Filters and the Filter-Combiner

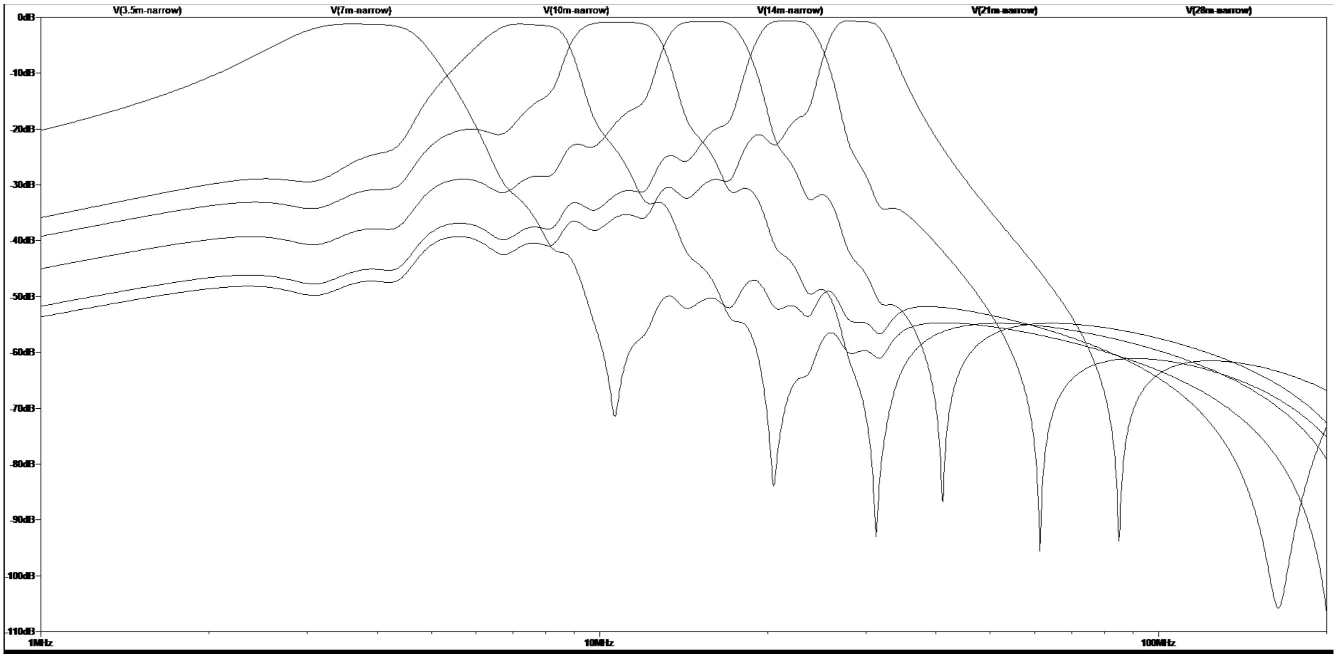

Illustration 1: Six-Band Filter-Combiner Response Spectrum

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Introduction

This document covers the requirements and design details of the Turn Island Splitter-Combiner, as well as simpler single-band filters and other filter options. There is a bit of basic tuned-circuit lore, given at the hand-waving level and without serious mathematics.

While the Filter-Combiner is discussed here in the context of the WSPRSONDE, it can also be used to combine multiple low-power signals from other transmitters, be the outputs square or sine waves. The Filter-Combiner is a bidirectional device, and has also been used to split the output of an antenna into multiple single-band signals, for use with narrow-band SDR receivers.

WSPRSONDE filter requirements

The *WSPRSONDE* transmitters generate a 1W square wave output, which must be filtered to provide a clean transmitted signal. Here is the raw output of a channel set to 3.5 MHz:

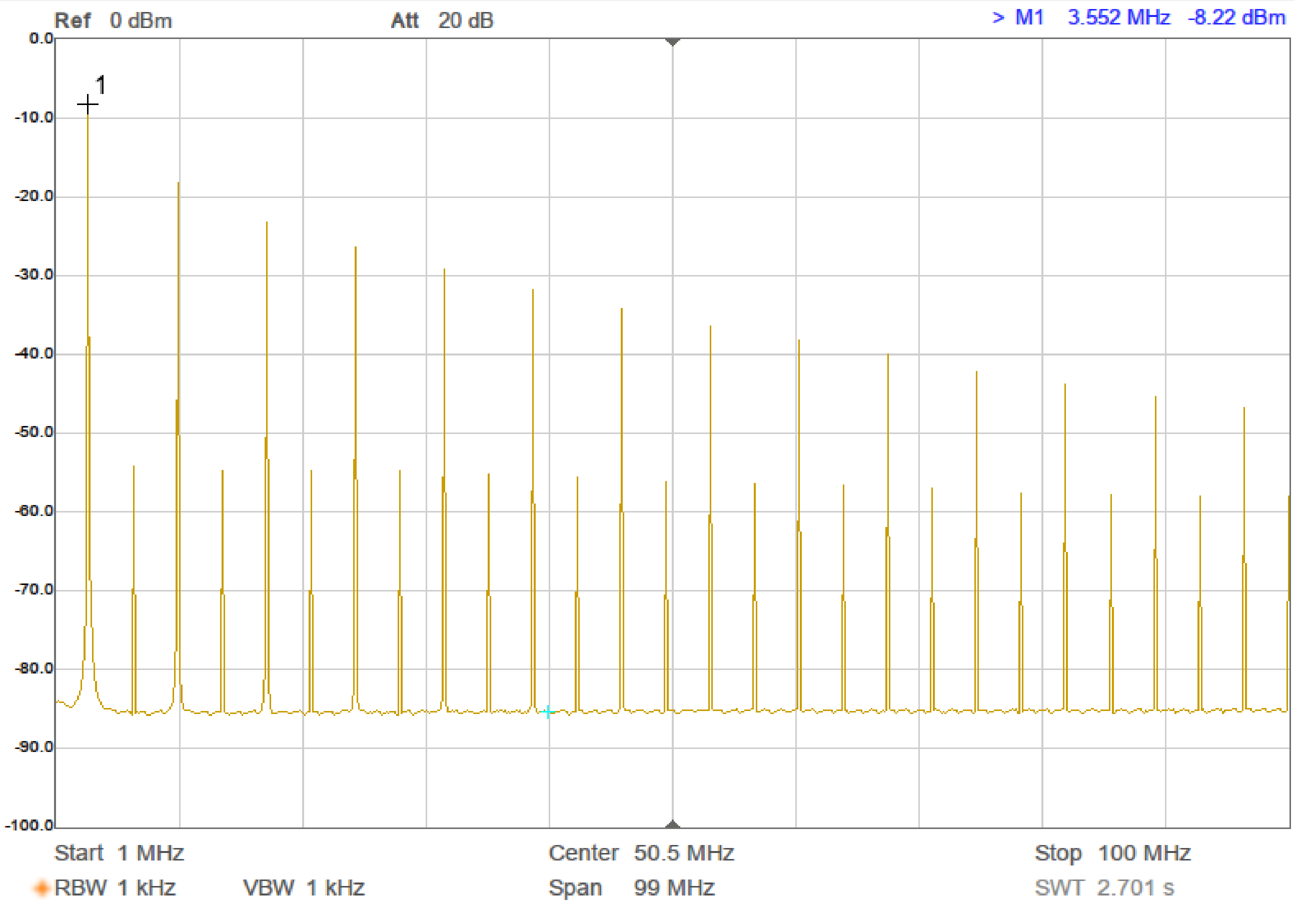


Illustration 2: Square Wave Output, 3.5 MHz Fundamental

Note that the odd harmonic levels are quite close to the theoretical values, with the third harmonic at -9.5 dBc (Decibels relative to the carrier). The even harmonics are caused by the not perfectly symmetrical waveshape, but these are low, less than -50 dBc.

If we set a target of -45dBc or lower for the transmitted harmonics we will need a filter attenuation of at least 36 dB at the third harmonic.

Since we intend to combine multiple filters so they feed a single antenna, we also need to maximize input port-to-port isolation and minimize filter-shape distortion caused by connected adjacent-frequency filters. Poor isolation will cause the output of one amplifier to modulate the output of another. The amplifiers in the WSPRSONDE are essentially switches so this intermodulation is minimal, but other classes of amplifier may be more sensitive. The filter-combiner adjacent-port isolation goal is better than than 20dB, which results in WSPRSONDE intermodulation artifacts of -60 dBc or less.

Combiners

There are several different types of RF combiners. These are often bidirectional and can be used as either a splitter or a combiner.

The simplest is the resistive combiner (or splitter). This is not frequency sensitive, but incurs significant loss in the resistors, and there is no port-port isolation beyond the intrinsic loss.

A less lossy design is the transformer hybrid. When the inputs are of the same frequency and phase the hybrid can combine the inputs with practically no loss at all. Port-to-port isolation can be quite good, often better than 20dB. But when the frequencies are different, as they are with the WSPRSONDE, half the power is dissipated in a termination resistor.

One frequency-sensitive device is the Diplexer. This typically has a low-frequency port, a high-frequency port, and a common port. These use low-pass / high-pass filters which can be realized with lumped-elements (inductors and capacitors), transmission-line elements, or a combination of these.

The Duplexer is similar to the Diplexer, and is used to allow a transmitter and receiver to share a common antenna. These usually have extremely sharp cavity resonators instead of simple filters.

Since we are using the known ham-band frequencies, we can design a combiner that simultaneously has low loss and high isolation. And because of this combiner topology we also get excellent harmonic filtering. This design is the Filter-Combiner.

L-C Filters, “Q”, Bandwidth and Loss

Basic Series-Resonant Network

Selecting filter element values and component types always involves compromise, especially when it comes to the inductors (good capacitors are practically perfect, at least when compared to inductors). Below you can see the effect that “loaded Q”, or the ratio of filter element reactance to the surrounding source and/or load impedance, has on the filter bandwidth. Here we are using essentially perfect inductors:

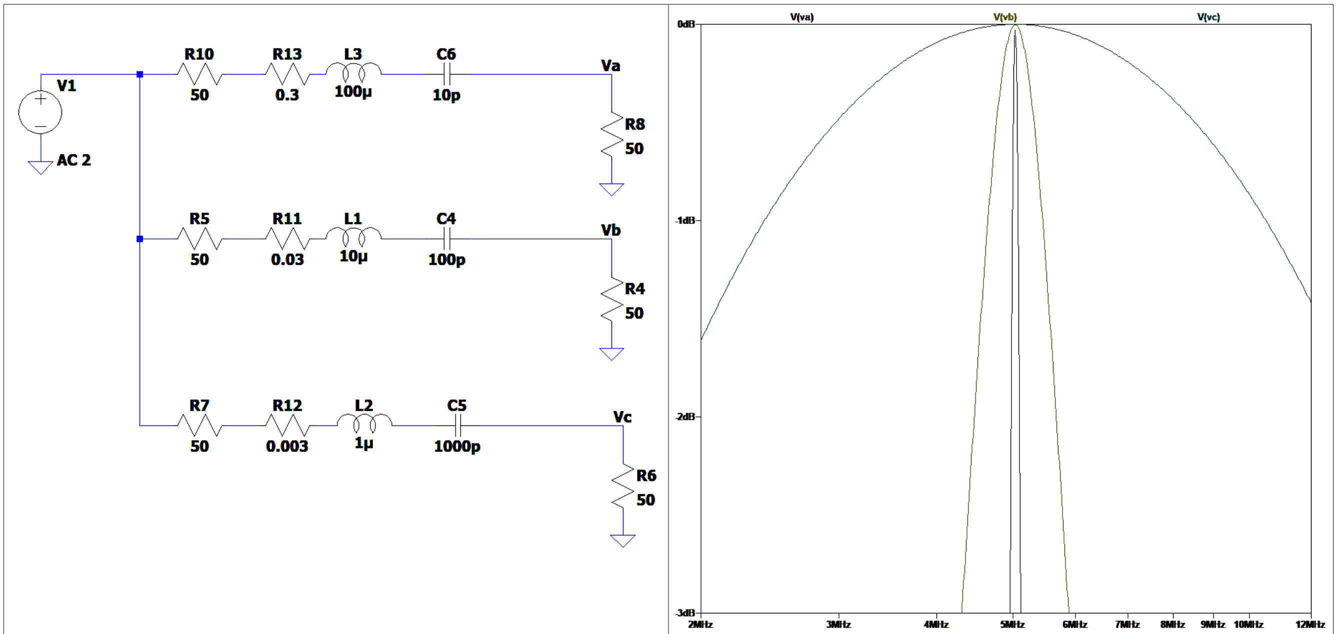
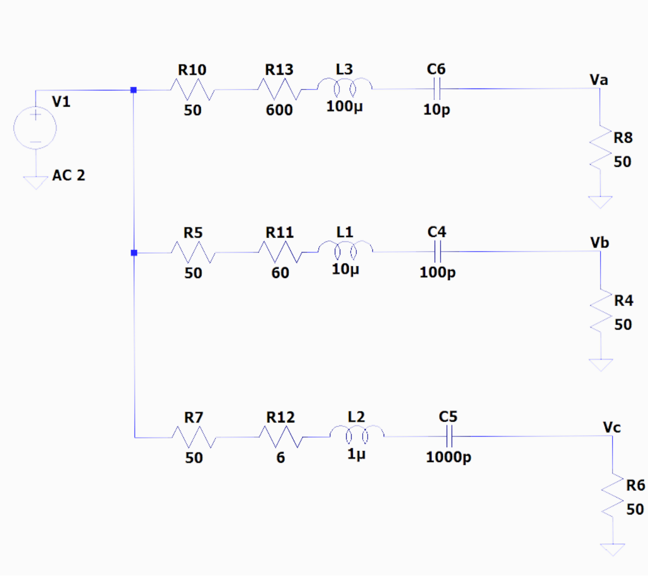


Illustration 3: Bandwidth vs loaded Q, inductor Q = 10,000

Series-Resonant Network Effects of Inductor "Q"

Now we replace our unobtainable perfect inductors with mid-grade surface-mount inductors. These inductors have a significant loss, due mainly to DC wire resistance and impedance caused by the skin effect. The "Q" of an inductor is the ratio of it's inductive reactance to its resistance at a given frequency, and here it has been set to about 20 by the series resistors R11, 12, and 13.



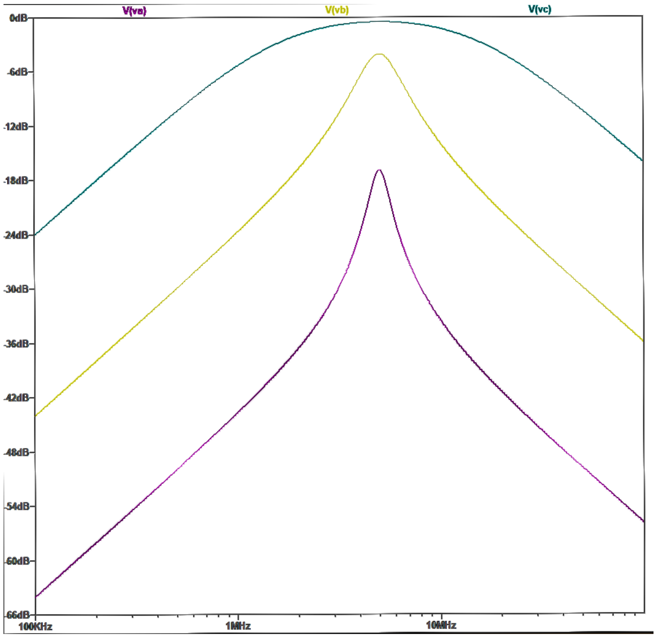


Illustration 4: Bandwidth and loss, inductor Q=20

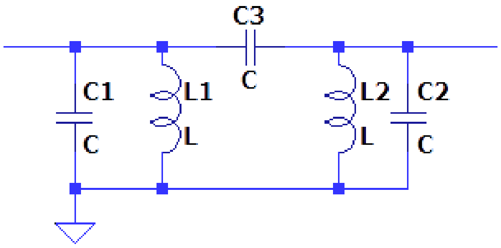
You can see how the bandwidth and loss are affected: The narrower the bandwith, the higher the loss. This must be taken into account in the filter design.

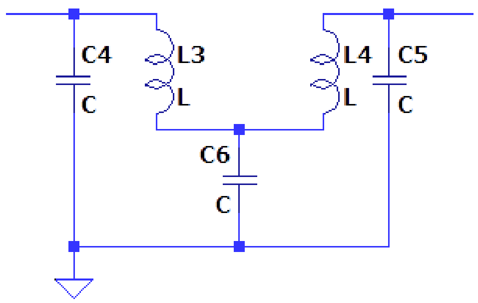
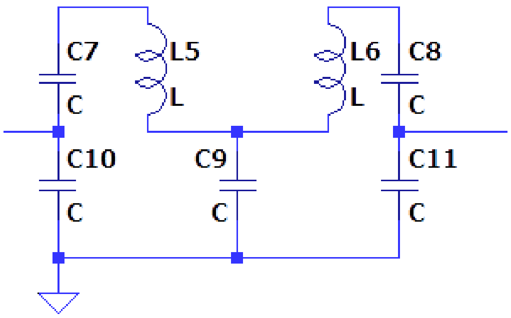
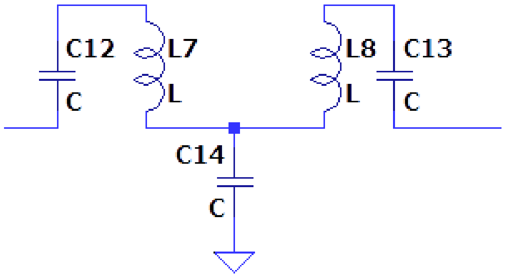
Another parameter of concern in practical inductors is the Self Resonant Frequency. At this frequency the inter-winding capacitance resonates with the inductance, forming a parallel-resonant circuit. You can see this effect above 100 MHz in the frequency-response simulation on the title page, and this can affect filter performance, especially at higher frequencies.

Coupled Filter Networks

Coupling two filter sections will give us more flexibility in the filter passband and the filter skirt shape.

This is the classic top-coupled tank circuit. The coupling capacitor C3 can also be replaced by an inductor (which will change the skirt response from highpass to lowpass.)



This can also be bottom-coupled, with a capacitor or inductor as the coupling element. The coupling can be done at the junction of the tank-circuit inductors (shown here), or at a junction of the tank capacitors.	
To optimize source and load impedance matching the tank capacitors, or inductors, can be tapped. All of these changes will have effects on the skirt response.	
This can be converted into a series-resonant circuit, as used in the Filter - Combiners.	

Coupled Series-Resonant Networks

Here we can see how the amount of coupling affects the filter passband response. The uppermost filter has a small amount of coupling (a large coupling capacitor value), resulting in a low-amplitude single-peak response (undercoupled). As the coupling increases from critically-coupled (a single peak) to strongly overcoupled we can see the response flatten, and then develop a douple-peak. In the filter-combiner we want to have a slightly overcoupled response, with a roughly flat-top passband shape. This minimizes sensitivity to component tolerance.

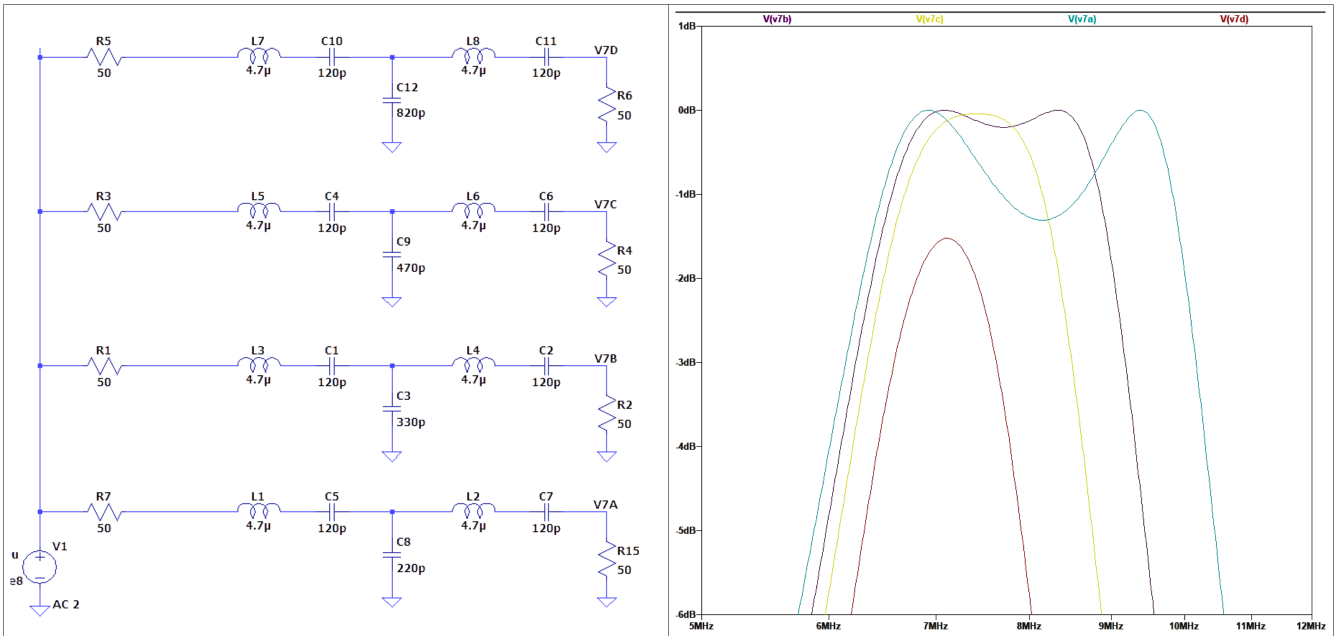


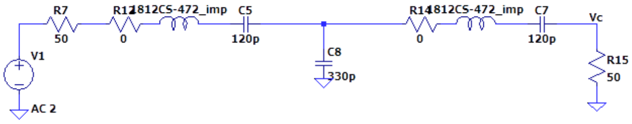
Illustration 5: Coupling - under. critical, over-coupled

Capacitor-Coupled Series-Resonant 7 MHz Network

This is a filter that could be used on the 40-meter band. The inductors used here are small surface-mount parts made by Coilcraft. These have a medium Q, typically in the 20 to 50 range.

Here you can see that the coupling capacitor (C8) causes the high-frequency shirt to be much steeper than the low-frequency skirt. The third-harmonic (21 MHz) attenuation is about 40dB.

Note that spectral plots have a logarithmic scale on the frequency axis, rather than the typical linear scale seen on a spectrum analyzer.



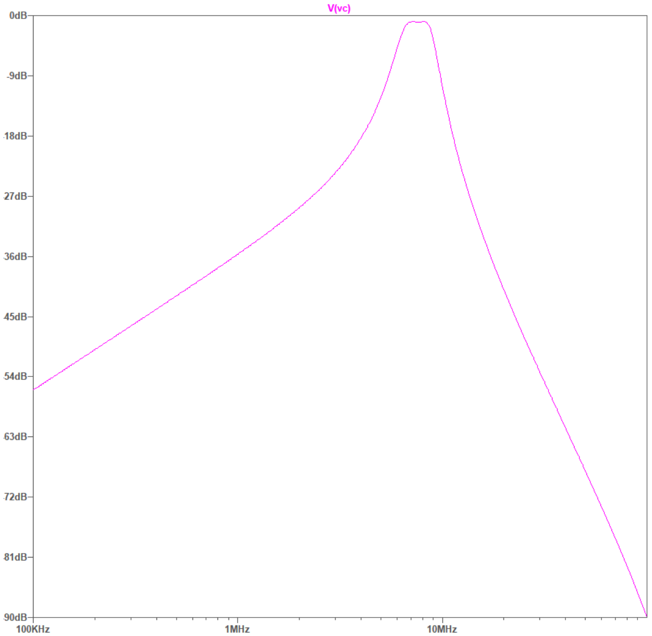
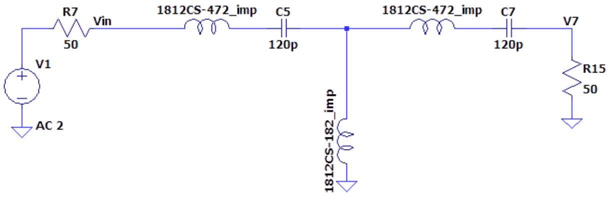


Illustration 6: Filter response with C coupling

Inductor-Coupled Series-Resonant 7 MHz Network

Here we have replaced the coupling capacitor with an inductor. Note that the low-frequency skirt is now the steeper one.



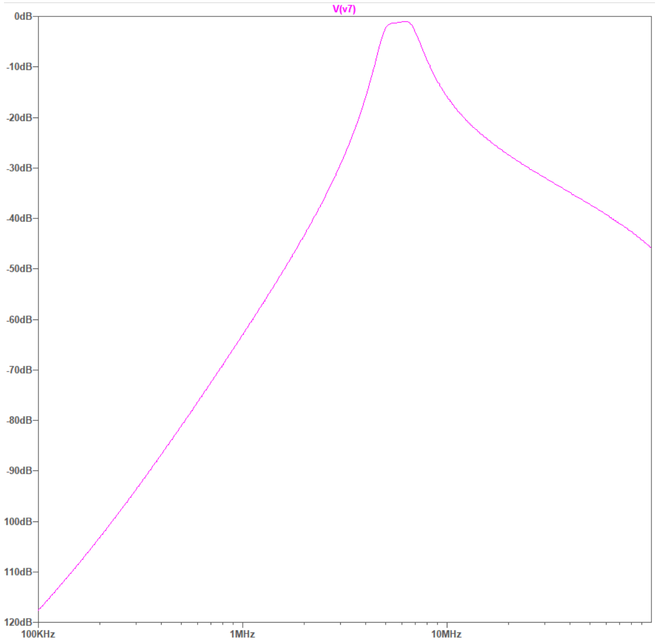
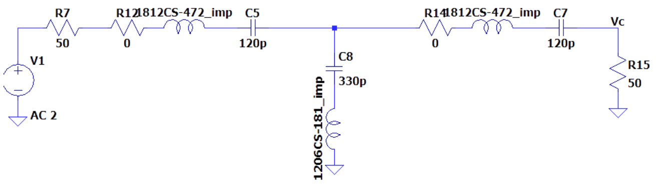


Illustration 7: Filter response with L coupling

Coupled Series-Resonant 7 MHz Network With Harmonic Notch

By replacing the coupling element with a series-tuned LC pair, a third-harmonic notch can be introduced. The ultimate attenuation is compromised, but the main thing we are trying to eliminate is the third harmonic. This is a good compromise.



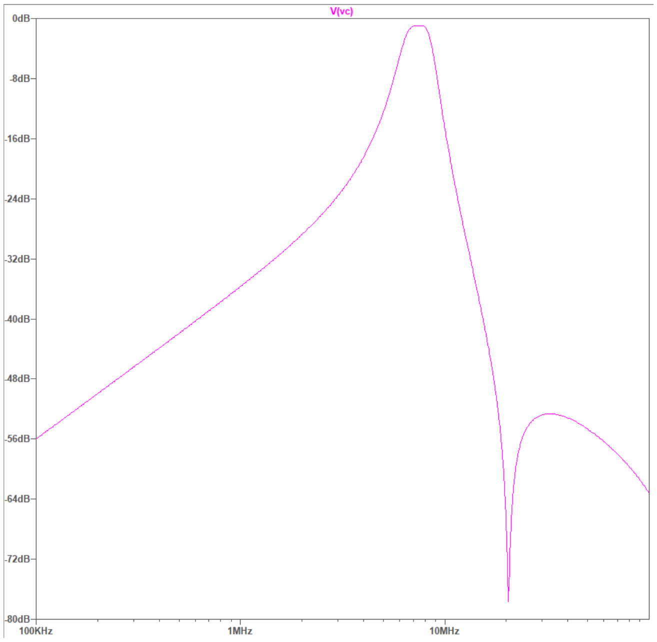


Illustration 8: Filter response with L-C coupling

Impedance: Coupled Series-Resonant 7 MHz Network

A symmetric filter of this sort will, at the center frequency, have an input impedance that is close to the load impedance. As this is a series-resonant design, the port impedance will rise as the frequency departs from the center. This is exactly what we want when we connect multiple filter outputs together in the filter-combiner. Below, you can see how the input impedance varies over frequency when connected to a 50 Ohm load. The center-frequency impedance value is approximately 50 Ohms.

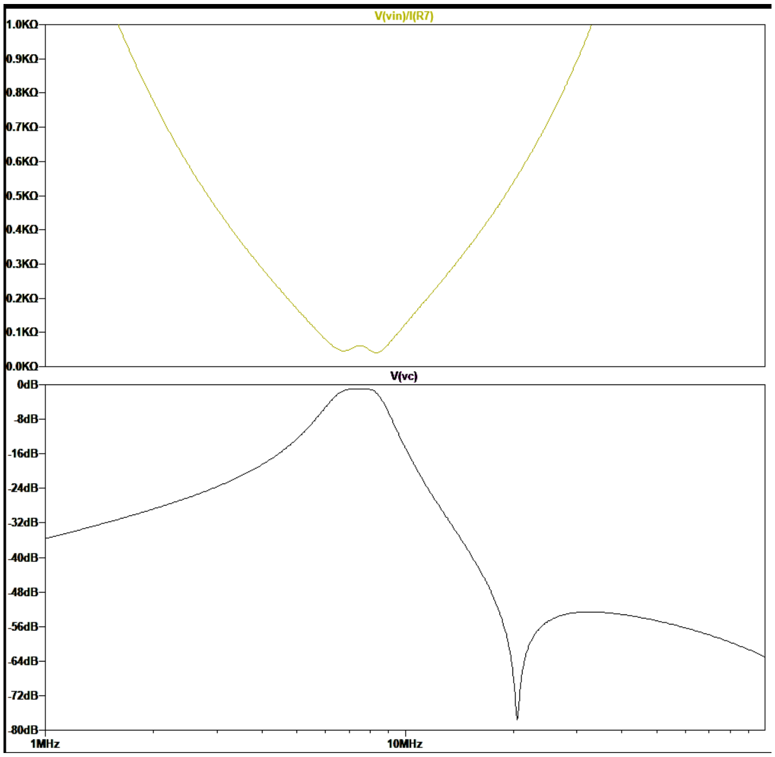


Illustration 9: Impedance with 50 Ohm load

But when we have no load on the output port, the input impedance drops to about 5 Ohms at mid-band. At the center frequency the filter network is acting similarly to a quarter-wave transmission line!

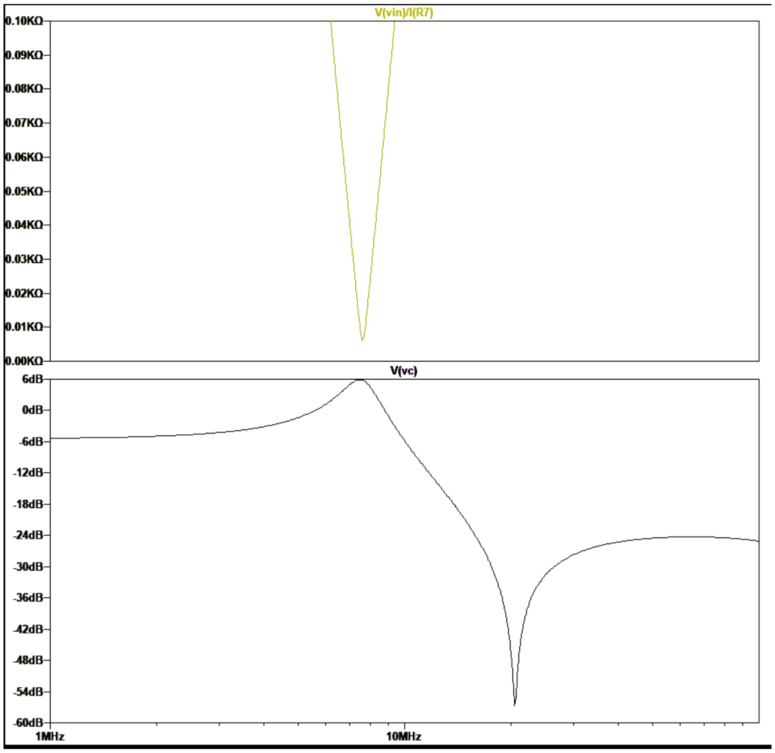


Illustration 10: Impedance with open-circuit load

I do not recommend using the filter-combiner with the output (antenna) port disconnected, as the transformed low impedance will put excessive loading on the transmit amplifiers. Since the WSPRSONDE outputs have active overload-shutdown the amplifiers will not be damaged, but it's probably better to not rely on this protection.

Below you can see the opposite effect, where a short-circuit at the filter-combiner antenna port results in a fairly high impedance at the input port. Here the mid-band impedance is about 500 Ohms. This will cause no damage to the output amplifiers.

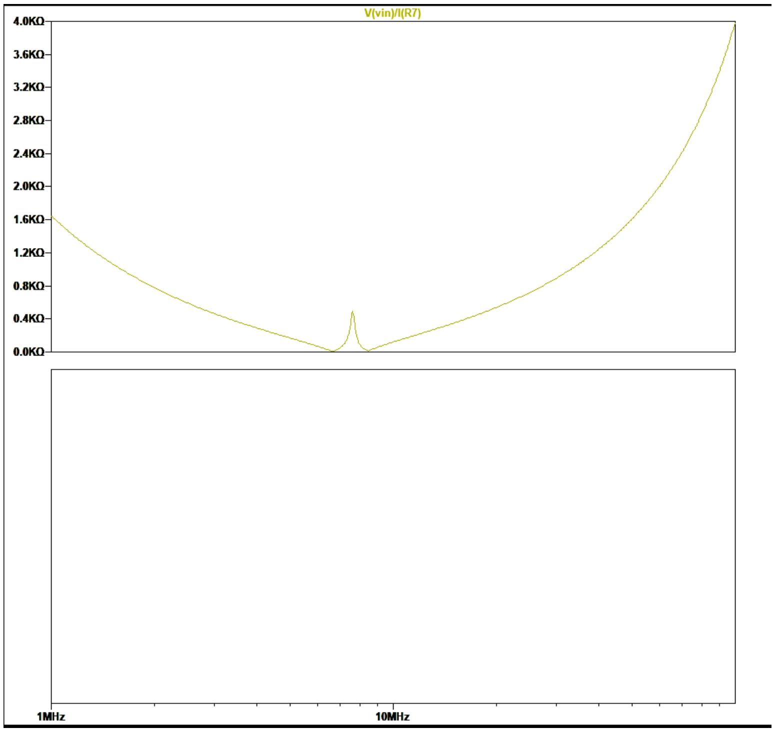


Illustration 11: Impedance with short-circuit load

The Six-Band Filter-Combiner

The Six-Band Filter-Combiner uses six of these series-resonant filter sections, covering the 80, 40, 30, 20, 15, and 10 meter ham bands. It also includes a -40dB monitoring tap at the antenna port. The inductors used are the Coilcraft “1812-CS” series in the coupled filter pair, and the Coilcraft “1206-CS” series for the smaller coupling inductors. The capacitors are all surface-mount 1206 COG/NPO types. Inductor and capacitor tolerances are 5%. Here is the output of this Filter-Combiner when connected to the WSPRSONDE:

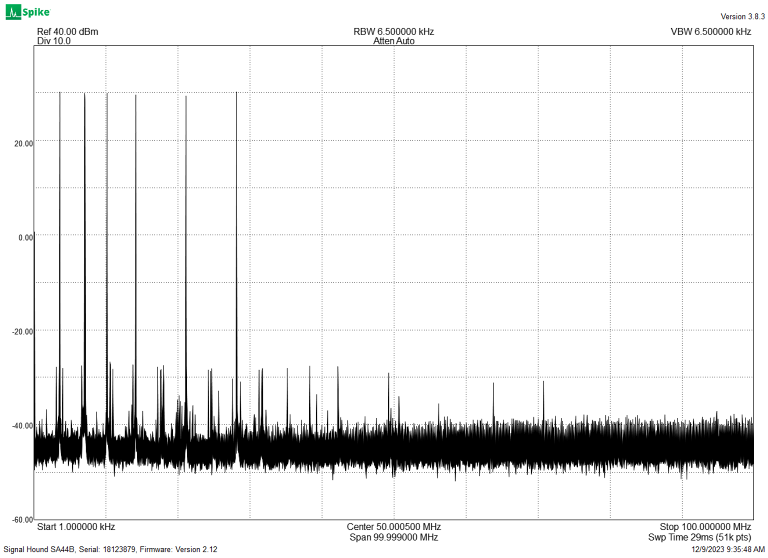


Illustration 12: Six-Band Filter-Combiner Output Spectrum

Each section of this Filter-Combiner has this configuration:

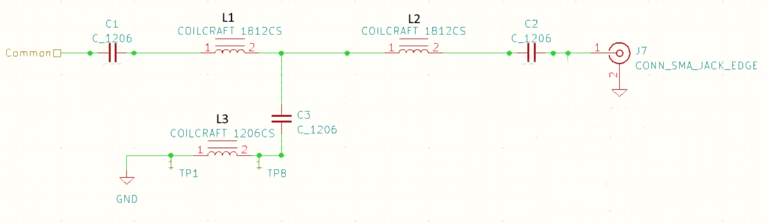


Illustration 13: Six-Band Filter-Combiner Schematic

Single-Band Filters

When an single output channel will be connected to an antenna, a simpler filter may be used. We do want to remember that the 1W square wave output is rich in harmonics, and a filter that provides a low impedance to the higher frequencies, such as the familiar pi network below, will essentially short out these harmonics causing a high current drain in the amplifier. This may not cause amplifier shut-down, but still should probably be avoided. The pi network is ***not*** the preferred filter configuration.

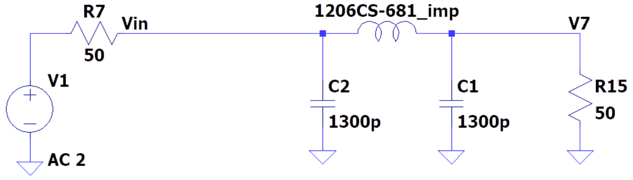


Illustration 14: Pi low pass filter

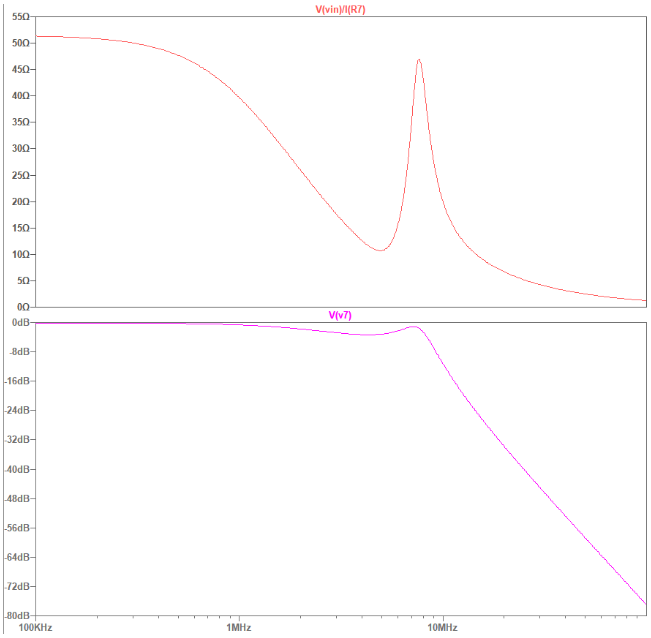


Illustration 15: Pi LPF response and impedance

The inductor-input “T” filter shown below is a better choice. As you can see, the impedance rises rapidly above the design frequency, significantly reducing the amplifier current. Even without the third-harmonic notch, this filter still provides a comfortable amount of harmonic attenuation.

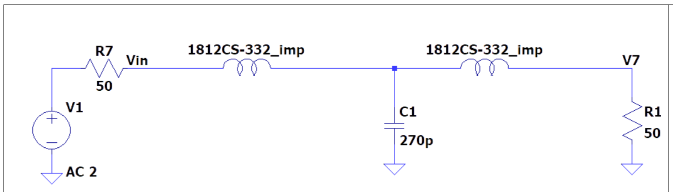


Illustration 16: T low pass filter

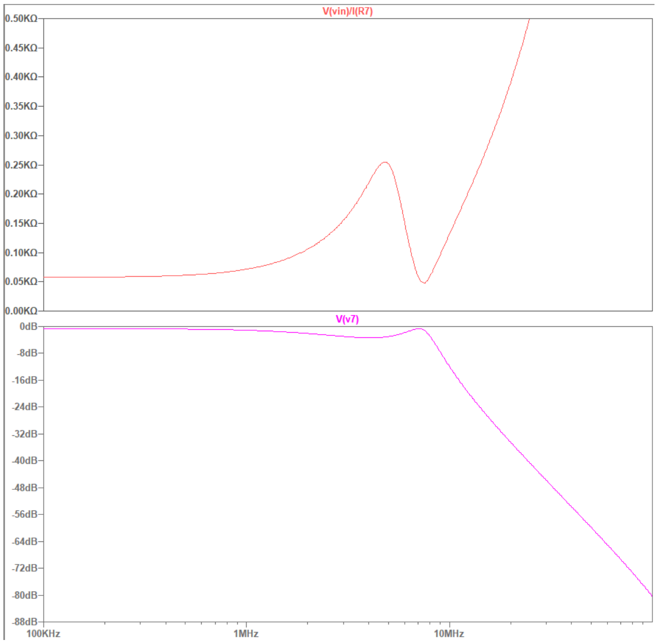


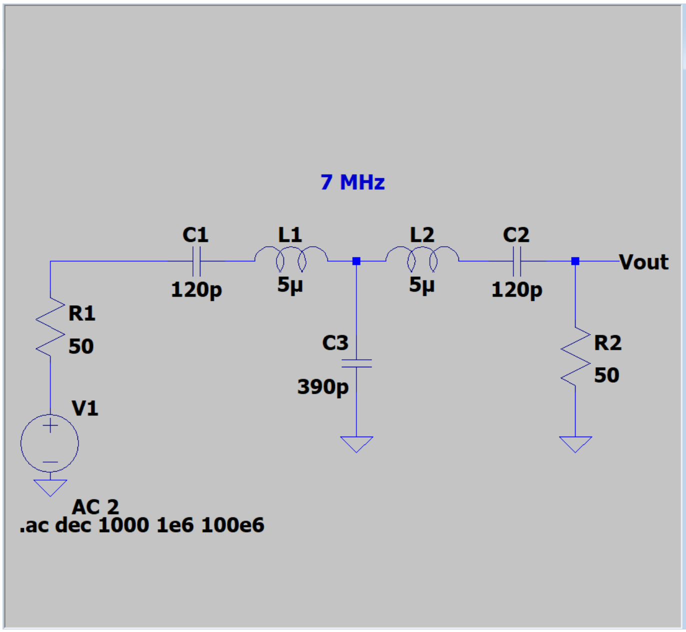
Illustration 17: T LPF response and impedance

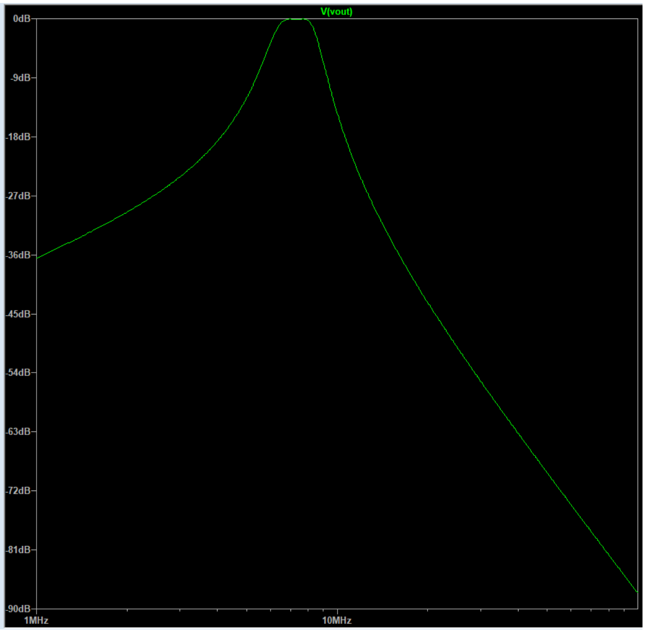
Neither the pi or the T filter are suitable for use in a combiner circuit, as the off-channel impedance would interfere with other connected filters.

Using Toroid Inductors

Most of the above has involved medium-Q surface-mount inductors, but of course these filters can be implemented with iron-powder toroid cores which have a typical Q between 100 and 200. With this improved inductor we can achieve narrower filter bandwidth while still maintaining a low loss. However with a narrow bandwidth comes increased sensitivity to component tolerance, and this limits how sharp we want to make the filters. But the higher Q inductor lets us improve the harmonic attenuation without needing the third-harmonic notch in the filter section coupling, and a reasonable tradeoff among these various factors can provide a useful filter.

Hand-winding these toroids is quite tedious, but if you want a combiner with more narrowly-spaced bands, or capable of higher power then the toroids are the way to go.





The table below shows the component values I use in the 7-band filter-combiner. Since the toroid inductance is affected by winding technique, and board layout can be a factor (especially at the higher frequencies), some some squeezing or spreading of the toroid windings may be necessary.

Frequency (MHz)	C1, C2	C3	L1, L2	Toroid
3.5	220 pF	1000 pF	12 uH	T37-2, 50 turns #32
5	150 pF	680 pF	6.5 uH	T37-2, 40 turns #30
7	120 pF	390 pF	5 uH	T37-2, 35 turns #30
10	75 pF	270 pF	4.5 uH	T37-2, 34 turns #30
14	56 pF	220 pF	2.5 uH	T37-6, 28 turns #28
21	39 pF	150 pF	1.7 uH	T37-6, 22 turns #26
28	27 pF	100 pF	1.2 uH	T36-6, 20 turns #26

In order to fit more of the ham bands between 160 and 6 meters into a filter-combiner, we need to make the filters narrower. To do this we increase the reactive impedance of the filter sections by increasing the inductor values and reducing the capacitor values. This will introduce more loss, but with high-Q toroids this additional loss can be minimal.

But the problems of component tolerance are not so easily overcome. As an example, here is a filter-combiner that covers the eleven ham bands from 160 to 10 meters:

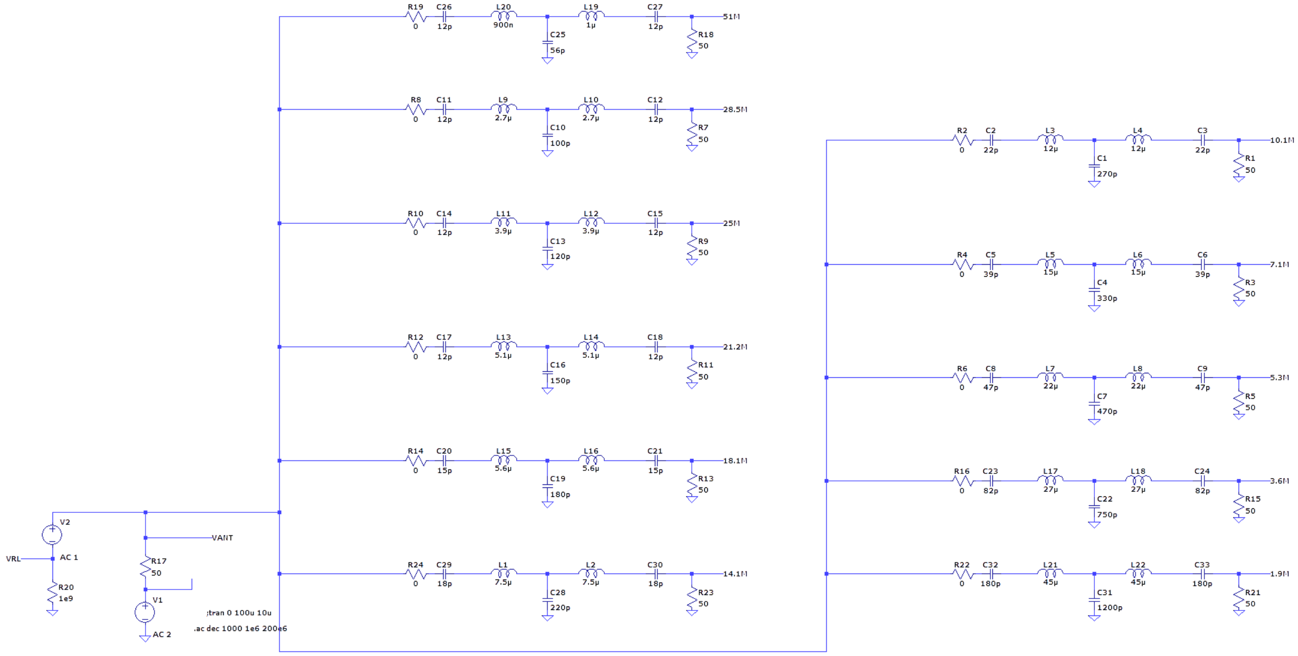


Illustration 18: Simulated Eleven-Band Filter-Combiner

Here is the simulated response:

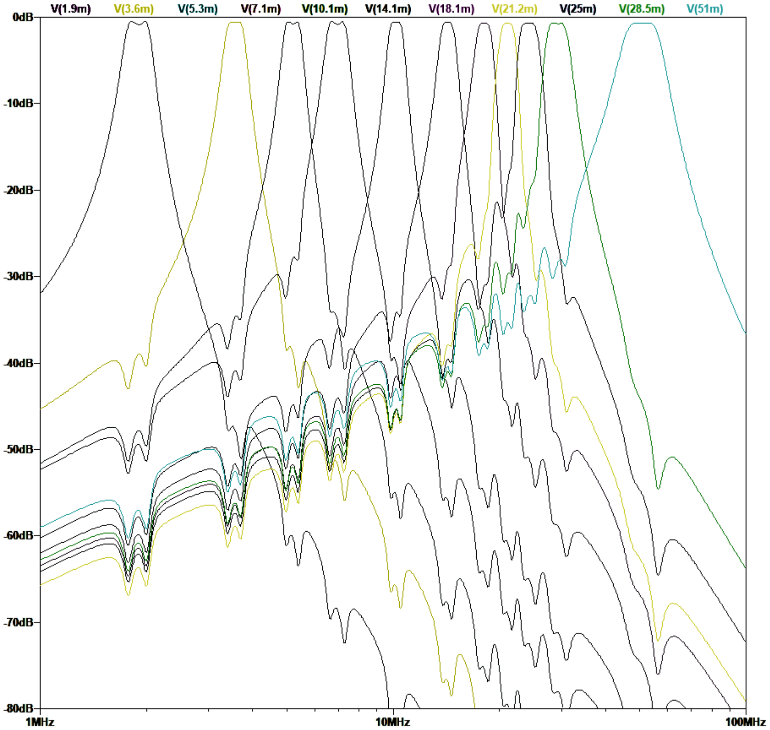


Illustration 19: 11-Band Simulated Response

And a close-up of the three most closely-spaced filters:

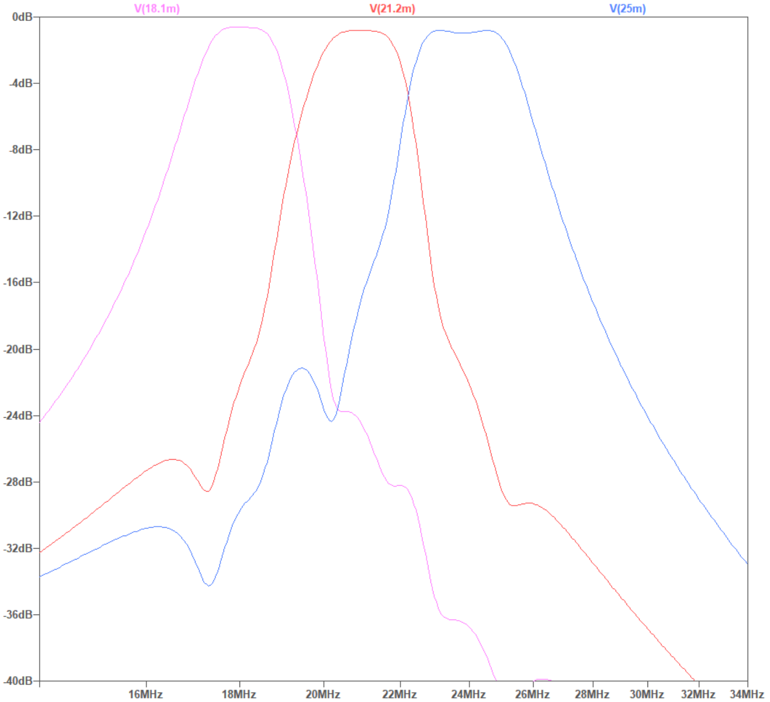


Illustration 20: 11-Band Simulated Response Detail

This actually looks pretty good, but watch what happens when we run a Monte-Carlo simulation with the component tolerances set to 5%:

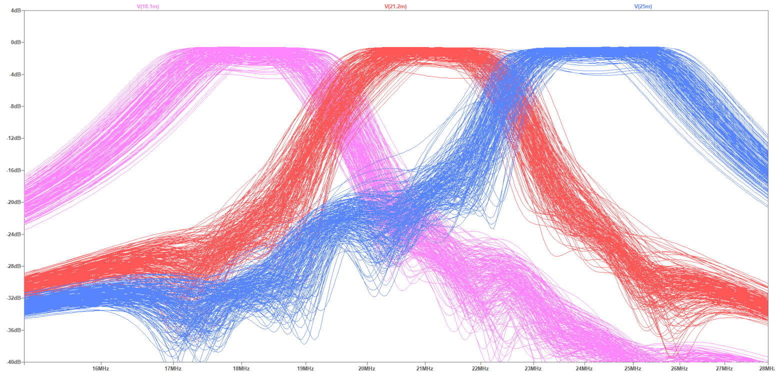


Illustration 21: 11-Band Response With 5% Tolerances

As you can see, the attenuation and adjacent-port isolation can suffer greatly. This design could be made to work with careful component selection and adjustment of the toroid windings, but it's going to be quite time-consuming and the task will require the proper test equipment. This looks like a job for the motivated hobbyist, not something that could be produced at an attractive price.

Antennas

The WSPRSONDE has eight outputs, potentially generating signals for eight ham bands ranging between 160 meters and 6 meters. Turn Island Systems has the 6-Band Filter-Combiner (80, 40, 30, 20, 15, 10 meters), and as a special order item the 7-Band Filter-Combiner (which adds the 60 meter band). So how do we transmit on eight bands? And is there a single antenna that can handle all these bands?

This is a challenge. A center-fed dipole is good on the fundamental, and can usually be made to work fairly well on the third harmonic (40 and 15 meters, for example). An off-center-fed dipole can perform on the fundamental and even harmonics (80, 40, 20, 10 meters), but supposedly can be trimmed for a good match on a few other bands as well. An end-fed half-wave works reasonably well on all harmonics (80, 40, 30, 20, 17, 15, 12, 10 meters).

The EFHW-8010 antenna from myantennas.com (and there are no doubt similar antennas from other suppliers), has proven to be a good match to the 6-Band Filter-Combiner, and several of these have been deployed to good effect. Some WSPRSONDE sites have added additional antennas, with individual filters, for the 17 and 12 meter bands, or the 6 meter band.

Obviously there are many other types of antenna than these simple wire ones. If you have a log-periodic that covers the full HF band by all means use it!

In some cases with a multiband antenna the SWR on a particular band can be excessive and cause amplifier shutdown. One compromise solution is to put a 3dB (or more, or less) attenuator on the channel output (remember, this is a 1W transmit power level). While reducing the transmitted power, it also reduces the SWR seen by the amplifier. In marginal cases you can also increase the allowable current-draw of the amplifier (see the WSPRSONDE “OVER” command).