Homebrew

We look at band pass filters.

WHAT IS IT? A band pass filter (BPF) is a circuit that will allow AC signals with frequencies within a certain range to pass through with relatively low attenuation. For obvious reasons, the band of frequencies that are allowed to pass through the filter are known as the passband. The range of frequencies that are outside the passband are known as the stopband. The BPF is one of the most fundamental circuits used in radio communications. All practical radio transmitters and receivers will employ some form of BPF. A bandstop filter has the opposite effect to a BPF. The bandstop filter rejects signals at frequencies within a certain range and passes frequencies outside of this range. Bandstop filters have many applications in radio communications. Typical applications include receiver AF or IF notch filters, IF trap filters and resonant co-ax stubs to suppress transmitter harmonics.

The simplest form of BPF consists of just a single LC resonant circuit. The LC circuit can be configured for either parallel or series resonance. Both types are equally suitable for use in a bandpass or bandstop filter. **Figure 1** shows how a simple LC circuit can be used as a BPF. The circuit of Figure 1a is a parallel resonant circuit, while Figure 1b is a series resonant circuit. R1 is the input impedance of the filter (in this case, the output of a signal generator) and R2 is the filter output load impedance. Passive LC filters are usually designed to operate with a specific input and output impedance. Such a filter will only give the desired response when terminated by the correct impedances. The example filter designs presented here are symmetrical in that the input and output are interchangeable and the input impedance is the same as the output impedance. These filters are doubly-terminated types which means that both ends of the filter must be correctly terminated. The input must be driven from a source of the correct impedance and the output must also be terminated correctly. As 50Ω is well established as the standard impedance value for inter-stage connections, many filters are designed for a resistive termination of 50Ω at each end.

The parallel resonant circuit in **Figure 1a** presents a high impedance at the resonant frequency. At resonance, the inductive

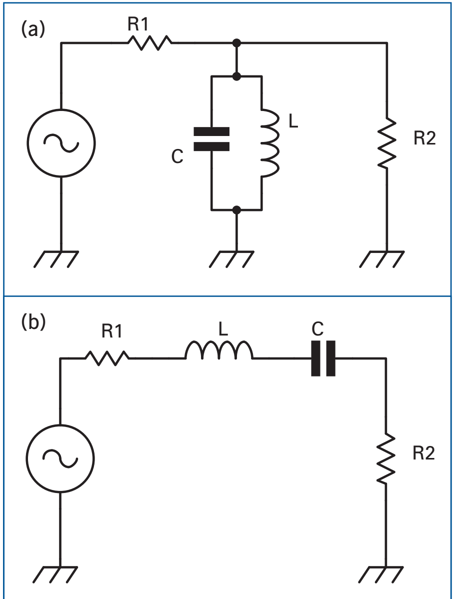

FIGURE 1: Simple band pass filter of (a) parallel and (b) series resonant form.

reactance of L and capacitive reactance of C are equal. These equal and opposite reactances effectively cancel each other out at the resonant frequency. As I have used perfect lossless components in the computer model of this circuit, the impedance of this LC circuit is infinitely high. This is not possible in a practical circuit. In the real world, the inductor and capacitor will always have some losses. Good quality capacitors tend to have very low losses in the HF range. A typical ceramic capacitor will have a Q of several hundred. The Q of high quality air-spaced capacitors is so high that they can be considered to be lossless for most practical purposes. Most of the losses in LC circuits tend to occur in the inductor. The Q of an inductor is simply the inductive reactance (X_L) divided by the resistance. $Q=X_L/R$. The resistance is due to resistive losses in the coil, core losses in the coil former and losses in other objects that are in close proximity to the coil. Typical Q values for RF inductors range from about 50 – 300. A small moulded choke might have a Q towards the bottom end of this range; a coil used in the output matching network of a high power transmitter could be expected to have a Q of several hundred.

The resonant frequency of an LC circuit is given by the well known formula $f = 1/(2*\pi*\sqrt{(L*C)})$, where L is in henries, C is in farads, f is in Hz and 2*pi = 6.283. As henries and farads are inconveniently large units for use at radio frequencies, this formula can be simplified to $f = 159.154/\sqrt{(L*C)}$ where f is in MHz, L is in μH and C is in pF.

MEASURING Q. When we consider the Q of a resonant circuit, we must make the distinction between unloaded and loaded Q. In theory, it is a simple matter to measure the Q of a tuned circuit. A signal generator can be used to provide a test signal and an RF voltmeter can be used to measure the amplitude of the signal across the tuned circuit. In practice, things are a little more difficult. The presence of the measuring instruments will have some effect on the circuit under test. **Figure 2** shows a test rig for measuring the unloaded Q of a tuned circuit. The input from the signal generator is fed to the LC resonator via a very small value capacitor. The output from the resonator is via another small value capacitor. The output voltage is monitored using a sensitive RF voltmeter, an oscilloscope or a spectrum analyser. The value of the I/O coupling capacitors should be very small relative to C – typical values are around 1 – 2pF. A pair of simple wire probes in close proximity to the top of the tuned circuit is an ideal method of achieving sufficient I/O coupling while having negligible loading effect on the tuned circuit. The losses between the generator and the 50Ω resistor at the test circuit output should be somewhere in the region of 30 – 40dB.

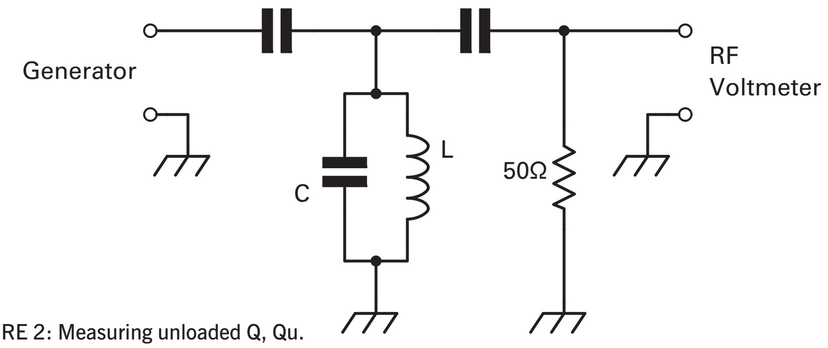

FIGURE 2: Measuring unloaded Q, Qu.

WHAT IS Q?

Q, or quality factor, is a dimensionless unit that reflects the effects of electrical resistance within a component or tuned circuit. It can be measured by methods including reference to the bandwidth of a tuned circuit or its 'magnifying factor', ie the apparent voltage 'gain' when a tuned circuit is stimulated at its resonant frequency – see the 'Measuring Q' section.

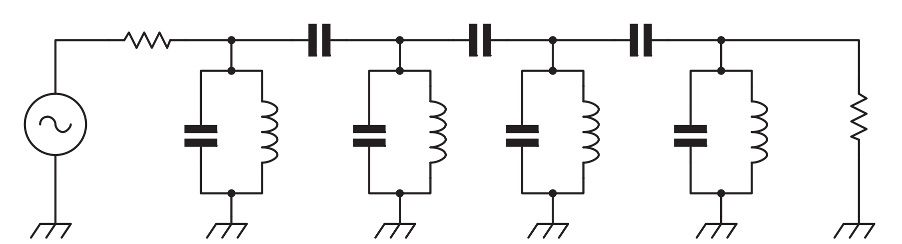

FIGURE 3: Four LC resonators coupled to make a 4th order bandpass filter.

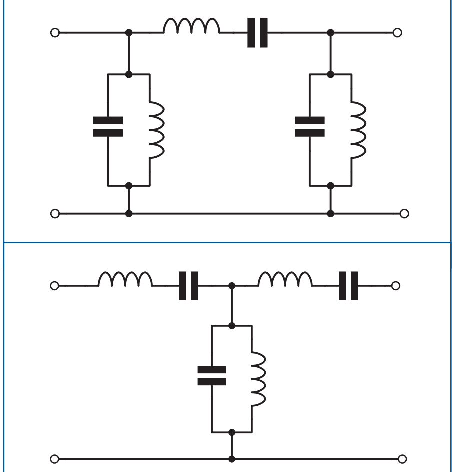

FIGURE 4: Simple 3rd order bandpass filter.

Lower losses would indicate that the test circuit has a significant loading effect on the tuned circuit. To measure Qu (unloaded Q), the generator should be tuned for peak measured output. This is the resonant frequency, f_0, of the LC circuit. The generator should be slowly tuned below this frequency until the output voltage falls to 0.7071 times its peak value. This frequency should be noted carefully and then the generator should be tuned above the resonant frequency until the output falls by the same amount. These two frequencies are the -3dB (half power) bandwidth points. The unloaded Q is the resonant frequency divided by the difference in frequency between the -3dB points or $Qu=f_0/BW$. The Q of the tuned circuit will tend to be lower when it is part of a passive filter network because of loading by the filter termination and the other components in the filter network.

The impedance of a parallel LC circuit at resonance is $Z = Q^2R$ where Q is the unloaded Q and R is the loss resistance. We will assume that the inductance of L in **Figure 1a** is 568.4nH (which is an inductive reactance of 50Ω at 14MHz) and that the series resistance of L is 0.5Ω. As we know that $X_C=X_L$ at resonance, this also tells us that $X_C=50\Omega$ at 14MHz. We will assume that the capacitor is effectively lossless at this frequency so that the unloaded Q of the circuit is simply X_L/R or 50/0.5 = 100. This figure is readily achieved in practice: my test circuit has a Qu of more than 200. $Z = Q^2R = 100^2*0.5 = 5000\Omega$. At resonance this is a pure resistance of 5kΩ. Provided that the input and output resistance (R1, R2) in Figure 1a is relatively low (well below 5kΩ) we can expect this simple bandpass filter to have very low losses near the centre of the passband.

The bandwidth of this simple single resonator LC filter is inversely proportional to the value of the terminating resistors. Bandwidth decreases and losses increase as the value of R1 and R2 is increased. The opposite is true of the series resonant BPF in **Figure 1b** where bandwidth is reduced and losses increased with decreasing values of R1 and R2.

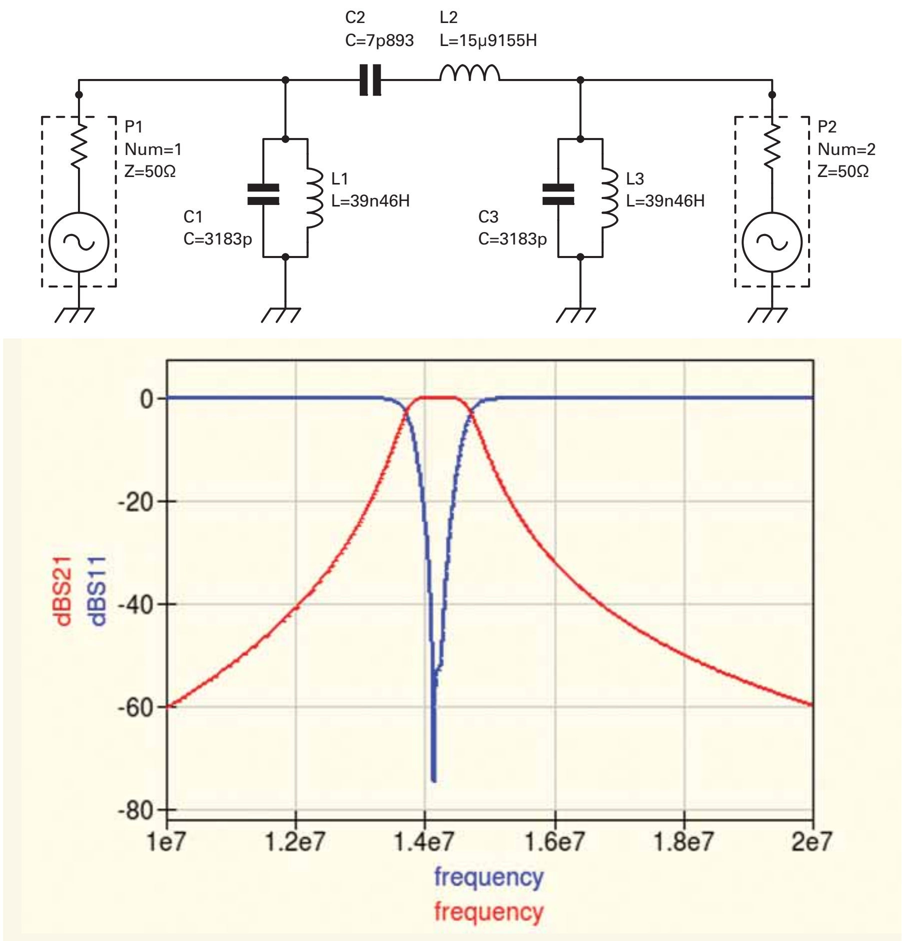

FIGURE 5: Circuit diagram and performance of a 14.2MHz bandpass filter.

MULTI-POLE FILTERS. There are many practical applications for a single resonator filter. The output network of many valve amplifiers is just a simple LC network. The bandpass characteristics of simple LC ATUs provides useful attenuation of out of band signals. However, there are many situations where a more elaborate filter will be required, not least because there are practical limits to the selectivity that can be achieved by a single tuned circuit. Trying to achieve extremely narrow bandwidths and/or high values of stopband attenuation using just a single resonator will result in very high losses in the circuit and insanely large or small component values. Where high performance is required, it is usually much easier to use two or more coupled resonators instead a single high Q resonator.

Figure 3 shows how four LC resonators can be coupled to make a 4th order BPF. Coupling between each resonator is via capacitive top-coupling. The addition of extra LC resonators greatly improves the skirt selectivity when compared to the simple LC filter described above. The degree of coupling between each resonator is determined by the value of the coupling capacitors. If suitable values of coupling capacitor and terminating impedances are chosen, it is possible to design a filter with the desired bandwidth, insertion loss, passband ripple, stopband attenuation, stopband ripple and so on. As with the LPF designs in previous Homebrew projects, it is possible to design a filter with minimum passband ripple (Butterworth type) or a Chebyshev type filter that has a certain level of passband ripple as a trade-off for improved stopband attenuation.

The filter at the top of **Figure 4** shows a very simple 3rd order BPF. This filter is particularly easy to design. If the components values suggested below are used, it has similar characteristics to the classic Butterworth BPF. The filter is directly connected to the terminating input/output impedance without any attempt at tuning or matching. When the filter is designed for the standard 50Ω I/O impedance, it does tend to require some rather inconvenient component values, especially at LF and VHF. However, it is quite easy to build for the HF bands.

The reactance of the components in the parallel resonant circuits at the ends of the filter is $Z0/Q_f$ where Z0 is the I/O impedance (usually 50Ω) and Qf is the filter Q (centre frequency divided by bandwidth). The reactance of the components in the series resonant circuit in the centre of the filter is $2Z_0/Q_f$.

If we are to design a filter with a centre frequency of 14.2MHz and a bandwidth of 1MHz (7%) the reactances are 3.5211Ω for the parallel sections and 1420Ω for the centre section. The standard formulae for X_L and X_C give us 3.5211/(6.2831*14.2) = 0.03946µH and 1/(6.28*14.2*3.5211) = 3183pF respectively for the parallel sections and 1420/(6.28*14.2) = 15.92µH and 1/(6.28*14.2*1420) = 7.893pF for the centre section.

Figure 5 shows the schematic and the frequency response of the filter with these values. For the benefit of the lazy constructor, the QUCS simulation software has a handy filter design tool that can be used to design Butterworth and Chebyshev filters of this type.

As we have seen earlier, the bandwidth and passband shape of many filter types is dependent on the I/O terminations. It is common practice to tune the end sections of a filter so that they provide a good match to a desired I/O impedance without disturbing the passband characteristics of the filter. Various methods are used for matching the filter to its termination. Series or shunt capacitive coupling is often used. Inductive coupling in the form of a coupling link or transformer is often used. A coupling link can prove very useful when PIN diode switching of multiple filters is required. The link winding provides the necessary match to the filter termination and a DC path for the PIN diode current **[1]**.

If any arbitrary collection of coils and capacitors are cobbled together in a random fashion, the end result will probably be a filter of some kind. There is a great variety of different topologies. Each has its own advantages and shortcomings. **Figure 6** shows some of the most commonly used BPF circuits. Circuit 6a uses capacitive coupling between the two resonators (Cm) and capacitive end coupling at the filter input/output (Ce). The circuit at 6b is very similar except that it uses a shunt coupling capacitor (Cm) instead of the series coupling capacitor in the first circuit. As a general rule, shunt coupling capacitors are large in value compared to C and series capacitors are small compared to C. The circuit at 6c uses series resonant LC circuits in place of the parallel LC circuits at 6a and 6c. This filter also uses shunt coupling capacitors. As with the single resonator test circuit described earlier, filter bandwidth and insertion loss is dependent on the values of the termination impedance and shunt capacitor values. This circuit is functionally identical to the crystal ladder SSB filter used in previous projects **[2]**. It will be evident from the schematic that this circuit has a lot in common with the pi type of LPF.

The process of designing a BPF can be simplified greatly if we accept a few compromises in the design process. Filters can be designed using normalised tables of coupling (k) and end loading (q) values. A single filter design can be used to cover more than one band.

On HF there are really only two types of bands. There are wide bands like 160m, 80m and 10m that have a bandwidth of 8 – 12% of the centre frequency. The other bands are relatively narrow, around 2 – 4% of the centre frequency. This means that it is

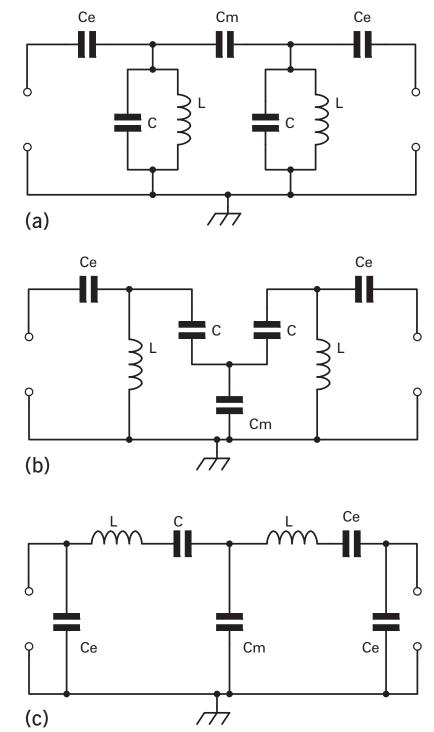

FIGURE 6: Common BPF circuits. (a) capacitive coupling throughout, (b) capacitive shunt coupling at the middle and (c) with series resonant elements and capacitive shunt coupling.

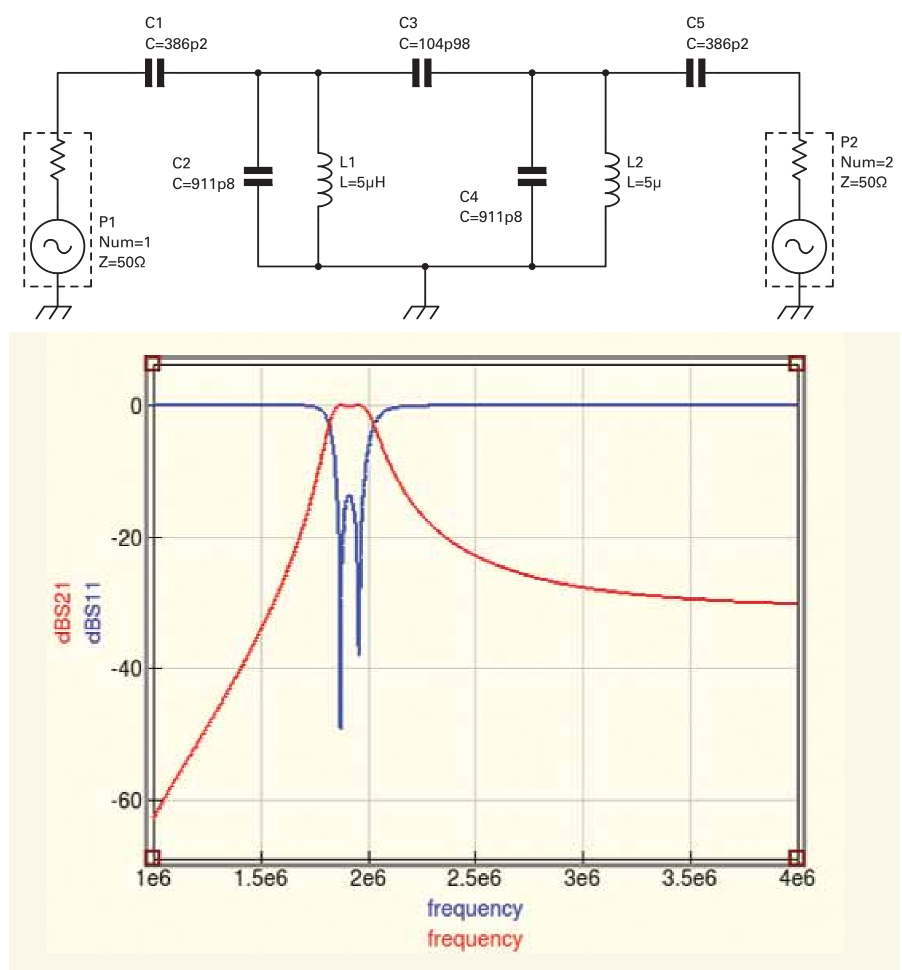

FIGURE 7: Practical 160m Chebyshev filter circuit and its response.

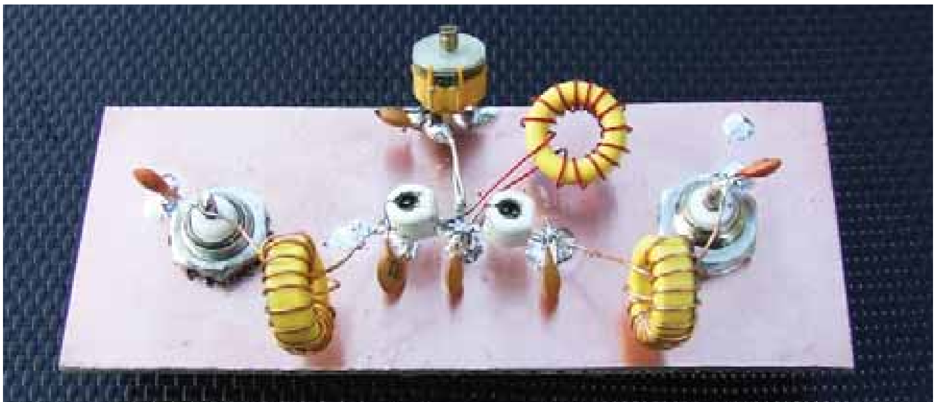

PHOTO 1: A home made HF 3rd order bandpass filter. Note VHF-style construction techniques.

possible to cover all nine HF bands using just two filter designs. If a wide filter is designed for 160m, it is very easily scaled to work on 80m and 10m. This is just a simple matter of using the X_C and X_L values from the first filter to determine the component values required to build filters for the other bands. Similarly, a filter designed for 40m would scale well to 30m, 20m, 17m, 15m and 12m.

PRACTICAL FILTER. I set about designing a 1dB ripple Chebyshev BPF filter based on the circuit in **Figure 1a** using the procedure described in Chapter 3 of EMRFD **[3]**. The filter was designed for a centre frequency of 1.9MHz and a BW of 200kHz. 5μH inductors were used for the initial design. The calculated component values are: C=911.8pF, Cm=104.98 and Ce=386.2pF. The filter schematic and response are shown in **Figure 7**. The L and C reactances for this filter are L=59.7Ω, C=91.79Ω, Cm=797.92Ω, Ce=216.89Ω. It is worth noting that the reactance of C+Ce+Cm=59.7Ω to resonate with L at 1.9MHz. These reactance values can be plugged into another filter for 80m or 10m.

The above capacitors are not exactly standard values. To make a real world filter, we will need to tweak the values slightly. The capacitors were changed to 1000pF, 110pF (100+10) and 390pF, which are all standard values. This shifted the centre frequency of the filter to 1.85MHz but the basic passband shape remains intact. To re-tune the filter to 1.9MHz, the value of L was decreased slightly. The required value turned out to be 4.7μH which, by a happy coincidence, turns out to be a standard value.

It is quite unusual to build a BPF from fixed components without having any method of fine tuning the filter. It is common practice to make the inductors tunable by winding them on slug tuned formers or alternatively, to make some of the capacitors variable.

You will notice that the passband of this filter is quite asymmetrical. This type of filter has much greater stopband attenuation below the passband than above the passband. This is typical of filters with capacitive top coupling. The filter in **Figure 6c** has the opposite type of response. This filter has excellent attenuation of higher frequencies and relatively poor attenuation below the passband. It is possible to get a more symmetrical response by cascading two filters, one of each type. This approach was used in some of our previous projects **[4]**, **[5]**. Greater skirt selectivity and stopband attenuation can be achieved by adding more resonators to the filter. EMRFD presents data for designing N=3 filters, which is not too difficult to extend to higher order filters.

The physical construction of BPFs can be quite critical. It is quite easy to achieve good stopband attenuation over a few octaves at HF. It is not so easy to build a HF filter that has good VHF and UHF attenuation. Good VHF practice should be followed, even for HF and LF filters. Component leads should be kept short and you should pay close attention to grounding. **Photo 1** shows a home made 3rd order BPF that was built dead-bug style on a copper ground plane. Input/output is via BNC connectors that are mounted directly on the ground plane. This filter has excellent stopband attenuation up to about 250MHz, but it has some spurious responses which are only about 30dB down at 400-500MHz.

It is not possible to do an in-depth study of band pass filters within the narrow confines of *Homebrew*. The interested reader is referred to *EMRFD* and *IRFD* **[6]** for further reading. As usual, all of the computer simulations were run on QUCS.

REFERENCES

[1] http://homepage.eircom.net/~ei9gq/bpf100.html
[2] Homebrew, *RadCom* March 2006.
[3] Experimental Methods in Radio Frequency Design, Hayward, Campbell, Larkin. ARRL, 2003.
[4] Homebrew, *RadCom* February 2006.
[5] Homebrew, *RadCom* May 2007.
[6] Introduction to Radio Frequency Design, Wes Hayward, W7ZOI. ARRL, 1994.