9 MHz Filters Built With Inexpensive Crystals

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Quartz crystals are abundant in the popular parts catalogs leading many experimenters to use them to build homebrew crystal filters. The Covid-19 pandemic of 2020 has many of us staying close to home, offering spare time to build such filters. This report offers some designs that can be duplicated by the builder without going through a detailed design procedure. The results may also be of interest to those doing their own design.

9 MHz has been a popular intermediate frequency since the early days of single sideband. This follows from a popular band imaging type receiver or transmitter for the 75 and 20 meter bands with just one 5 to 5.5 MHz local oscillator. I wondered if the available crystals in the catalogs would work well in crystal filters.

My experiments started with the purchase of ten crystals specified to have a 9 MHz frequency with a 30 pF load.(ref 1) The ten crystals were numbered and then measured with a vector network analyzer (VNA.) Analysis of the data provided the series and parallel frequency of each "rock", the motional inductance and capacitance, the unloaded Q, and the parallel capacitance. A simple filter or two might be built from the small sample, but more crystals would make it much more practical. A second order was placed for an additional 25 crystals. These were combined with the first 10. Data is shown in Fig 1. The crystals purchased from Mouser Electronics were manufactured by IQD. The Mouser part number and average crystal parameters are found in Fig 11.

9 MHz crystals, from two Mouser orders		
Sorted		Sort by Freq.
9xtals#5.xls		
	file=9xtals#5	
xtal #	f	Filter
6	390	
24	420	
3	421	
5	431	CW3
17	436	CW3
21	436	CW3
11	437	CW5
31	442	CW5
2	445	CW5
27	447	CW5
29	447	CW5
22	451	SSB6-2K
25	452	SSB6-2K
7	456	SSB6-2K
15	457	SSB6-2K
28	465	SSB6-2K
1	472	SSB6-2K
26	472	SSB4
30	473	SSB4
18	475	SSB4
19	482	SSB4
10	484	SSB6-2r5k
33	491	SSB6-2r5k
14	495	SSB6-2r5k
34	504	SSB6-2r5k
9	506	SSB6-2r5k
20	523	SSB6-2r5k
16	524	
12	535	
4	553	
8	556	

Fig 1. A table showing most of the 35 crystals used in these experiments. Relative frequencies and the crystal numbers are listed, ordered according to frequency. The sorting was done in Microsoft Excel. The table shows which crystals were used in each filter.

The experiments concluded with five crystal filters having been built, shown below in Fig 2. The simplest filter used just 3 crystals while the more complicated circuits used 6. All of the filters were designed with XLAD, a program that was part of Ladpac, a suite of programs offered with EMRFD. (ref 2) All of the filters use a 50 ohm termination at each end. That is, the filters should "see" a wideband 50 ohms at both input and output. Measurements were done with a VNA designed and popularized by Paul, N2PK. A Nanovna would be a suitable alternative. The N2PK VNA data was exported to our computer where it was plotted in Excel. Almost all of the capacitors used in the filters are standard values. It is generally important to use the values shown. In a few cases, parallel combinations of standard values have been used.
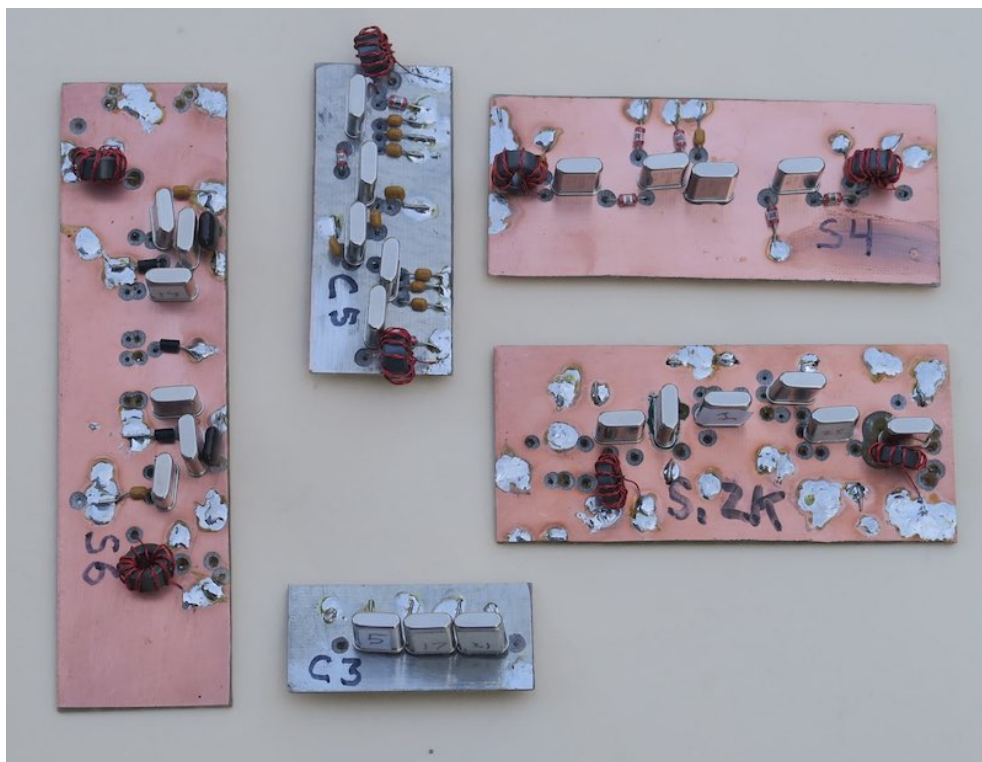

Fig 2. These are the five filters built from a batch of 35 crystals.

Building the filters.

My goal with this project was to present filters that can be duplicated by the experimenter-builder with only modest experience. We designed both CW and SSB compatible bandwidth circuits, built the filters, tested them, and compared the results with computer simulations. Schematic diagrams and measured results are presented for the 5 filters.

The commercial crystal filters that we purchased from KVG and from the transceiver manufacturers in earlier times usually required a 500 ohm termination at both ends. This was compatible with diode filter switching and was a generally handy impedance for amplifiers that might follow. I elected to

include transformers with most of the filters so that they may be terminated with 50 ohms at each end. This is compatible with modern RF switching integrated circuits. I've used the Peregrine Semiconductor PE4283, but there are other parts to be found in the catalogs. The Skyworks AS-169-73LF seems to be a popular part and is still listed in the Mouser catalog at this writing. Both of these SMT parts are SPDT RF switches that can be used to change between filters or to switch a filter between receive and transmit functions in a transceiver.

The very first thing that a builder must do once he or she receives an order from a parts source is to measure the relative frequency of the crystals. This can be done with the simple oscillator shown in Fig 3. Absolute frequency accuracy is not important.   All that these measurements really must do is allow the crystals to be matched to each other.
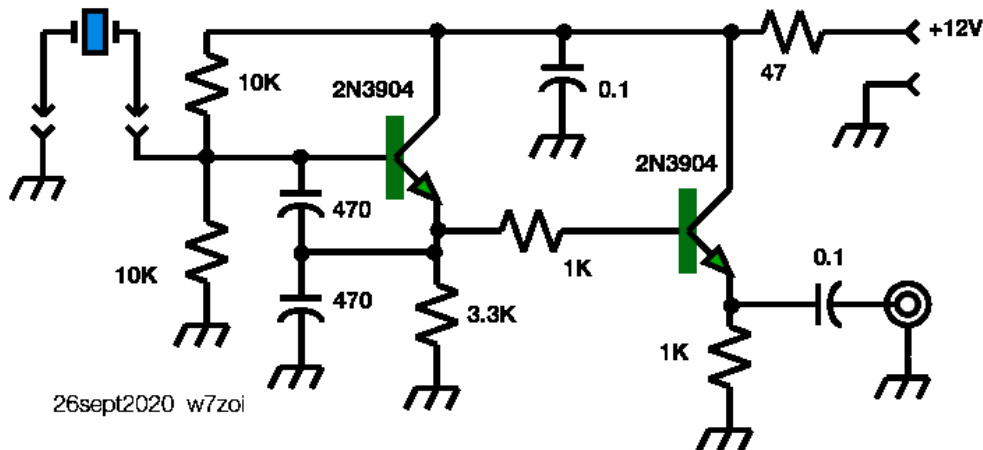

Fig 3.   Oscillator suitable for matching crystals.

Best results occur when a counter with a 1 Hz resolution is used. See Fig 14. If not available, 10 Hz will suffice. This would include the built-in counter in many popular imported oscilloscopes. Watch for temperature effects when changing crystals during measurement. This can produce a 10 Hz error. I often use gloves when measuring a batch of crystals.

No additional measurement equipment is required, although it's always instructive (and fun) to do as much measurement as possible.   The crystal matching measurements are important.   We have found that good crystal filter results are possible with crystals matched to 10% of the filter bandwidth. Hence, a usable CW filter with a 500 Hz bandwidth requires crystals that all within 50 Hz of each other.   A 200 Hz match can be used for a SSB filter with a 2 kHz bandwidth. I usually use a tighter match, which is easy to do once a moderate number of crystals are available.

Each of the filters to be described below will use essentially identical crystals within the filter.   For example, the 4 element SSB filter used 4 crystals within a 10 Hz range. See Fig 1. Once the 4 are selected, any crystal in the set can be used in any position in the filter.   Not all lower sideband crystal ladder filters are designed this way.

Filter Frequency

A commercial crystal filter specified to be at 9 MHz would have a center frequency of 9 MHz, probably with an accuracy of 50 or 100 Hz. Figure 4 shows that this not the case with the filters presented in this

note.   **Generally, it is not practical to build homebrew filters that will seamlessly retrofit into commercial equipment.**
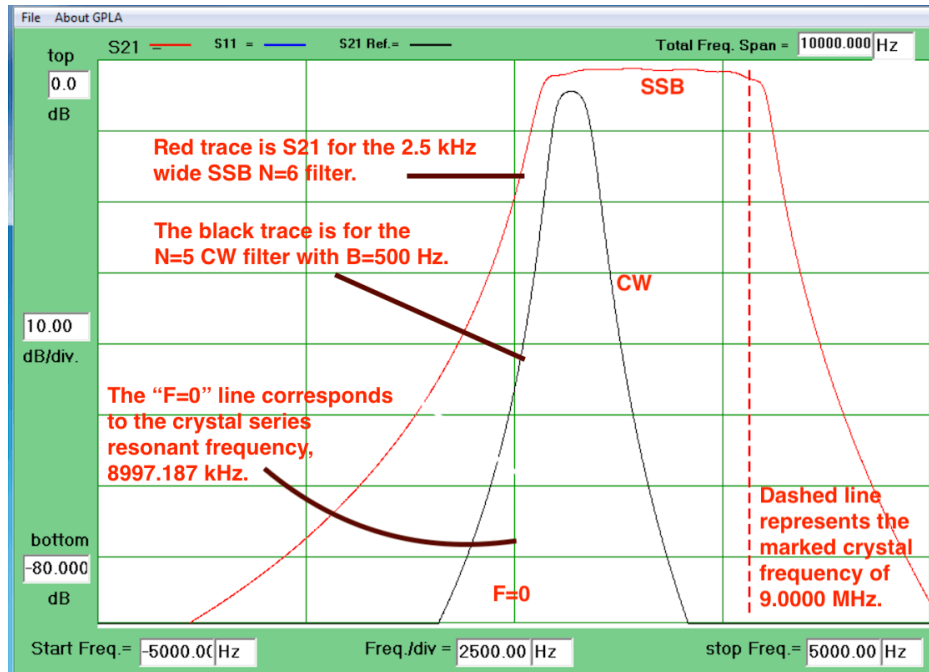

Fig 4. Plot showing a CW and a SSB filter, the way they relate to each other, and their frequencies.   The crystals were specified as 9 MHz, but that is with a 30 pF load capacitance. (See Reference 1 for an explanation of "load capacitance.")   None of the filters presented in this note are centered exactly at 9 MHz.   This plot is a computer simulation, but others in the report are actual measurements.   9 MHz is marked in all plots.

CW Filters

CW filters are generally easier to design and build than the wider bandwidth SSB circuits.   The two CW filters were both designed for a Butterworth shape.   They offer a rounded peak shape, which usually means a minimum of ringing.   The simplest CW filter shown in Fig 5 uses only 3 crystals.   The bandwidth was confined to 330 Hz which allows the filter to function with 50 ohm terminations. Transformers were not required.   This N=3 filter required no tuning capacitors in series with the crystals.   In spite of the simplicity, this filter will sound great in a simple CW receiver.   This is the bottom most module in the Fig 2 photo.   There are no capacitors showing in the photograph.   The capacitors are SMT types on the bottom of the board.   Capacitor type (SMT or leaded) and board layout are up to the builder.

Y1, Y2, Y3 : 9 MHz IQD Crystals
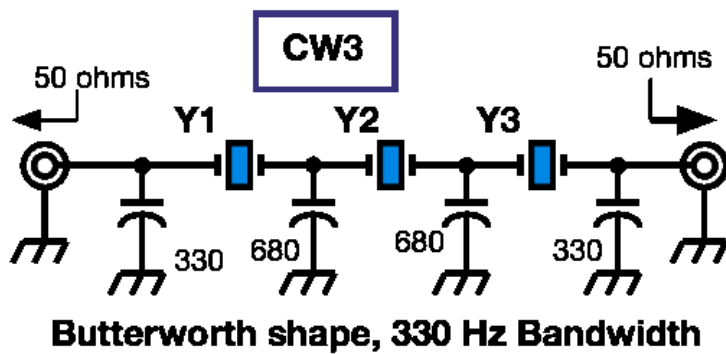## Mouser part # 449-LFXTAL064523BULK
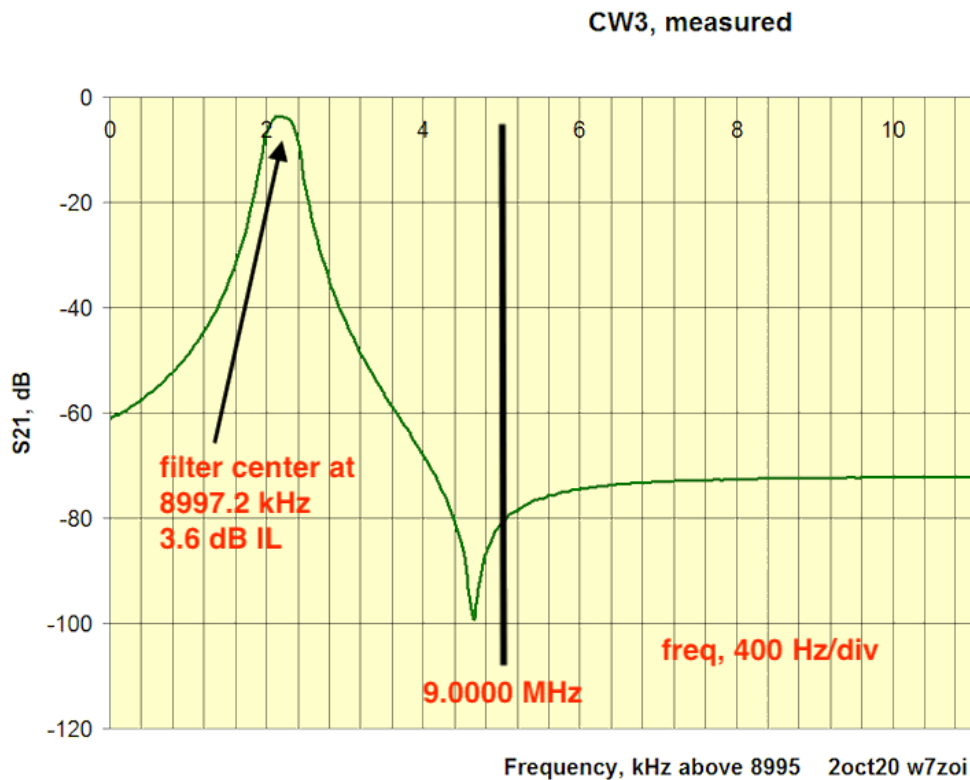

Fig 5. N=3 CW filter.

Fig 6.   Measured performance of the N=3 filter. The CW filters were measured with 50 Hz frequency steps in the VNA sweep.

The next CW filter, Fig 7, uses 5 crystals.   The design bandwidth for this circuit was 500 Hz.   This design had an insertion loss of nearly 5 dB.   The IQD crystals that I measured had a high enough unloaded Q (average = 124K) to support even narrower bandwidth if the builder willing to do a redesign, but higher insertion loss should be expected.
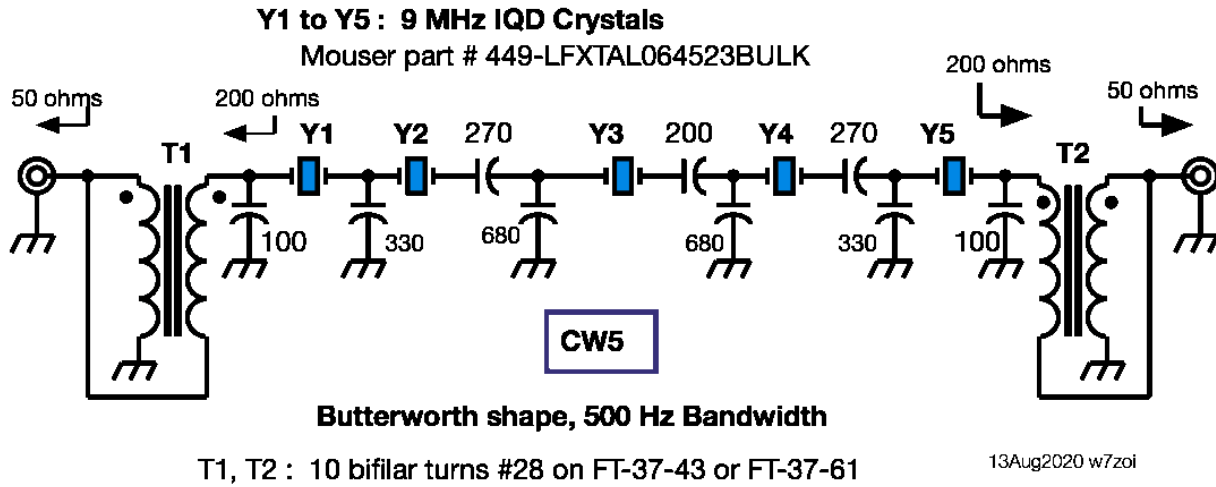
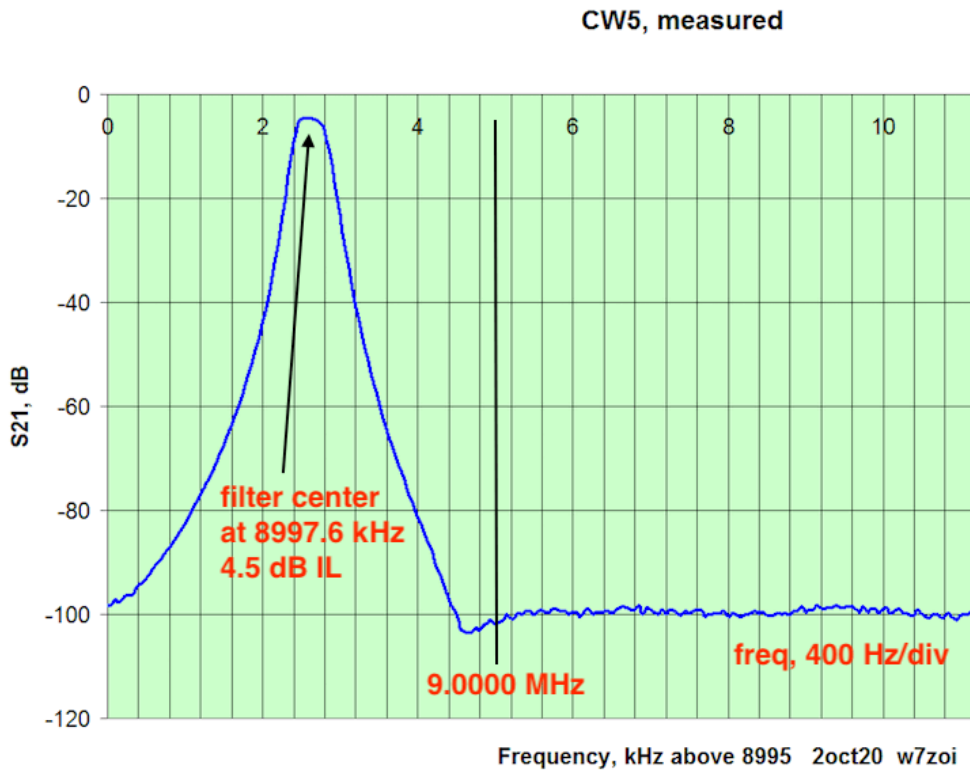**Fig 7. CW filter with five crystals.**

Fig 8. Response of the N=5 CW filter. Note the excellent stop-band attenuation.

SSB Filters

Designing and building filters with a SSB bandwidth presents greater challenge than the CW filters, but homebrew filters are still very practical at 9 MHz.   The following three filters should be easy to build.   All of them use a Chebyshev shape.   This shape with some passband ripple allows filter terminations of 200 ohms.   This is then easily matched to 50 ohms with a simple, bifilar wound toroid.   The first SSB filter uses just 4 crystals.   This filter would be ideal for a simple receiver, or an initial SSB transmitter.
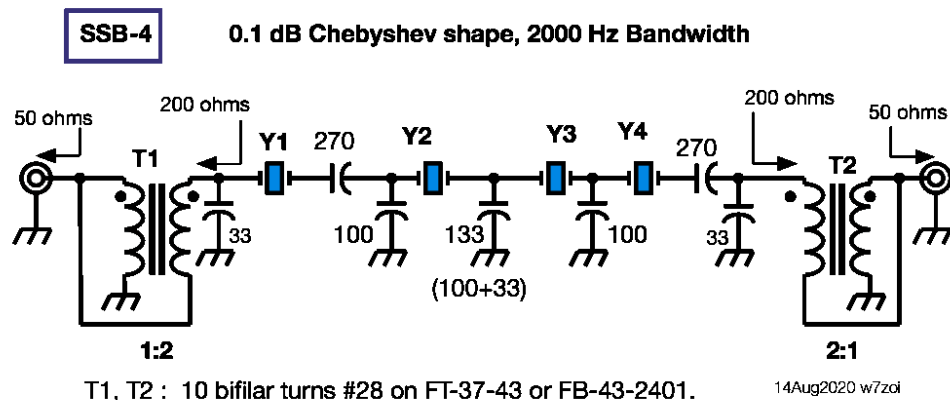
SSB-4 **0.1 dB Chebyshev shape, 2000 Hz Bandwidth**

Fig 9. A 4 pole SSB filter. The coupling capacitor between Y2 and Y3 is 133 pF, consisting of a parallel combination of standard values.
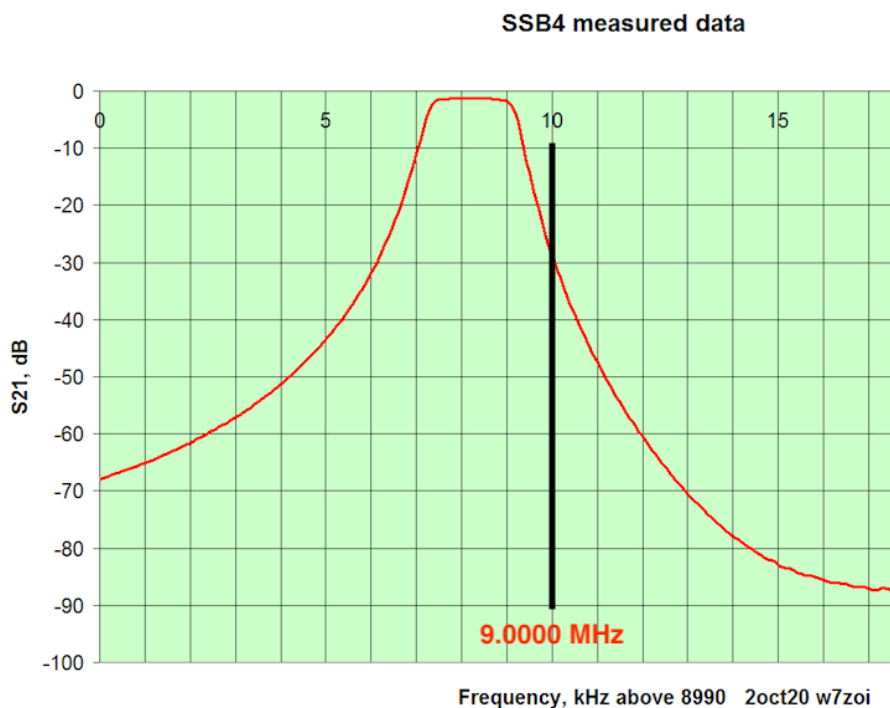

Fig 10. Response of the simple SSB filter.

The next two filters have identical circuit diagrams. The two filters have bandwidths of either 2 or 2.5 kHz, determined by the capacitor values. The filters I built used some parallel capacitor combinations, depending upon what was available in the junk box. Specifically, 133 pF was realized with a 100 and a 33 pF capacitor. 360 pF was the parallel combination of two 180 pF parts. Use what is available, but don't stray too far from the values shown. The higher passband ripple of 0.25 dB allowed us to stick with simple transformers at the ends. The 2 kHz design is the easier one to build with a cleaner passband and better stopband attenuation.
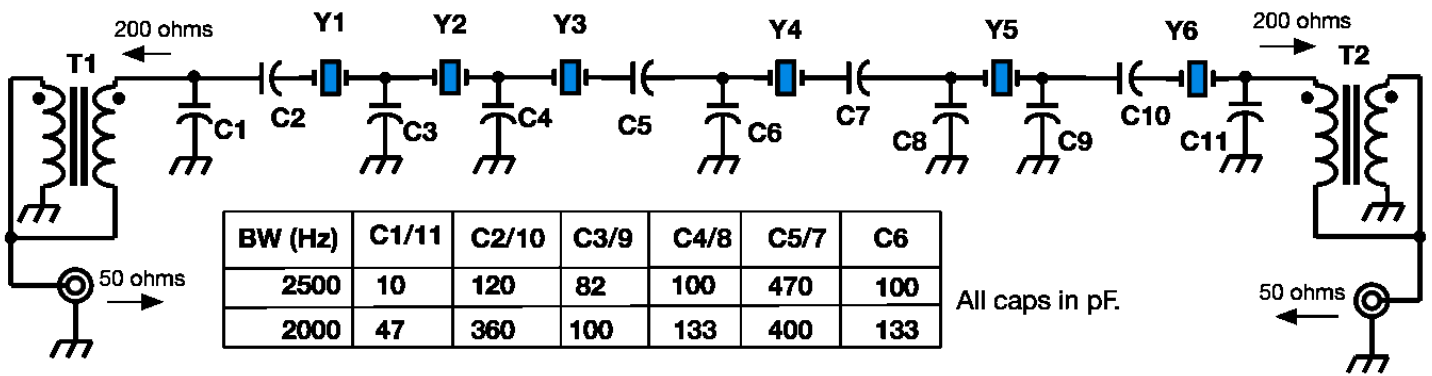
Fig 11. Schematic for two filters, each using six crystals.   The table shows the capacitor values for the desired bandwidth.
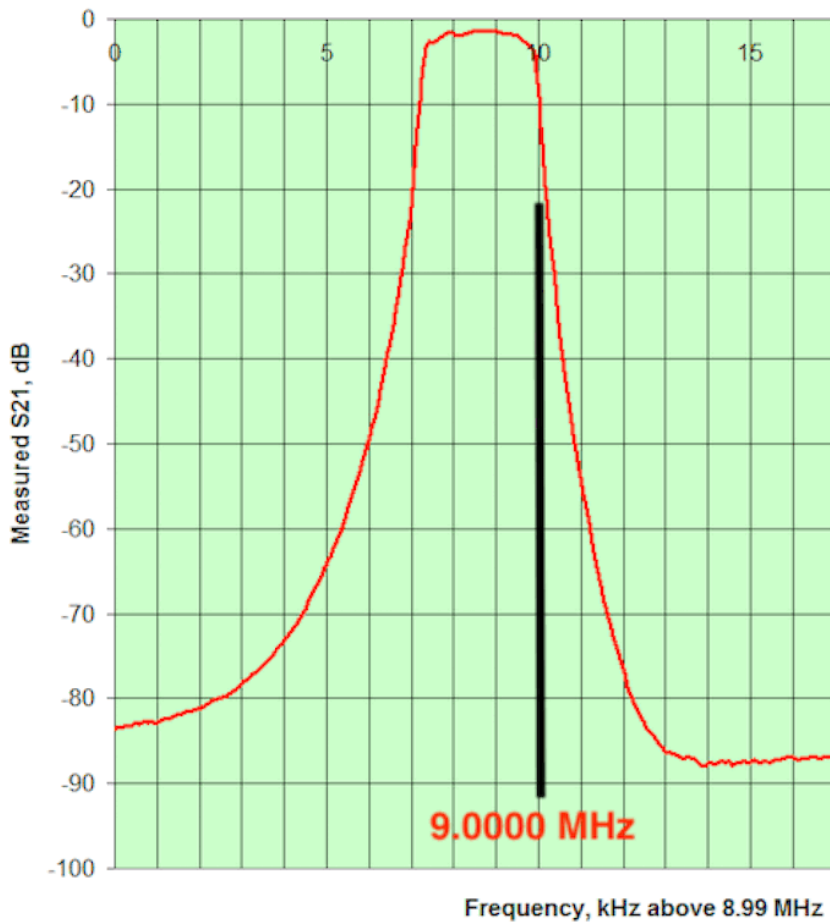

Fig 12. Response for the wider 6 pole filter with nominal bandwidth of 2.5 kHz.
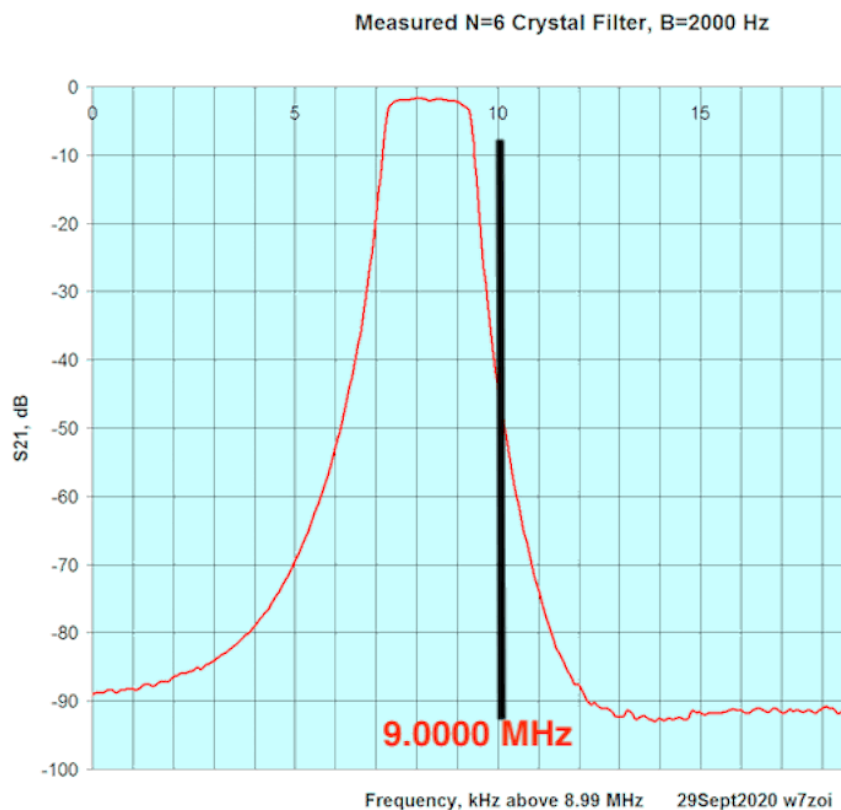
Fig 13. Response for the 2 kHz wide SSB filter.

How many crystals?

The experimenter wanting to build nothing more than a single CW or SSB filter can probably get by with an order for 10 or 15 crystals.   20 parts would probably do well if a set of filters is desired.   Note that I got 5 filters out of a batch of 35 crystals with enough extras for BFO application.

Moving Filter Frequency.

Some builders will want their filters to be at a slightly different frequency than those shown in the figures.   This is possible, but it is not trivial. Tweaking a capacitor or two won't do the job while preserving filter shape. For example, the 6 pole filter of Fig 11 has series capacitors $(C2, C5, C7, C10)$ with four of the six crystals.   A tuning capacitor serves to move that mesh frequency so that all 6 meshes in the filter are at the same frequency.   A program is included in the Ladpac suite of programs called "Meshtune.exe."   This allows every mesh in a filter to have a new series capacitor to be calculated.   See the software manual and the references 3 and 4.

An interesting variation might be to purchase a set of crystals that are 1.5 kHz higher than the ones used in the filters of this report.   The crystal parameters should be essentially the same as those that were presented here, so the same designs should remain.   But the center frequency will be 1.5 kHz higher. These crystals would be used to build CW filters that better line up with the SSB filters.

BFO Crystals.

It should not be necessary to purchase extra BFO crystals. Pick the lowest crystal in the measured group to be in a beat frequency oscillator below the filter passband. Any unused crystal in the same set should work as a BFO on the high side of the filter passband.

1 Hz Frequency Counter

Many experimenters now own a digital storage oscilloscope that has a built-in frequency counter. But the counter has only 6 digits of data displayed on screen. 7 digits would be required to read the frequency of a 9 MHz crystal to 1 Hz resolution. The circuit of Fig 14 provides this accuracy, and more. One of the 9 MHz crystals is used in an oscillator to heterodyne the output of the Fig 3 oscillator to baseband.
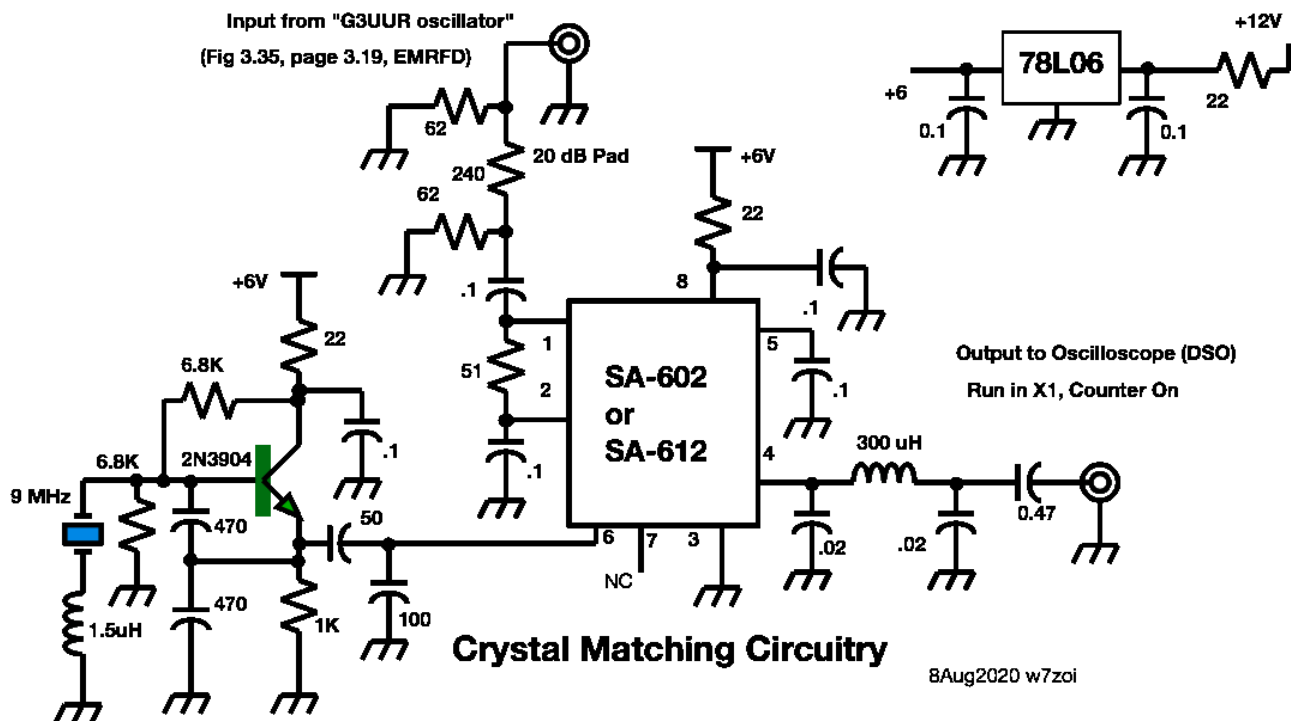

Fig 14. Optional circuit to mix the output of a 9 MHz oscillator down to baseband where it can be observed with a resolution of 1 Hz, or less. A 1.5 uH toroid inductor was inserted in series with the crystal. This can be 19 turns of #28 wire on a T50-6 toroid core.

Conclusions

This has been an enlightening project, producing a variety of filters for a minimal investment. The prototype filters presented here were all built on double sided board. The top where the crystals reside is the ground plane. The bottom contains a grid of islands generated with a hacksaw. Holes are drilled for leaded capacitors. The holes are carefully enlarged (countersunk) on the ground foil side to allow capacitor leads to go through the holes without short circuiting to ground. SMT capacitors can be used on the bottom side. It will be necessary to drill holes to connect some bottom pads to the ground plane. Two of the five filters were built with SMT parts.

Some makers may want a kit of parts and may not want to go through the process of selecting crystals. Inexpensive 4 pole kits are available from Inrad.net/home.php .   Go into the website and then find "filter kits."   These filters have a 9.000 MHz center frequency.   I have no direct experience with these kits, but have heard favorable comments from other builders.

References:

1. http://w7zoi.net/filters/30pf-stuff.pdf
2. Hayward, Campbell, & Larkin, **Experimental Methods in RF Design**, ARRL, 2003.   (out of print)
3. http://w7zoi.net/filters/meshtune_exact.pdf
4. http://w7zoi.net/filters/genfil.pdf