Mixed Form LC Bandpass Filter

Wes Hayward, w7zoi; 23, 24 and 25Aug, and 9Dec 2008

Abstract

The traditional LC bandpass filter uses parallel resonators with coupling in the form of small capacitors between high impedance nodes. End section loading is realized with either inductive coupling to an end inductor or with a series capacitor connected to a low impedance termination. This circuit degenerates into a high pass filter in the stopband. An alternative form is sometimes used where all end loading and resonator-to-resonator coupling is realized with shunt capacitors. This circuit degenerates into a low pass filter within the stopband. This study considers a mixed form. The resonators still look generally like parallel tuned circuits, allowing small capacitors between high impedance nodes to couple between elements. However, the end section loading is realized with the pseudo low pass methods. The result is a filter with a symmetric frequency domain shape and better than normal attenuation within the VHF stopband. The ideas are used to design 2, 3, and 4 element filters at HF as well as VHF.

Introduction

The underlying concept central to the design of most bandpass filters is the Dishal Method (See Zverev, Chapter 9.) What Dishal tells us is that we can design our filters of any polynomial (Butterworth, Chebyshev, etc.) by controlling the loaded Q of the resonators at the filter ends and the coupling between resonators. This sentence is important; it is essentially a complete summary of most of our design work. In this study, we will change the format of the end resonators to be the one we would use with a filter using series resonators. But we will still couple out of that resonator with small series capacitor to the next element, just as if we had a parallel tuned circuit. The basic concept is illustrated in Fig 1.

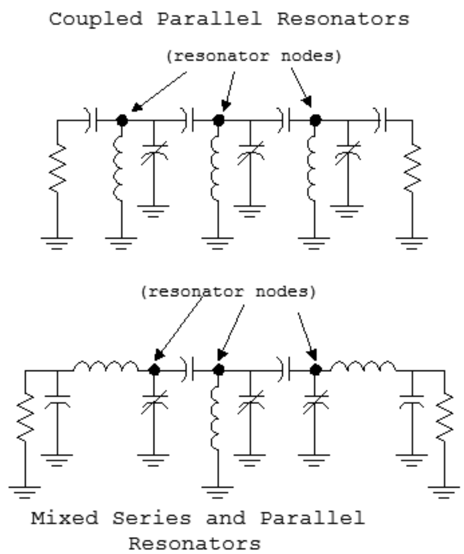


Fig 1. The top figure uses parallel resonators while the bottom one uses series resonators at the ends, but a parallel tuned circuit in the middle.

The end transformations are summarized in Fig 2.

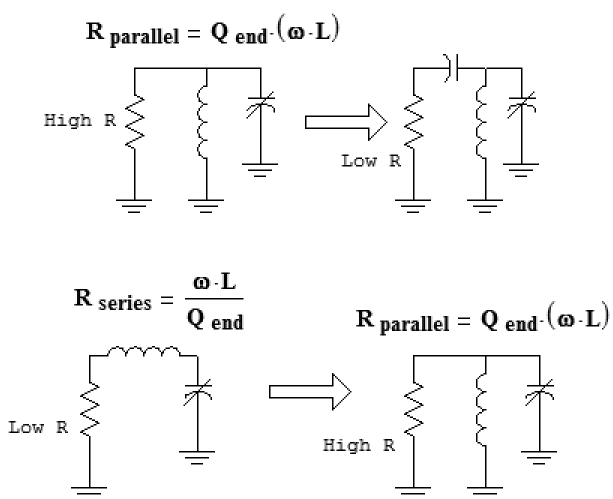
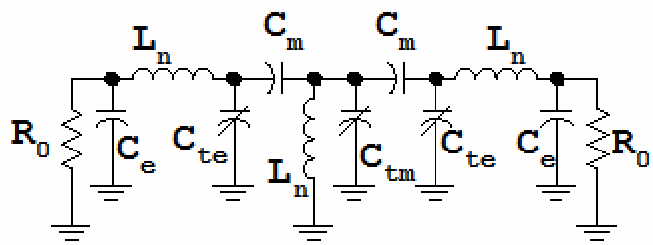


Fig 2. End transformations.

The design is summarized with the following equations for a triple tuned circuit:

Triple Tuned Circuits with Mixed Resonators.

End resonators have series L with one end going to termination and other to a grounded tuning cap. Middle resonator is just a classic parallel tuned circuit with small coupling caps.



Independent Variables: **f** (in MHz), $\mathbf{L_n}$ (in nanohenry), $\mathbf{Q_u}$, **B** (in MHz), $\mathbf{R_0}$.

$$\omega := 2\cdot\pi\cdot f\cdot 10^{6} \qquad L := L_n\cdot 10^{-9} \qquad Q_f := \frac{f}{B} \qquad q_0 := \frac{Q_u}{Q_f}$$

$$C_0 := \frac{1}{\left(\omega^2\cdot L\right)}$$

N=3 Butterworth k=0.7071 and q=1.0.

$$Q_e := \frac{1}{\left(\frac{1}{q\cdot Q_f} - \frac{1}{Q_u}\right)}$$ (This is Q of end section, denormalized.)

$$K := \frac{k}{Q_f}$$ (And this is the denormalized coupling coef.)

$$R_s := \omega\cdot\frac{L}{Q_e} \qquad C_e := \sqrt{\frac{R_0 - R_s}{R_s\cdot\omega^2\cdot R_0^{\,2}}}$$

$$C_m := C_0\cdot K$$ **But, this is the wrong Cm. See refined form below.**

c, cc, and ccc are intemdiate variables.

$$c := \frac{C_e^{2}\cdot\omega^{2}\cdot R_0^{2}+1}{C_e\cdot\omega^{2}\cdot R_0^{2}}$$

(c is the series equivelent capacitance at the termination.)

$$Z := R_s + j\cdot\left(\omega\cdot L - \frac{1}{\omega\cdot c}\right)$$

Doing the math produces cc, which is the capacitance we will use for the end for coupling calculation. Actually, we must use the geometric average of cc and C0 for this, ccc, because the middle resonator is a classic parallel circuit.

$$cc := \frac{\frac{1}{\omega}\cdot\left(\omega\cdot L - \frac{1}{\omega\cdot c}\right)}{R_s^{2} + \left(\omega\cdot L - \frac{1}{\omega\cdot c}\right)^{2}}$$

$$ccc := \sqrt{cc\cdot C_0}$$

$$C_m := ccc\cdot K$$ **(coupling cap)**

$$C_{te} := \left(\frac{1}{C_0} - \frac{1}{c}\right)^{-1} - C_m$$

(end tuning cap)

$$C_{tm} := C_0 - 2\cdot C_m$$

(middle tuning cap)

Design Examples

A 10% wide TTC at 10 MHz was examined. BW=1. I did simulations of this filter (red) and a classic one with coupled parallel resonators. The comparison is shown below.

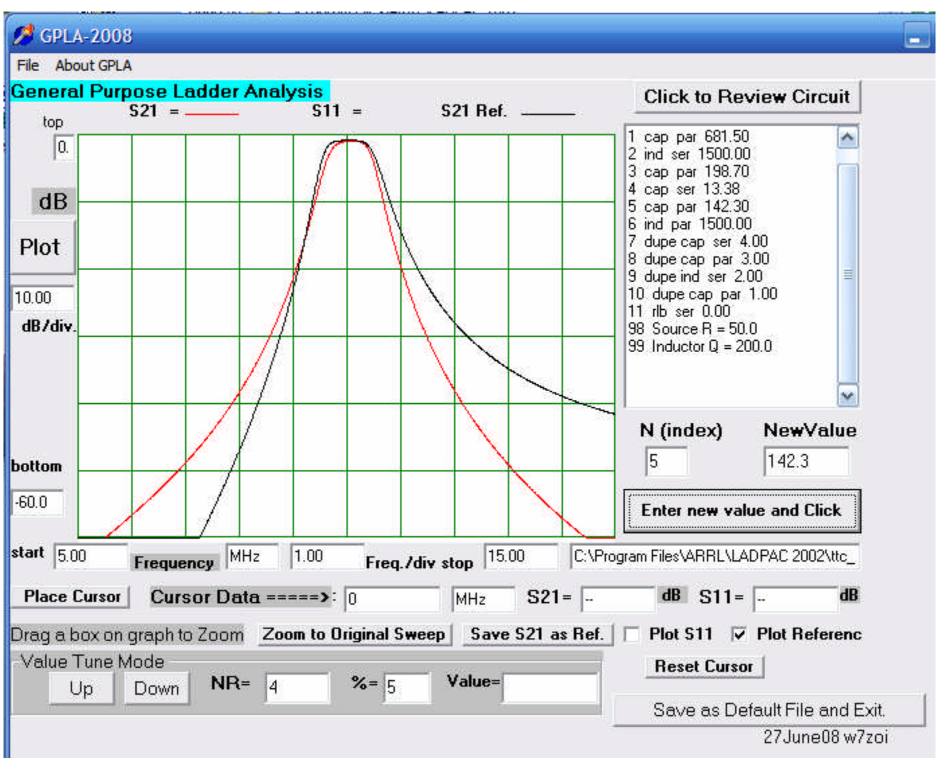


Fig 3. Comparison of a mixed form bandpass filter (red) and one with parallel tuned circuits (black). Note the improved symmetry. These filters have a 1 MHz bandwidth at 10 MHz.

Two of these third order bandpass filters were constructed at VHF. The pragmatic goal here was to generate a simplified filter for use in our DC-70 MHz spectrum analyzer, which uses a first IF of 110 MHz.

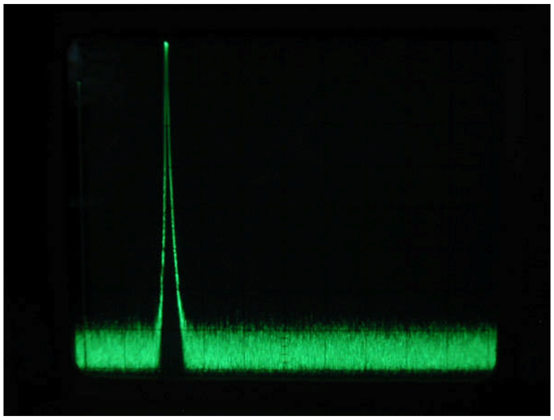


Fig 4. Response of a VHF filter tuned to 110 MHz. The sweep extends from DC to 500 MHz. This measurement was done with a spectrum analyzer and tracking generator.

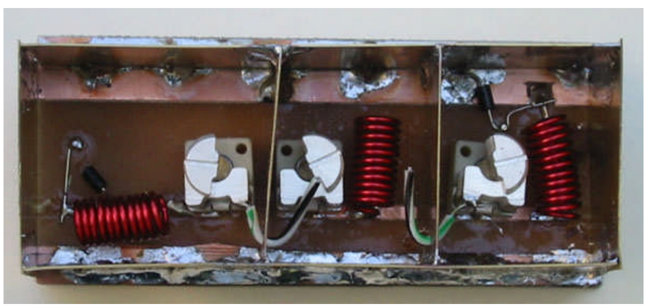


Fig 5. Inside view of "Filter 1," which used air dielectric 2-10 pF trimmer capacitors (ceramic insulation), 100 pF ceramic shunt end capacitors, and "gimmick" capacitors from the end resonators into the middle. The coils are wound with #18 wire and consist of 10.5 inches of wire wound into 11 turns on a ¼-20 machine bolt. SMB coax connectors extend through the base, which is circuit board material. The walls and shields between resonators are 1 inch brass strips from a Hobby Shop. This filter is "semi-ugly." That is, it's a breadboard, but has a pattern on the side of the board containing the components. This was cut by hand. The other side serves as the circuit ground.

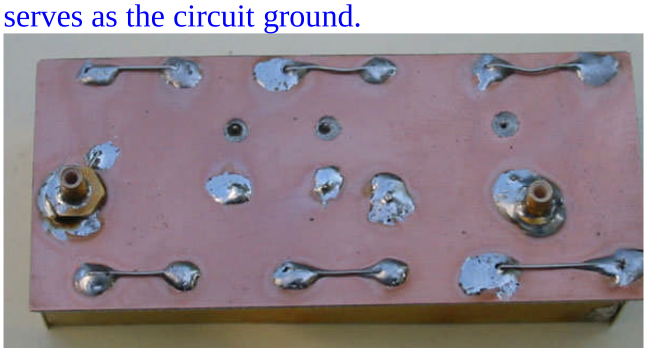


Fig 6. Outside view of "Filter 1." The coax connectors and the trimmer capacitor terminals can be seen sticking through the board. The wires are connections to grounded foils on the other side of the board where brass walls reside.

A second bandpass filter was built for 110 MHz. The inductors were the same as used in the first filter. However, plastic insulation trimmer capacitors were used with completely ugly construction. This filter is shown below:

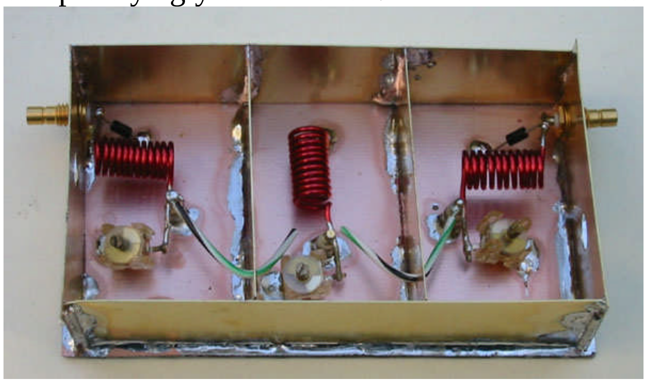


Fig 7. VHF bandpass "filter 2." This circuit uses plastic trimmer capacitors. Small Teflon standoff posts were used at the critical nodes, mainly as mechanical support. Without these, the filter was subject to vibration problems. The circuit is exactly the same as the first filter.

Filter 1 seemed marginally better with a slightly lower insertion loss. Filter 1 with the higher quality capacitors was easier to tune. Both filters are in the vicinity of 8 dB loss with a 2 MHz bandwidth. The shapes are excellent with good compliance with the simulated responses.

The next experiment was a 10% wide filter at HF. For this, I picked a circuit centered at 10.7 MHz, a frequency of general interest. I then measured the filter with a spectrum analyzer and tracking generator. The circuit diagram is shown in Fig 8 with a photo in Fig 9.

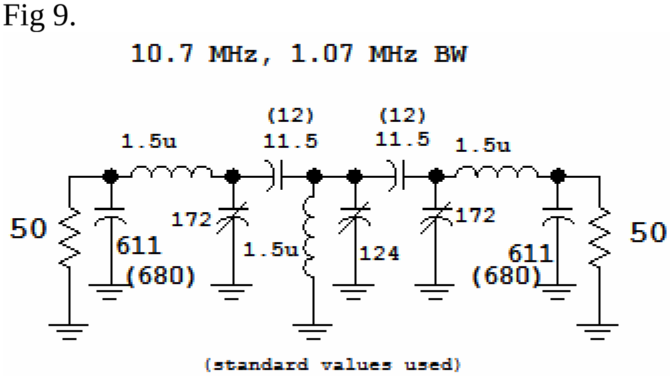


Fig 8. This filter was built with the components in parenthesis, for they were standard values on hand. The inductors were 21 turns of #22 enamel wire on T50-10 toroids. I used that core merely because I had a pile of them from an EBay purchase. I did not do a Q measurement.

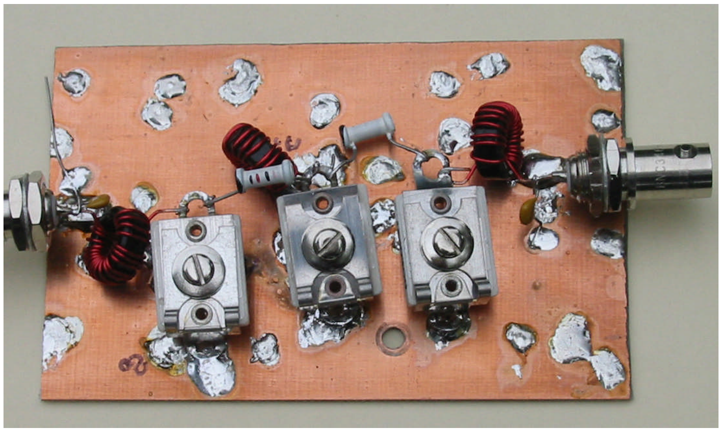


Fig 9. Photo of the prototype breadboard (ugly to the core) of a 10.7 MHz bandpass filter. Mica compression trimmers (9 to 180 pF) tuned the filter.   The scrap of circuit board material had been used for other experiments.

The test setup used for evaluation is shown below.

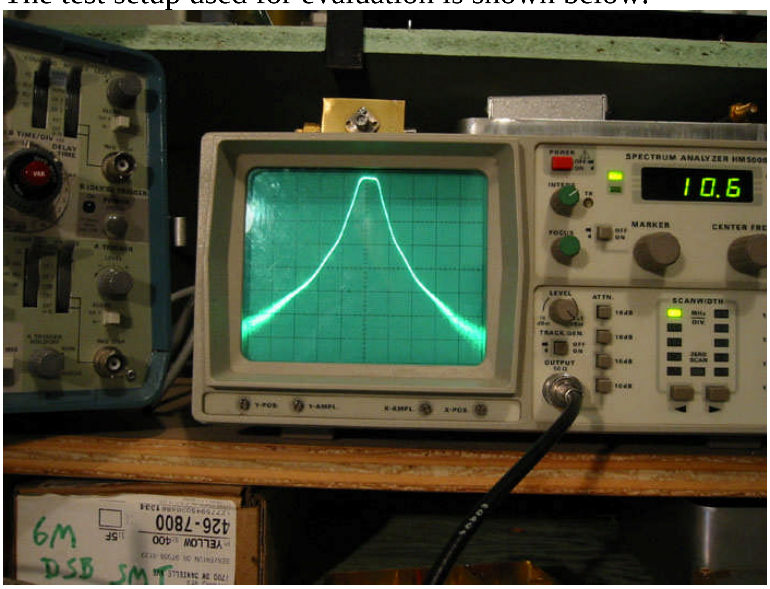


Fig 10. Test Setup.

Several photos follow that show the response.   Particular care was devoted to the stopband to be sure that the performance was not compromised by stray couplings.

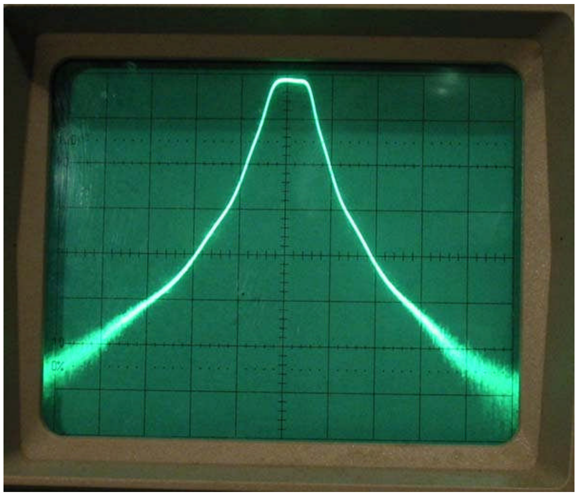


Fig 11. A 1 MHz/div and 10 dB/div plot, showing a good match to the simulation.

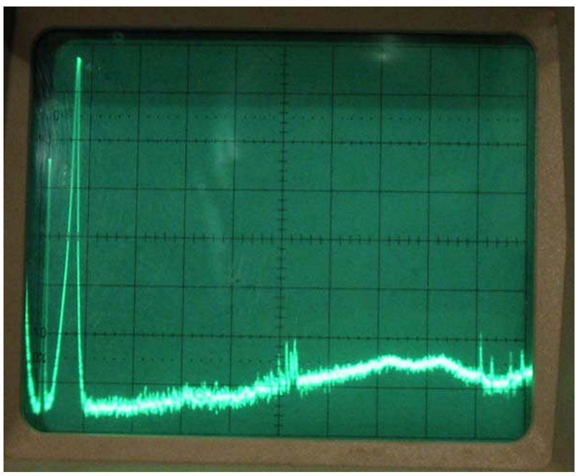


Fig 12. This plot covers the spectrum from near DC to 200 MHz.   Clearly there is some compromise in the VHF stopband.

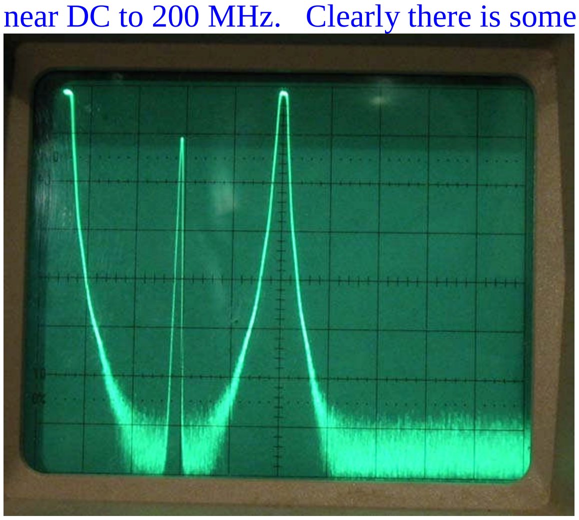


Fig 13. Plot with 5 MHz per division. The filter response is at the display center, so the analyzer image and zero spur are evident.

Having measured the 10.7 MHz filter with a spectrum analyzer and tracking generator, the next experiment examines the circuit with a Vector Network Analyzer.   The VNA used is one of the N2PK types. (See N2PK's work on the web.) Measurements were done from 5 to 16 MHz in 50 kHz steps. The data from 9 to 12 MHz is show below.

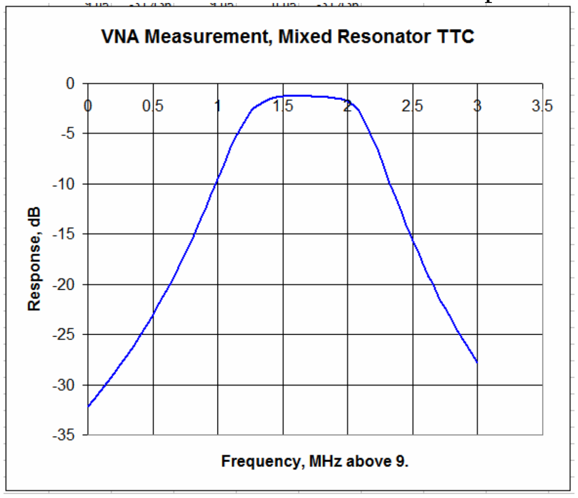


Fig 14. VNA measurement of the 10.7 MHz filter with 10% bandwidth. The measured insertion loss of this filter is 1.27 dB.

A Double Tuned Circuit

If the Triple tuned filter looked so good, would a double tuned circuit also be viable? The mixed resonator DTC is shown, with the calculated response. This filter was designed for a bandwidth of 1 MHz at 10 MHz center. The design equations are an obvious simplification of those presented for the triple tuned filter.

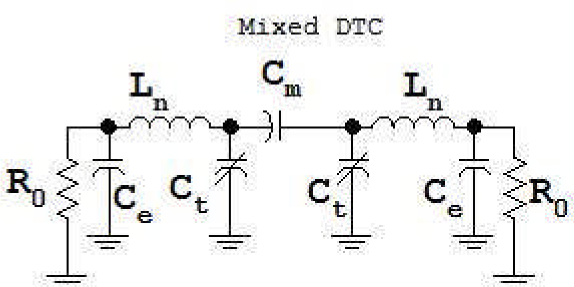


Fig 15. A Mixed form double tuned circuit. There is no parallel resonator. However, the end section loading is done with low pass circuitry while the coupling between resonators is high pass.

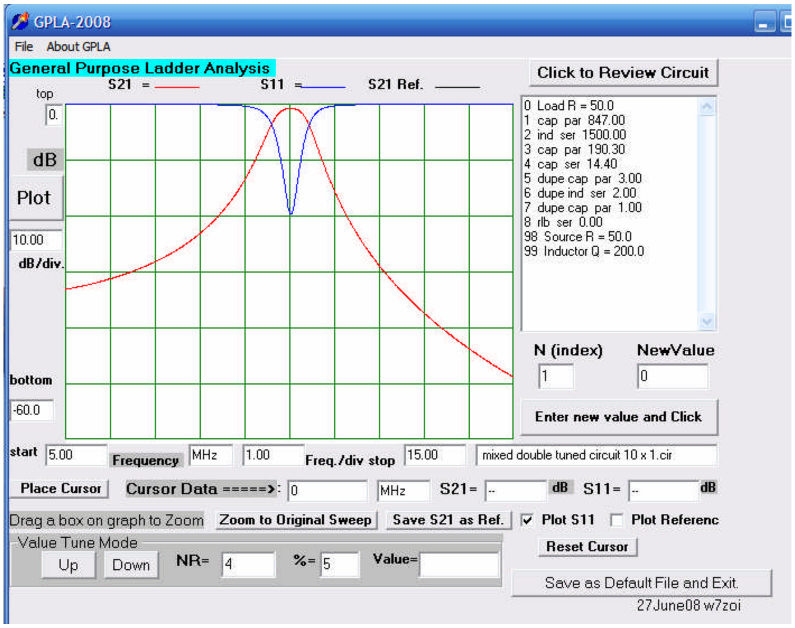


Fig 16. Simulation of the double tuned circuit of Fig 14. Clearly, this 10% BW circuit lacks the advantaged shape of the triple tuned circuit. It may still be a good choice in a narrower bandwidth.

A Filter with N=4

The equations were modified for the design of a filter at 10 MHz with a 1 MHz bandwidth. In all cases, the inductor was 1.5 µH with a Q of 200. The N=4 general circuit and a simulation of the response are shown below.

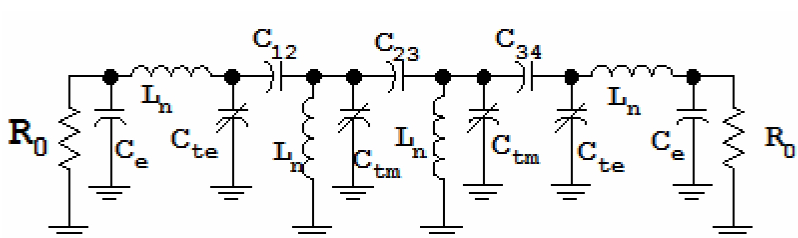


Fig 17. A mixed form bandpass filter with four resonators. The procedure is similar to the TTC design.

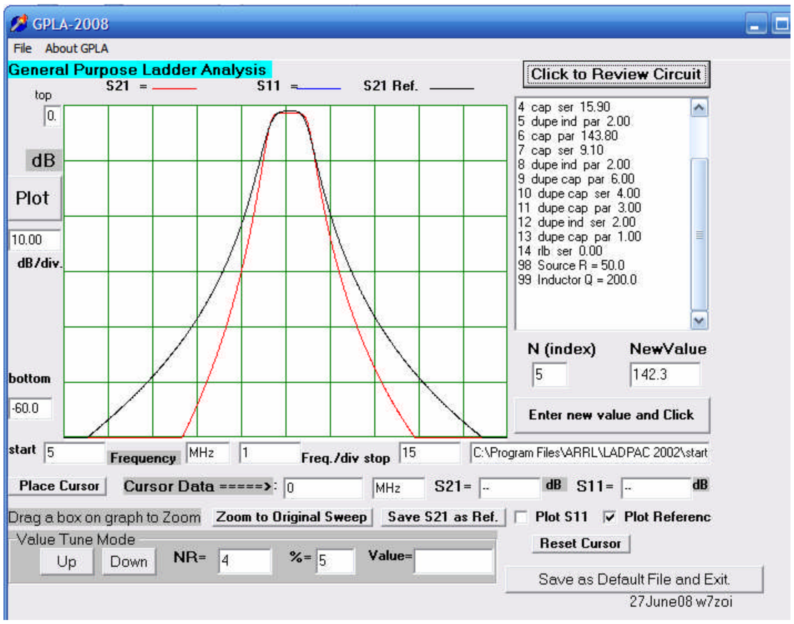


Fig 18. Response of a QTC (quad tuned circuit) and a TTC, both using a mixed form. The QTC is in red. Both filters were designed for a bandwidth of 1 MHz at a 10 MHz center frequency.

A friend, John Lawson, K5IRK, built one of the 4th order filters and measured a response much like that shown in Fig 18.