Using Your VNA to Demystify RF Filters

So you have a nano VNA (nVNA), it is a remarkable piece of kit, and great for antenna measurements, but what else can it do? Well, quite a lot, and this article will describe one other, use which is how to characterise inductors to to help make RF filters. Not only can you measure the inductance at the operating frequency of the filter, you can also accurately measure the unloaded Q (Qu) by what is known as the critical coupling method. This is very useful as it is the key to predicting the loss through a filter.

Measuring the Unloaded Q of an Inductors

In resonant circuits the unloaded Q (Qu) is a measure of how much resistance there is compared to the reactance and is important for determining the loss, with higher values of Qu indicating lower losses. It is important because resonance is when the input frequency to the circuit is close to the point where the reactance and susceptance of the inductor and capacitor exactly balance. Electrically this means that energy in the circuit alternates between magnetic and electric fields in the inductor and capacitor respectively. As a result significant current flows between the two, even if there is very little current in or out of the circuit. The Qu parameter quantifies the resistive part and it is current sloshing about between L and the C that then incurs energy loss. Also, it generally the case that inductors have poorer Qu than capacitors by at least a factor of 10. So while strictly speaking the measurement quantifies the Qu of the resonator as a whole, it is attributed to the inductor because by far the majority of the losses are in that element.

The Measurement Set-up

In this article it is assumed that you know how to calibrate the nVNA and that you have measured the inductance separately. You can use one of those handy component testers or the nVNA itself. I recommend using the nVNA, it is not much more work and tells you the inductance at the desired frequency of operation as well as how close that is to any self resonance problems. The component tester method is very approximate as it works at quite a low frequency.

The sketch in Figure 1 shows the measurement set up. I use a short piece of coax with an SMA connector on one end and the other end cut off with a short length of the outer stripped back. The capacitor C2 has a value that resonates with the measured inductor Lx and has to be the sort of good quality RF device intended for the eventual filter design. The capacitor C1 needs a little trial and error, start with a small fixed capacitor, 47pF is a good guess. Whether that is too large or small can be seen from the measurement itself. Adjust the fixed value accordingly and once you are slightly smaller than the right value add a small variable capacitor to give the degree of fine adjustment needed to get to the critical couple point.

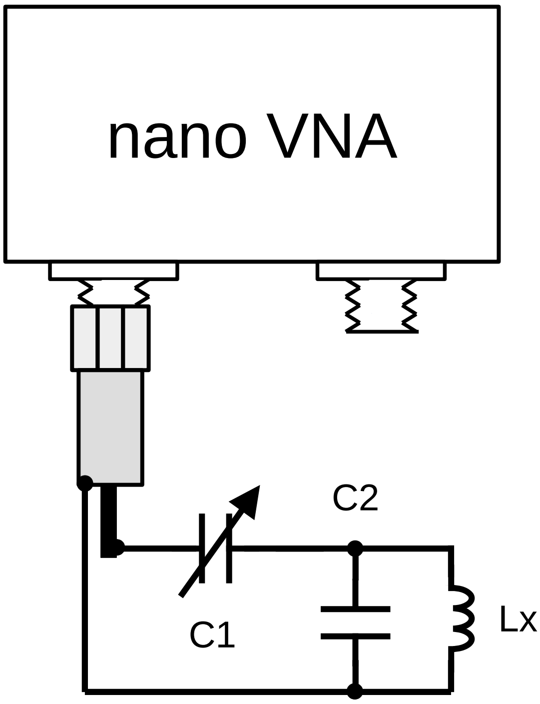
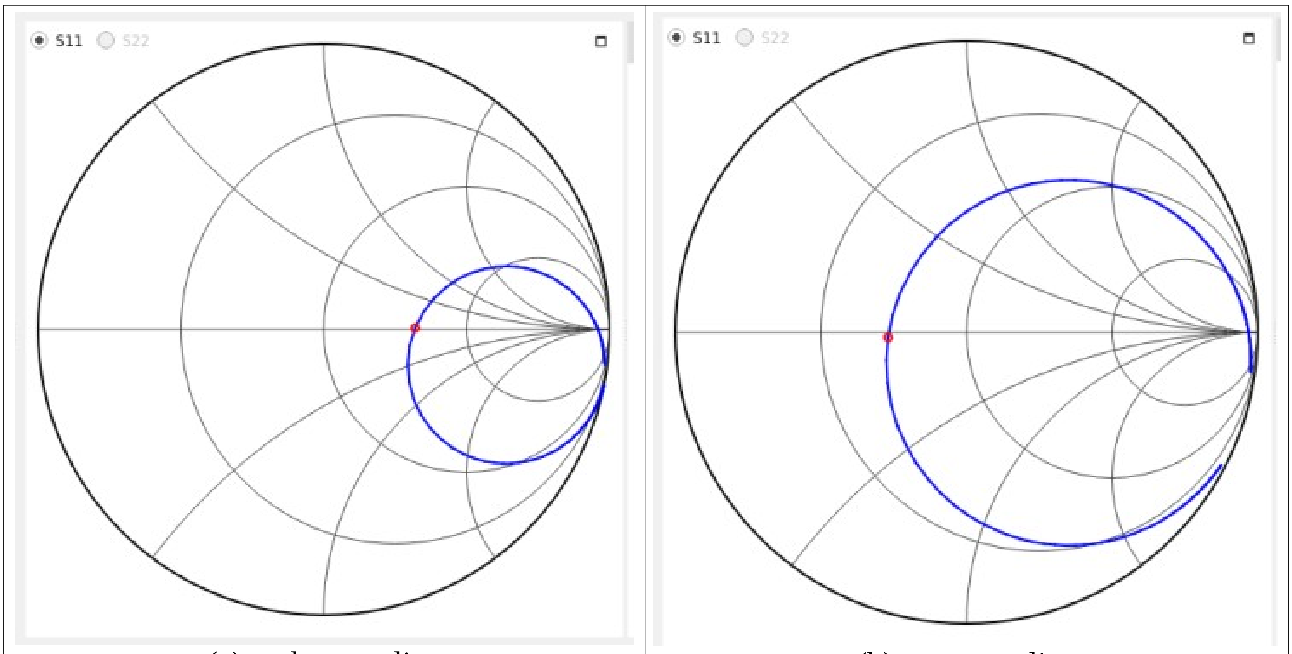


Figure 1: measurement set-up

The nVNA needs to be calibrated for this measurement with a frequency range round the desired filter design frequency. For a 7 MHz filter I used 5 to 10 MHz with 501 points. The sweep needs to be from slightly below to slightly above the resonant frequency and quite fine, especially for high Qu inductors, so while something like a 501 point sweep is quite slow it is needed.

Figure 2: measurement of coupling via the series capacitor C1



(a) under coupling (b) over coupling

The smith chart display nicely shows the resonance and whether the initial choice of capacitor C1 is too big of too small. Figure 2 shows typical measurements. Increasing frequency is always a clockwise arc on the smith chart and the under/over coupling demarcation line is the unit circle (R=50 normalised to 1). Notice that the measurement arc is slightly rotated clockwise relative to the unit circle, you can rotate back using the phase reference extension sliders on the nVNA control panel. Over coupling indicates that C1 is too large and needs to be decreased. If the measurement is under coupled add capacitance, then when close add the small variable cap at full mesh to see if that then becomes over coupled. For this I use a 50pF air spaced variable cap from an old radio.

Measurement Method

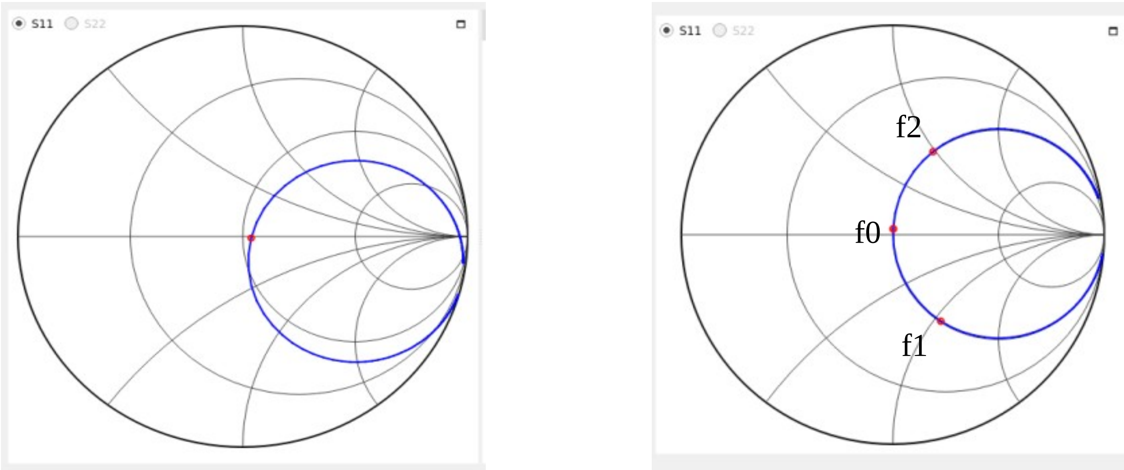
Once the right value of C1 has been established, to get to the critical coupling point, adjust the reference plane to line up the measurement arc with the unit circle and adjust C1 to exactly follow the circle. Then, using the marker function you can measure the resonance frequency (f_0) where the measurement arc goes through R=1 (j=0) and 2 other points which are where the arc goes through 1 ± j, these are designated f_1 and f_2, see Figure 3. From these 3 frequencies the Qu can be evaluated from:

$$Qu = 2 \cdot \left(\frac{f_0}{f_2 - f_1} \right)$$

For a high Qu inductor these 3 points are quite close together in frequency and you will see why a fine sweep is needed. Also, note that the resonant frequency f_0 does not need to be exactly that desired for the filter. The measured Qu is still accurate over a reasonable range of say within 10% of the filter centre frequency.

Also, for those that recognise the formula from elsewhere and to explain what is happening. Qu is the unloaded Q; but the resonator has to have some coupling (i.e. loading) to get energy in to make the measurement. The critical coupling point is where the loading loss via C1 exactly equals the internal loss of the resonator. Since the Q of one element combines with that of another in the same way as resistors combine in parallel. The total measured Q is $f_0/(f_2 - f_1)$ but that is made up of equal parts of the loading Q via C1 and the actual Qu of the resonator. Hence the factor of 2 in the formula.

Figure 3: adjustments for the critical coupling measurement



(a) adjusting C1 for critical coupling

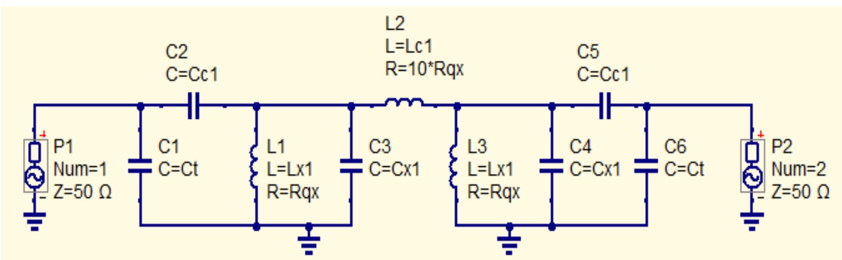
(b) S11 port extension increased to line up with the unit circle

The measurement in Figure 3 has the f markers at 7.345, 7.375 and 7.405 MHz giving a Qu of 246. Which is pretty good, as it is quite difficult to get much higher than a few hundred at these frequencies. The form of the inductor used in shown the photograph of the final filter in Figure 6.

Example RF Filter

To illustrate the practicality of this idea, it was used to characterise the inductors used to make a basic 2 pole preselector filter for an HF receiver. The schematic and simulated results using QUCS is shown in Figure 4 and Figure 5. It uses 2 inductors L1 and L3, having equal values (Lx) of the type measured above for the resonators. Note that there is also a third coupling inductor L2, but as that is not part of a resonator so the Qu of that is much less important and a standard part with moderate Qu can be used. Similarly the Qu of the capacitors is so much higher than the inductor that they can be ignored.

Figure 4: example filter schematic

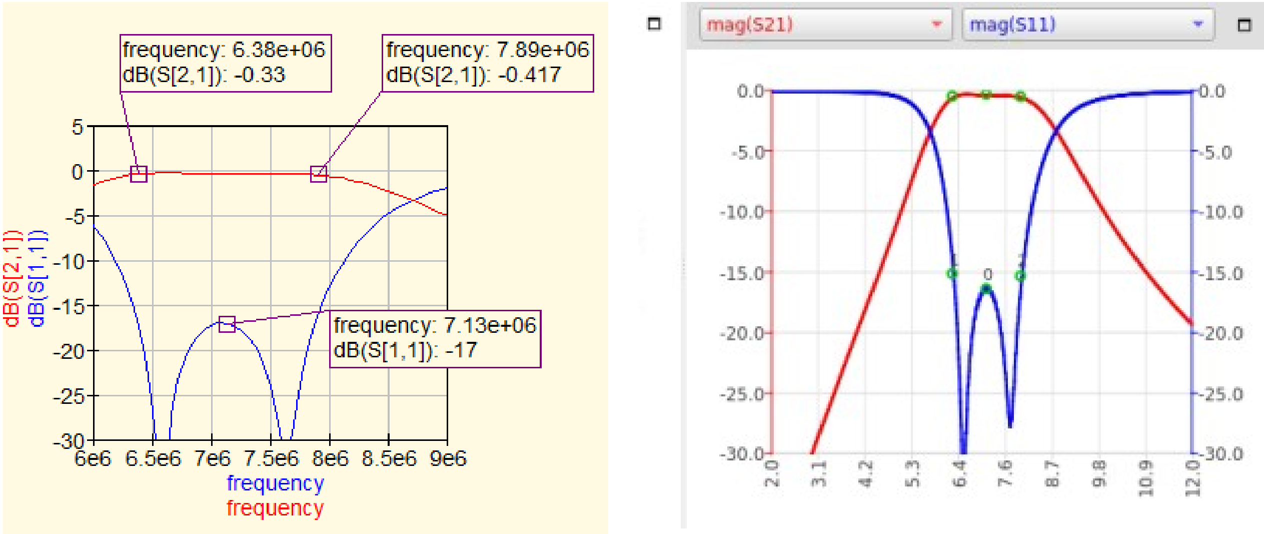


Ct = 100pF
Cc1 = 470pF
Lc2 = 2.2uH
Cx1 = 560 + 100pF
Lx1 = 760nH
Qu = 240

Inductor L2 is assumed to be 10x poorer Qu than L1 and L2

$$Rqx = 2\,pi \cdot 7 \cdot 10^6 \cdot \frac{L_{x1}}{Q_u}$$

Figure 5: a 7 MHz Test Filter



(a) QUCs Simulation

(b) Measured Filter response

Figure 5 also shows the nVNA measurement with markers indicating the bandwidth and loss at 6.324, 7.125 and 7.945 MHz with a passband loss of 0.5 dB, reasonably close to that predicted from QUCS. Figure 6 shows the construction of the filter and the style of the inductors used. The cores are blue/yellow with 19 turns of 22 gauge wire on what looks like T50-17 material.

Figure 6: photograph of test filter

Predicting Filter Loss

The loss through a filter (in dB) is related to the Qu as show in the equation below, where GD is the group delay and Fo the centre frequency. From this you can see that for a given filter design (a fixed GD and F_0) higher Qu values correspond to lower loss.

$$Loss(dB) = \frac{8.686}{Q_u} \cdot GD \cdot F_0$$

You may not be familiar with group delay, but don't worry as it can be calculated in QUCS and measured with your nVNA. It is the time take for a signal to travel through the filter and is proportional to the number of resonators in the filter and inversely proportional to the filter bandwidth. Incidentally this is essentially why narrow band filters have more loss than wider ones.

After you have made and measured a few inductors you get an idea of the range of Qu that can be achieved with the cores and things that you normally use. You can also evaluate those unknown cores in the junk box and weed out the ones that are only intended for LF. Saving time and heartache when erroneously trying to use them way beyond the intended frequency of operation.

Also, when you have a filter design, you can simulate it with QUCS, obtain the group delay and then get an idea of the loss you will get in a practical filter using the Qu values you have measured.

Summary

The nVNA is a revolutionary instrument for amateur radio. Giving access to measurements that previously required professional type (and cost!) equipment. That and free software such as QUCS opens up scope for useful experimentation and hopefully clarifying some of the mysteries that seem to be associated with filter design. In particular, measuring the Qu of the inductors gives essential knowledge as to what can be practically achieved for a particular filter design.