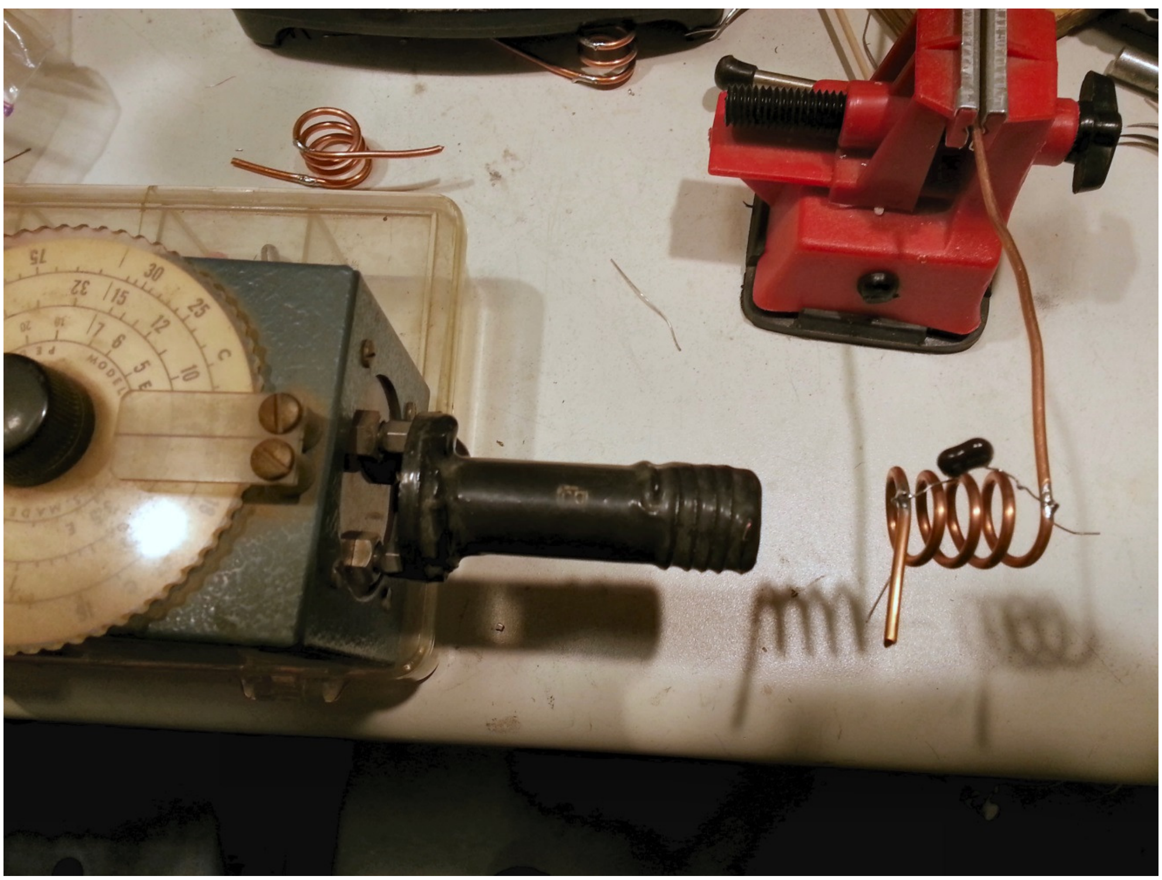


Figure 10 – Measuring coil inductance with grid-dip meter

Measured inductance is shown in Figure 11 for coils spaced roughly one wire diameter – the coil in Figure 9 has been stretched to roughly two wire diameter spacing, which decreases inductance by 15 to 20%. Squeezing the turns together increases the inductance by perhaps 5%. Stretching and squeezing the coils allows us to fine-tune the inductance after assembly.

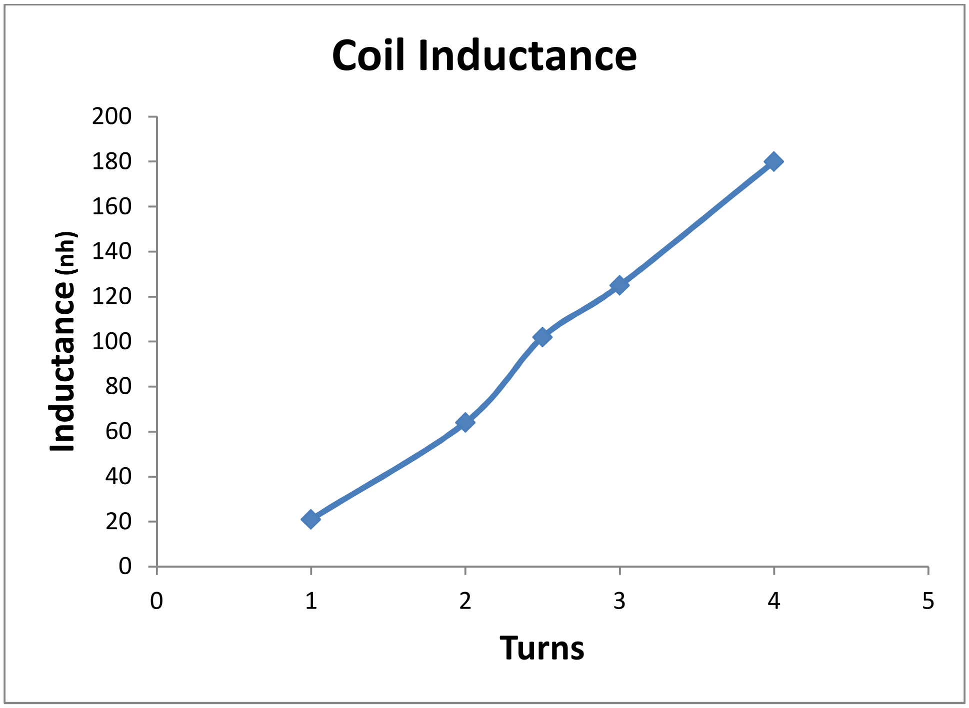


Figure 11 – Measured inductance of 0.5 inch i.d. coils of #12 AWG wire spaced one wire diameter

Construction

I didn't have a convenient metal box for inline construction like Figures 2 and 4, and I didn't want to do the metal work to add shielding between inline coils like Figure 4. Instead, I chose the square die-cast aluminum box shown in Figure 11, and tried to orient the coils for minimum coupling to minimize leakthru. The coils are shown after tune-up – the coil (L4) in series with the 25 pf cap has been stretched to resonate at 100 MHz.

The junction points for the inductors are supported on ceramic standoffs.

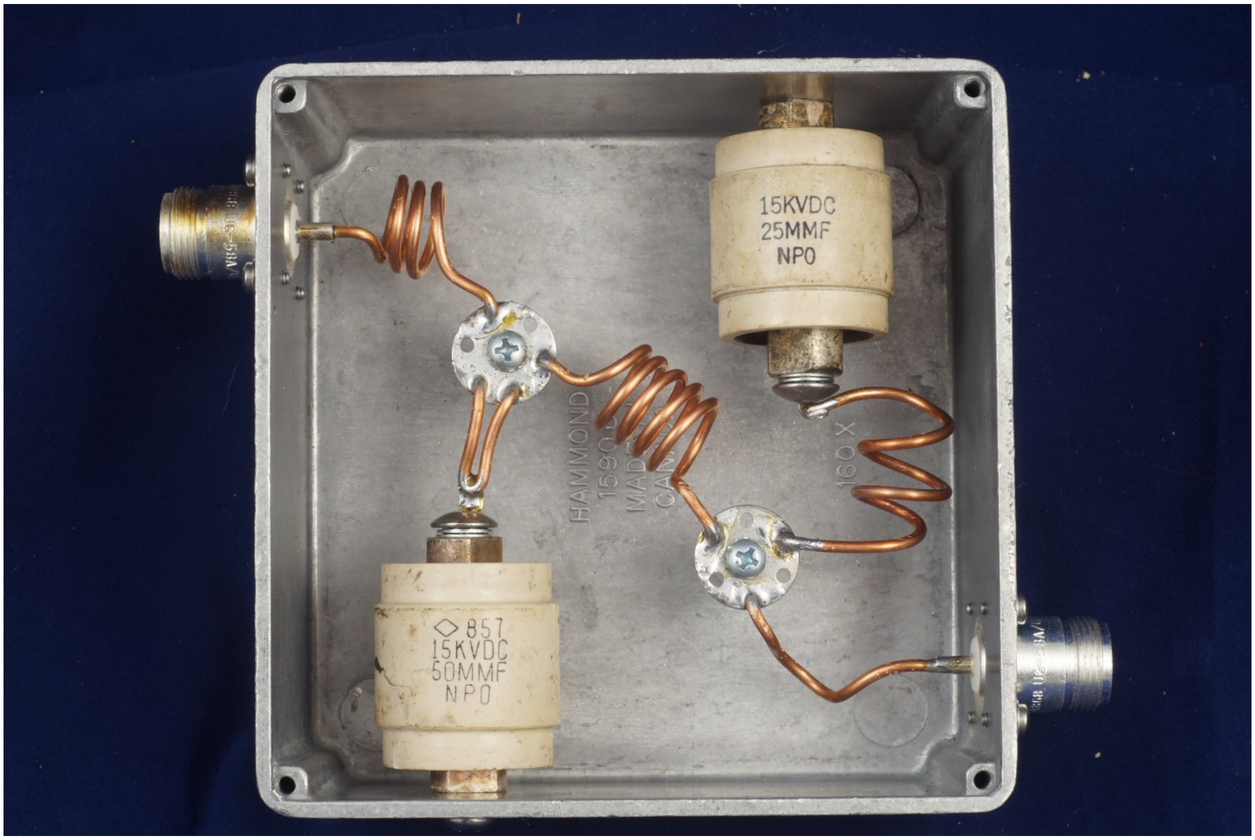


Figure 12 – Finished 6-Meter Filter with good harmonic suppression

Tuning

The inductors were chosen using the chart in Figure 11 to provide the inductance values in Figure 6. The initial test showed nulls at 89 and 110 MHz rather than the desired 100 and 150 MHz. Obviously, I hadn't accounted for the inductance of the doorknob capacitors, but now I could estimate it as 10 to 15 nh and reduce the coils accordingly. Since the desired inductance of L2 is 22 nh, most of it is in the capacitor. A single wire was still too much inductance, resonating at about 140 MHz, so I put two wires in parallel and squeezed them together to fine tune to 150 MHz. Then I stretched L4 to resonate at 100 MHz. Note that measurements must be made with the cover in place, since everything is affected by the cover.

At this point, the Return Loss curve wasn't very good, and it wasn't obvious which way to go with the other three inductors. I returned to the software and fiddled L1, L3, and L5 until the simulated curve matched the measured curve – then I could see which way to go. Fiddling in software is much easier than changing components, just using the "Undo" button when changes go the wrong way. I added a turn to L3, shortened L5, and did some squeezing and stretching for final tuning. The final result is shown in Figure 7.

What the books don't tell you

- All components have stray inductance, capacitance, and resistance, but the actual amount at a given frequency is usually found empirically.
- How much spacing between inductors is required to minimize coupling, and what is the effect of winding in the same direction, Figure 2, or opposite directions, Figure 4, or different orientations, Figure 11.
- Spacing is often more effective than shielding.
- Parallel wires, like L2 in Figure 11, have overlapping magnetic fields, so the inductance of two parallel wires is not half the inductance of one wire. Experimentally, paralleling two closely spaced wires reduces inductance by about 30% and three wires in parallel reduces inductance by about 50%.
- Inductance is defined for a closed loop of current, so the surrounding box and return current path are part of the inductance, and final tuning is empirical.

Lessons like these can be very expensive and painful to learn!

Performance

As shown in Figure 7, second and third harmonic frequencies are more than 60 dB down, while other, high frequencies are reduced by roughly 30 dB. The purpose of this filter is to suppress harmonics generated by an amplifier – other spurious frequencies should be removed before the amplifier by a low-power filter so that power is not wasted amplifying them.

Loss is less than the needle width of my power meter, something less than 0.1 dB. The filter was tested at 1200 watts key down with no apparent heating.

Summary

This filter works well, but it isn't something that need be copied exactly. Instead, I have tried to give enough instruction and insight so that you can build what you need with available parts. That's what hams have always done – tackle a problem, use what is available, and find a way to make it work.

Software simulation is useful for not only for design, but also for understanding what is happening when something isn't working as expected.

Postscript

After testing the filter at full power, I figured it was safe to try some on-the-air tests with the amplifier. Unfortunately, I didn't check the antenna VSWR first, and there was ice buildup on the beam, so several of the final transistors burned out. I later measured the antenna and found resonance had moved below 49 MHz, so the VSWR was at least 4:1. One problem with the MRI amplifier is that it is intended for pulse operation, so the transistors are run at 60 volts rather than 50 volts to get more peak power output. But they aren't very rugged at the higher voltage. Another expensive lesson!

References

1. http://www.bigskyspaces.com/w7gj/filters.htm
2. http://www.ham-radio.com/n6ca/50MHz/50appnotes/50tlpf.html
3. http://www.ifwtech.co.uk/g3sek/swxfiltr/swxfiltr.htm
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5. http://www.rfglobalnet.com/doc/ansoft-designer-sv-0001
6. www.linear.com