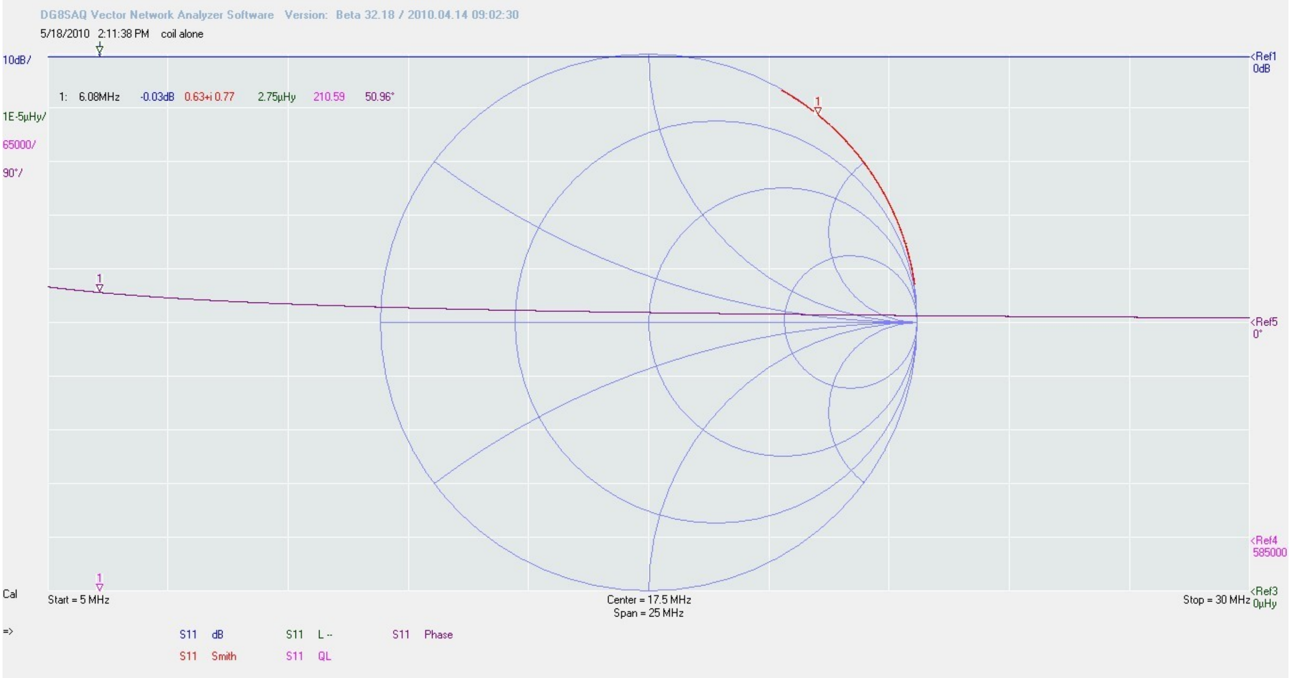
Chapter 4 LC circuits

In the chapters 2 and 3 we played with capacitors and inductors. With these two components you can form all kinds of nice and useful circuits. We use them most times in filters and oscillators. There are several ways to combine them. The most used configurations are parallel and serial.

We did see before that an inductor forms a reactance and as frequency rises the reactance becomes bigger. His little friend the capacitor is just the opposite. It's reactance decreases as frequency goes up. So this must give some great pictures. There must be a point where they are equal in reactance. And if they are equal wonderful things happen. The complex notation will be, for instance, 0+100 ohm for the inductor and 0-100 ohm for the capacitor. If you add those to you get 0+0. So that means |Z| is zero ohms. If we send a signal through this combination we get the situation that... ohoh, I'm forgetting something. This is going to be a practical manual so lets practice.

We take our famous DUT holder and take a nice coil. We solder it for use in an S11 measurement (terminate port 2 of the DUT-holder with the short) and do a open, load, short and also for later use a tru calibration up to 30MHz. This first sweep is to check our coil is really behaves like a coil.



We see here that we have a coil that is 2.75uH. The Q is 210. This is telling us something about the quality of the coil. This tells us the coil has a small real part and so there are not much losses. If the Q was infinitive high the energy stored in it's magnetic field would stay there for ever. It will not dissipate any power. However in the real world there is resistance and loss so the Q will be lower. The problem is that Q is used for different things in different situations. If you look in an engineering book you can find about a dozen formula's for Q. The Q for a capacitor, for a coil but also the Q for a LC circuit. And they make a difference between loaded and unloaded Q. So Qou never know :-)

In short:
Q tells something about the ability to store energy or in other words if there are losses.
Unloaded Q, the ability to store energy in a isolated situation.
Loaded Q, if you hook it up to something else, the energy stored can “leak” away so lowering the amount of energy in the circuit and lowering the Q. (some chapters ahead, about tuners, we will learn that a heavy loaded Q is not always bad.)
Q: used in resonant circuits tells us also something about the bandwidth.

More info about the loaded and unloaded Q. This is something you must know because it is rather fundamental in network analyse. We always talk about load matching. So for the non-engineers a maybe helpful analogy:

See it like this. The coil is a closed room and in there a bunch of rather hyper electrons are running around with no way to go. If there is a room next to it (capacitor) and we open the door, they are going to run from the one to the other, but still no escape. The problem is there are a bunch of electrons already running around in that room too. So if one leaves the first room there will be space for a critter from the second room to go to the first. Now he hook up a third almost empty chamber to both rooms. But this one has some nasty electron killers, we call it the "room of resistance". So now our little friends have more room and run all exited in all rooms but the ones that enter the resistance room sadly never return. So we lose some dear friends. The electrons do not like this and it degrades there **Q**uality in life.

So if we load the coil or LC circuit with external resistance we lose energy and even if the unloaded Q or component Q's are great, our loaded Q will sadly decrease. In an ideal LC circuit in resonance all energy from the coil goes to the capacitor and vise versa. This loop will go on for ever.

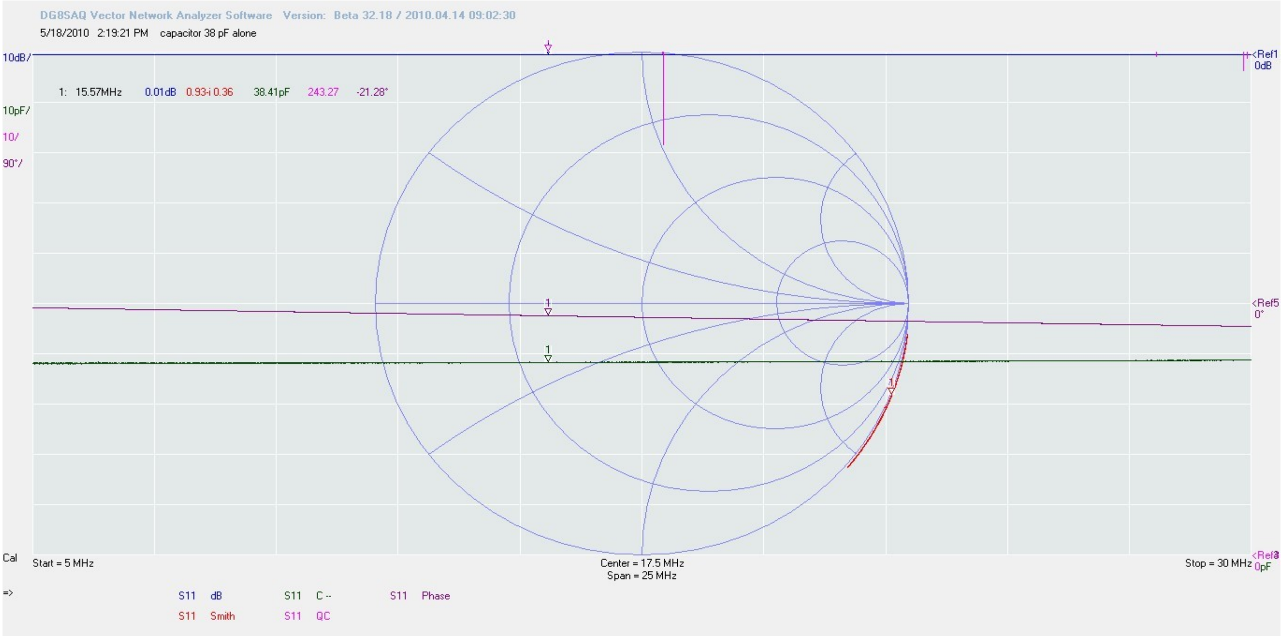
You see also some problems. You sometimes want a perfect Q to store lots of energy but the energy has to pass through. For instance in antenna's. So the total circuit has to have a low Q but the components must be as good as possible. Who said life is easy ?

We will see this effect later.

OK, we have our coil, now we need his buddy.

We take a 38pF ceramic cap or a variable air capacitor.

Nice, it turns out to be a real 38pF capacitor with a Q of 243. But I also used a variable one:



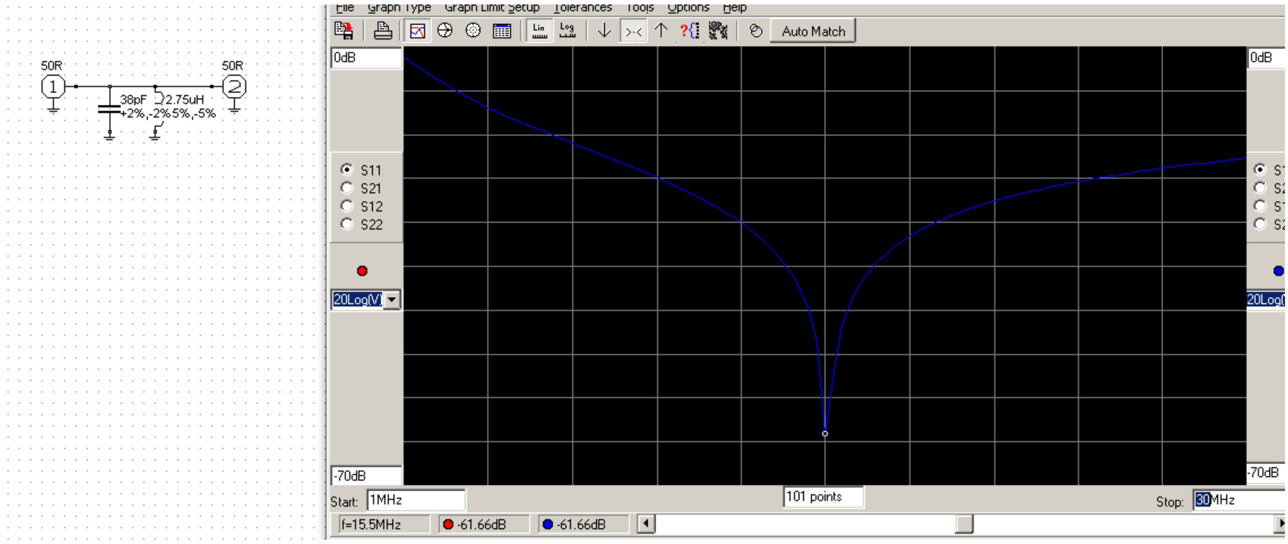
Also set at the same value but this one has a Q of 312. That is a bit better.

DG8SAQ Vector Network Analyzer Software   Version: Beta 32.18 / 2010.04.14 09:02:30

5/18/2010   2:22:40 PM   variabler aircapacitor 38 pF alone

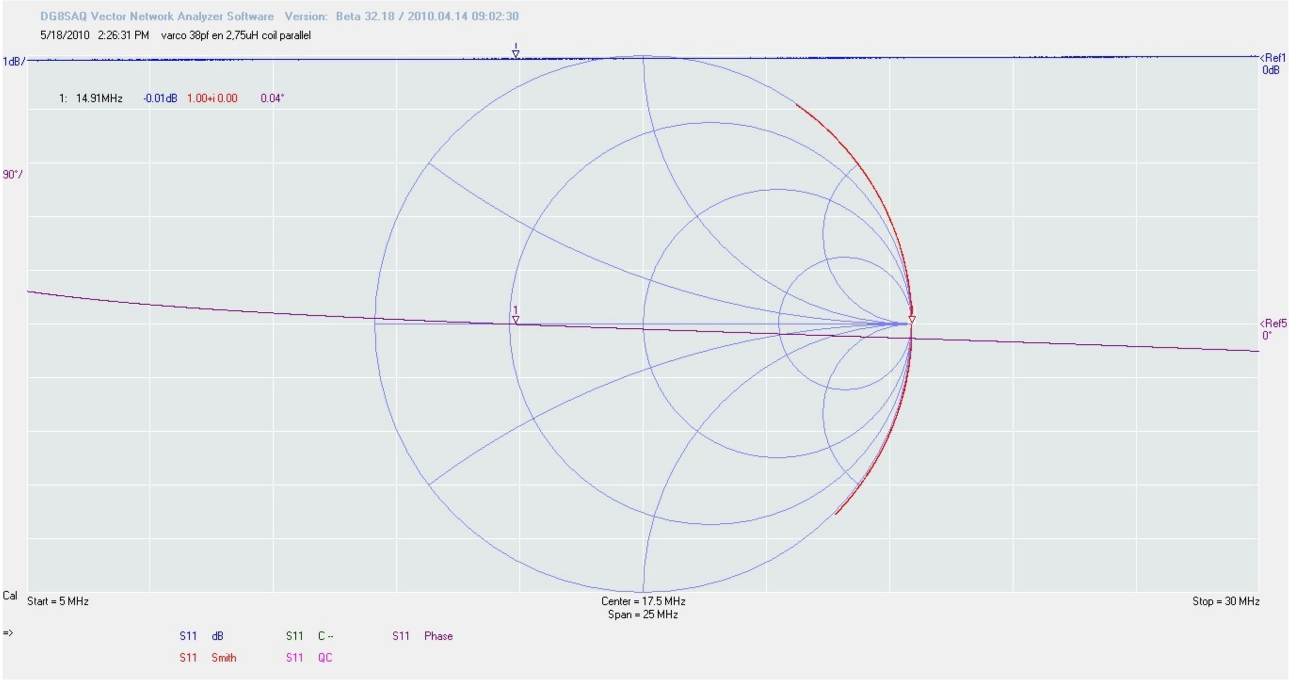
1: 15.57MHz   0.01dB 0.93-i 0.37   39.62pF   312.90   -21.94°

So what are we gonna do with these two. Lets hook them up in parallel . First as usual a simulation. This time in RF-sim.



Nice isn't it. We see a resonance at 15,5Mhz. You also see a strange thing. The signal behaves not symmetrical. The first half is done by the inductor, the second half is merely the work of the capacitor and you see, they do not have the symmetrical slope. If you look in chapters 2 and 3 you see at first a fast rise/fall and and later a slowly changing curve.

But now for real. We solder them both on our DUT holder from centre to ground and short port two on the DUT holder. Let us see:

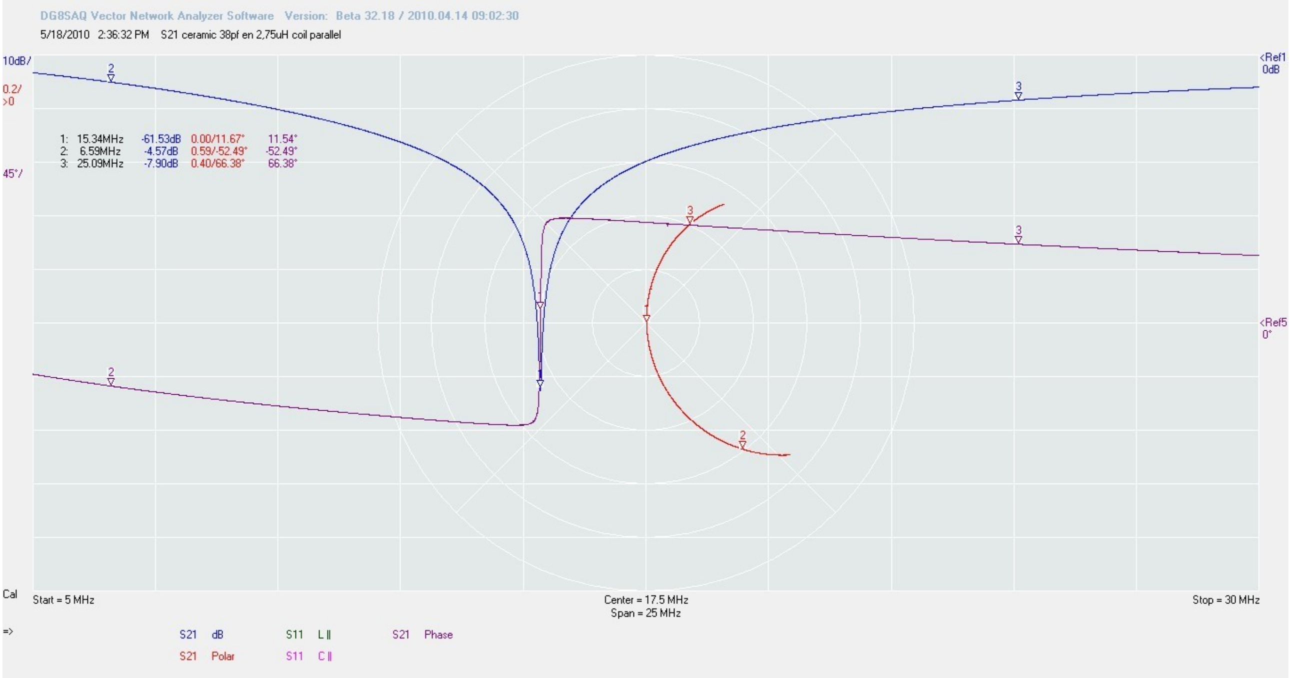


Here I used the variable capacitor. Bummer, this does not look like the other picture. At 15,5Mhz we do not see a thing. Must be the cap, lets try the other: you see it below:

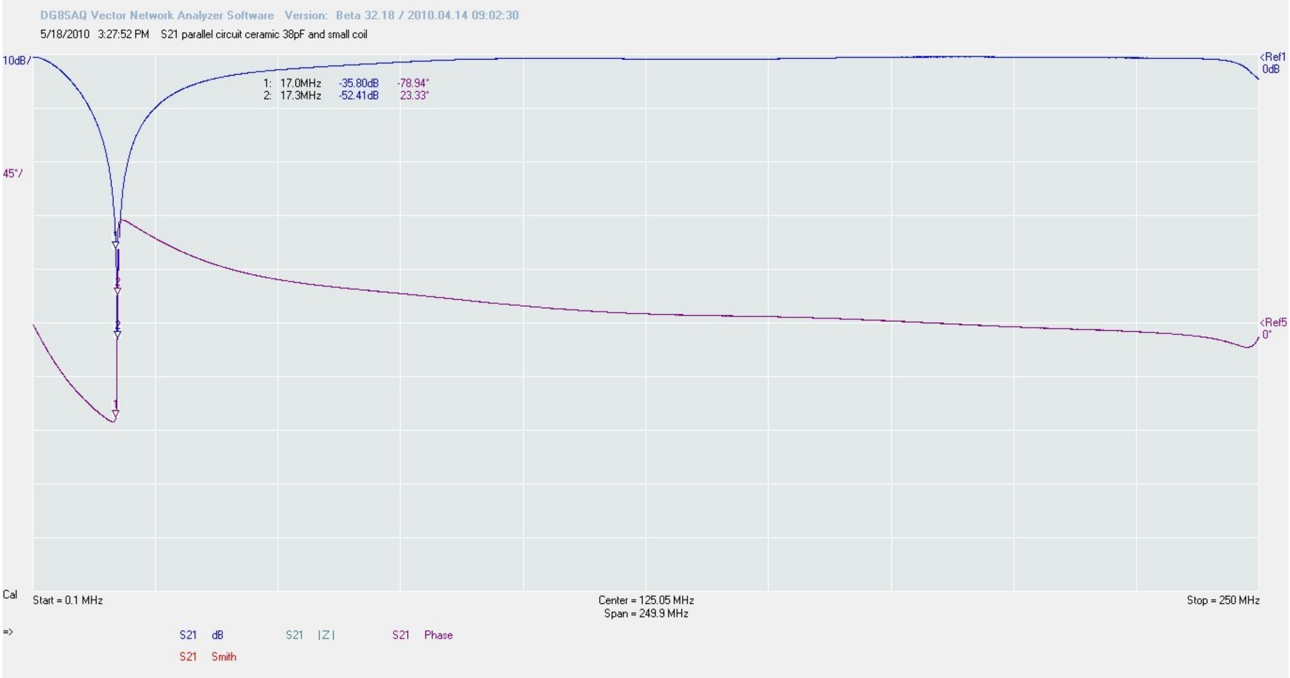
Also the same problem. Let examine why we see this. A circuit in resonance has a reactance that is almost zero. So in a parallel configuration this means that at the resonance frequency the signal is almost shorted to ground. At other frequencies it is a high impedance. But wait, we did a S11 measurement. So we see S11 in the form of the return loss. If there is resonance the phase will tell us. At that point the phase from the coil and capacitor cancel each other out so the combined phase will be zero and there will be a phase jump. As expected, we see it here at 15.16MHz, it is almost at the point we simulated. So S11 is not the way. But why does the simulation shows us what we want.

Simple, here the circuit is “captured” between the two ports so that has a 50 ohm resistor in parallel. So we measure the Return loss over the resistor influenced by the parallel circuit and that also “loads” the circuit. We get a voltage divider.

No problem, we remove the short from the DUT holder, hook up port 2 and try S21:



Yessss, this is what we want to see. We see the phase jump, we see the marker at the centre of the polar chart to prove it is ohms at the resonance frequency 15,34 MHz. But wait that was 15,16MHz. Now you see the effect of loading the circuit, resonance changes. If you want to use this as a filter you look at the 3dB points. That gave some problems. Both the 3dB point where out the screen. So the bandwidth is over 25MHz wide, the whole HF band. But it is not as bad as it looks. We learned about loaded Q. We did not think and loaded the circuit with only 50 ohms.



Just an in between. If we build the circuit and parts well, we get the picture above. This is up to 250MHz. So no other resonances like the picture below. There you see a compare between the two capacitors over a 250MHz sweep. You see the effect of the Q of the variable capacitor. The bandwidth is a bit more narrow. You also see the effects from wires to the capacitor and coil.

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DG8SAQ Vector Network Analyzer Software   Version:  Beta 32.18 / 2010.04.14 09:02:30
5/18/2010   3:12:30 PM   S21  2,75uH coil parallel together with varco (mem1) and with ceramic

1:   15.2MHz    -42.25dB    -0.76°    -55.79dB    -82.47°
2:   54.2MHz     -2.06dB    -0.84°     -0.30dB     31.86°
3:  143.7MHz     -4.82dB   -89.48°     -8.41dB     11.71°
4:  203.3MHz     -0.11dB  -177.83°     -9.86dB     -5.41°
5:  207.2MHz     -0.36dB    23.20°    -46.27dB     -7.44°
```

Series circuits:

The other much used combination is the series circuit. In this case the impedance at the resonance frequency is again low. So the centre frequency passes through. Only this time the circuit is not grounded. The other frequencies are only attenuated by the reactance and not shorted to ground. This is not as effective as the parallel circuit but sometimes you need wideband.

This time I used the 250Mhz calibration saved before. Just to let you see what happens.

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DG8SAQ Vector Network Analyzer Software   Version:  Beta 32.18 / 2010.04.14 09:02:30
5/18/2010   3:23:04 PM   S21 series circuit ceramic 38pF and 2,75uH coil

1:   14.8MHz     0.02dB     1.30°
2:  145.1MHz   -10.16dB   117.15°
3:  207.4MHz    -2.59dB     1.26°
4:   93.4MHz   -35.33dB    -2.75°
```
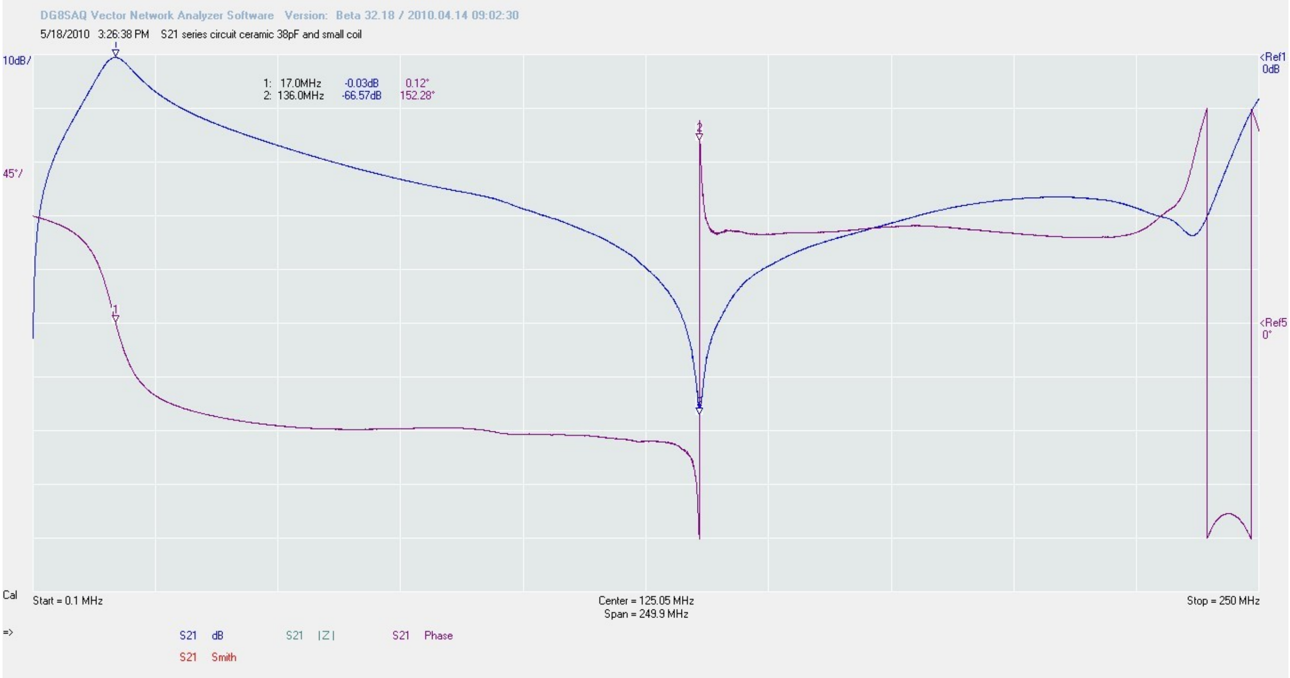

We see at 14,8Mhz the resonance. This indicated that the influence of the loading is bigger. The resonance frequency went down. We also see the phase jump. We see more resonances. At 93MHz we see a parallel resonance. But we did not use a parallel circuit so here we are looking at parasitic behaviour. Dangerous because this can cause a an amplifier to start oscillating at 93MHz.

On 145 and 207 MHz there are also series resonances. The one on 207 MHz is a real one. Look at the phase. The resonance at 145 MHz is what they call an amplitude resonance. The once we are interested in are phase resonances. Here the phase jump crosses zero degrees at resonance.



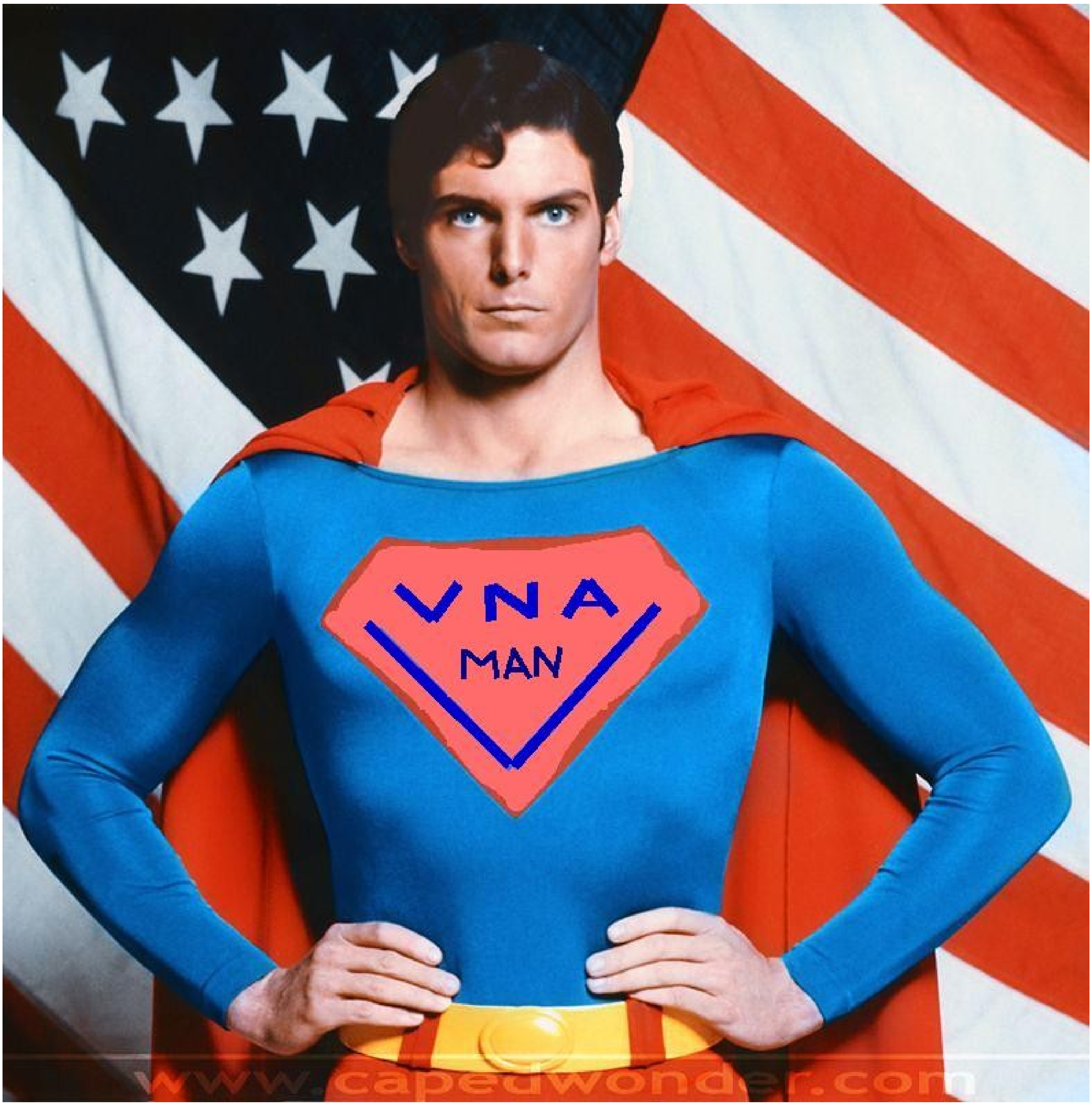
This is also a series circuit, but now with an other coil. This shows a really big parallel resonance. This is not a good build circuit. What have I done ? I had the coil almost flat at the ground surface. So I introduced a capacitor parallel at the coil.

But now we will try to do it better We have to unload the circuit. I mounted a parallel circuit between two 1K5 resistors and did the S21 deed. Watch out, this is 5-30MHz again.

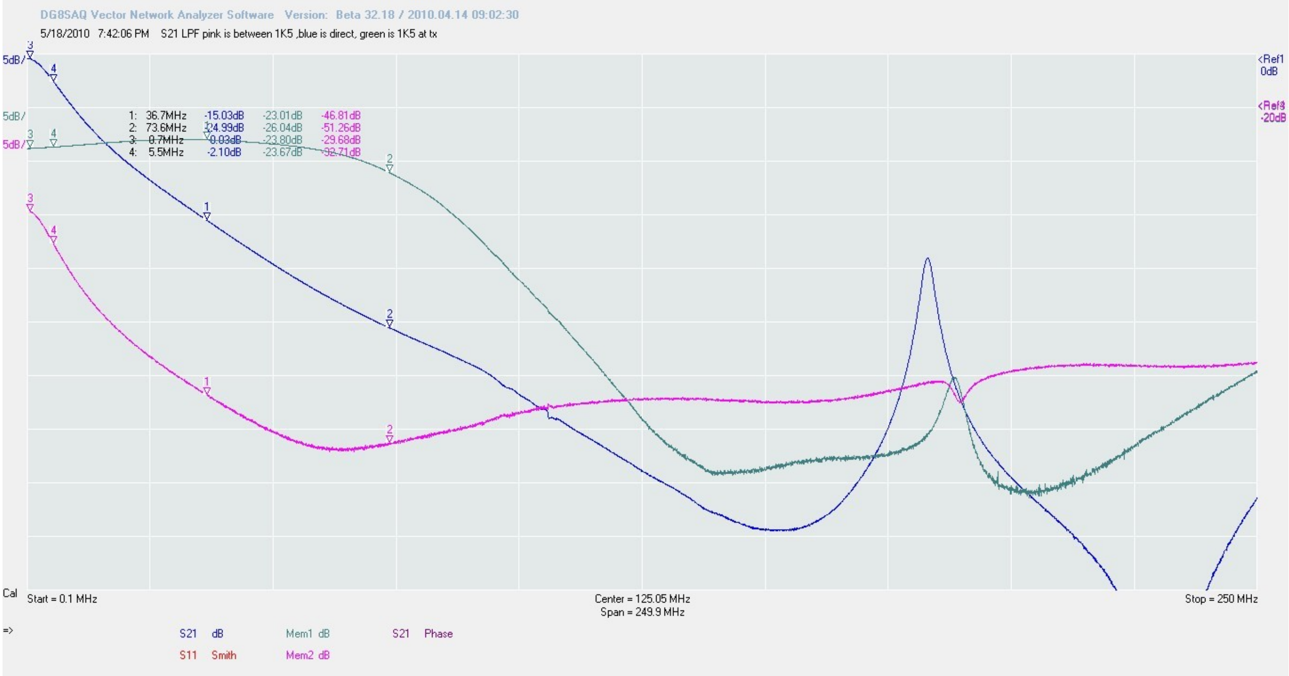
First look at the green trace in Mem1. It is attenuated by the resistors but you see it gives a much sharper dip as the pictures before. But we want to correct for the mismatch so after doing a SP2 2 port measurement to memory we open the tool menu and use the matchingtool. Type 1500 ohm at port 1 and 2 and you see trace 2. Even a better bandwidth.

This is something to take in account. If we use this circuit in front of a receiver, it sees 50 ohm in and out. It will be there, but doing almost nothing. If we embedded it for instance between two High Z buffer amplifiers so it is almost not loaded, we get a filter that is capable of doing a fair job just with one parallel circuit. The other option is to design a filter using combinations of L an C's to make a filter and match the impedance in one smooth move.

Filters, or using LC circuits with creativity.
So now I have used the magic word. Coils already scare the hell out of most people and the idea of them teaming up with other parts to do their voodoo things is too much. But not for you, you are the VNA man. (OK, are becoming VNA man soon , we should have some cool outfit like this :-))



But now for something completely different:



DG8SAQ Vector Network Analyzer Software   Version: Beta 32.18 / 2010.04.14 09:02:30

5/18/2010   7:42:06 PM   S21 LPF pink is between 1K5 ,blue is direct, green is 1K5 at tx

```
1:  36.7MHz   -15.03dB   -23.01dB   -46.81dB
2:  73.6MHz   -24.99dB   -26.04dB   -51.26dB
3:   0.7MHz    0.03dB    -23.80dB   -29.68dB
4:   5.5MHz   -2.10dB    -23.67dB   -32.71dB
```

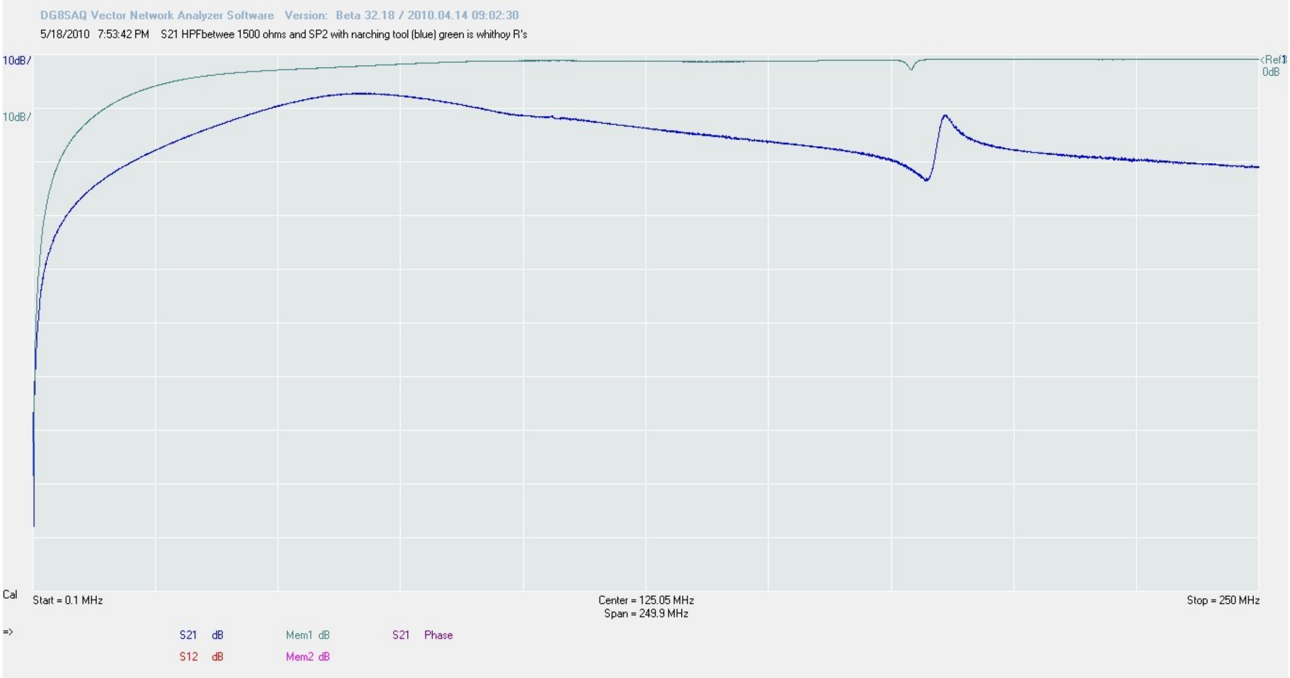
Take your DUT holder, solder the coil between port 1 and 2 and the capacitor between port 2 and ground. Load the calibration and sweep S21. It should look like the picture above. What should happen ? The coil attenuates the frequencies with increasing force as they rise. But behind the coil is the capacitor to earth. It forms a reactance that decreases with the increase in frequency so low frequencies are not bothered by it but the high onces that sneaked through find there Waterloo at the cap. So we created a Low Pass Filter. You see three traces.

The blue one is just the straight LPF, you see a declining line. Not a real steep filter and a very small part without loss, but it is doing it's job.

The green one has a 1K5 resistor in series at the rx port. This changes the form of the filter.

The pink is between two 1K5 resistors. This is to show you what the effects are caused by miss match and loading. So never just hook up your vna to a filter. First you have to know the input and output impedance. The matching tool can help you there. I show it in the next experiment.

High Pass Filter

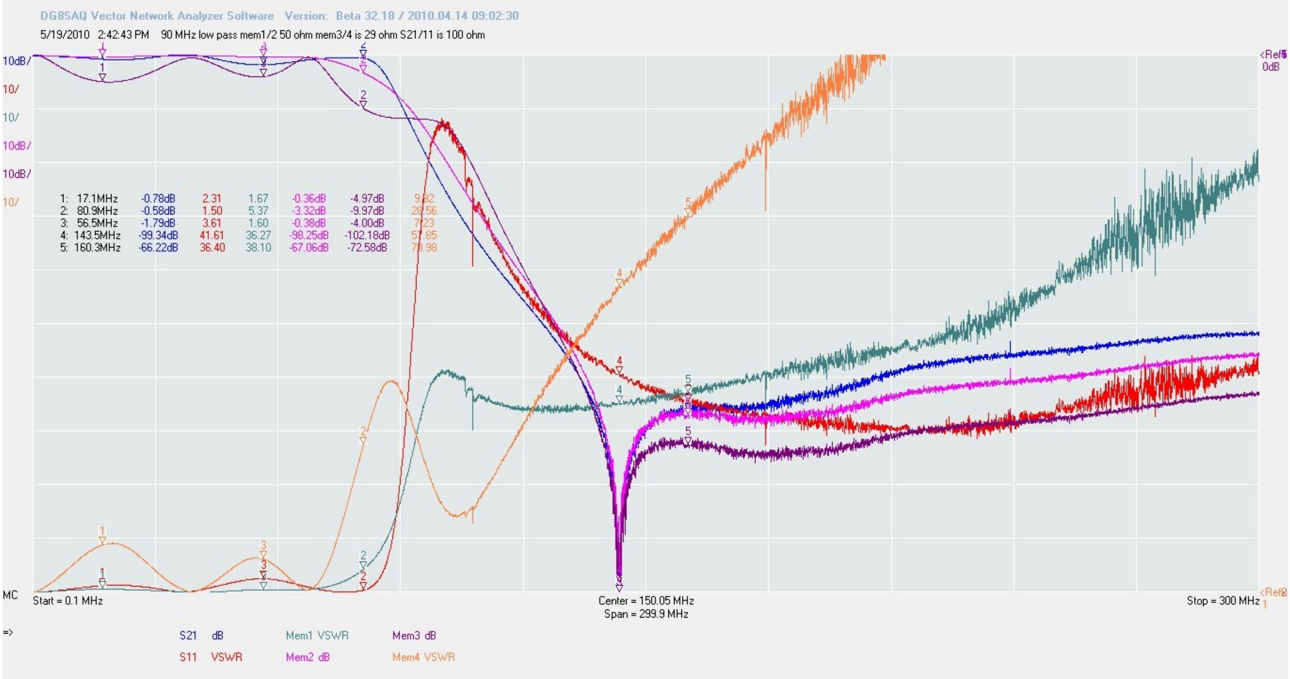


DG8SAQ Vector Network Analyzer Software   Version: Beta 32.18 / 2010.04.14 09:02:30

5/18/2010   7:53:42 PM   S21 HPFbetwee 1500 ohms and SP2 with narching tool (blue) green is whithoy R's

This time the capacitor is between port 1 and 2 and the coil is to earth. If we measure it without knowing the impedance (in this case the two resistors) the filter looks like the blue trace. This does not make you jump up in joy. Attenuation over the whole range.
But after a two port measurement we use the matching tool. We roll the mouse button to find the best value for the best filter shape. That is no attenuation of the high and as much as possible for the low ones. I placed the filter between two 1K5 resistors and with that value I got the green trace. There will be some stray capacitance and inductance. We can compensate for that too, but I did not do that. However you can play with it in the same tool.

Another test. This is a 90MHz low pass filter. I build it from 5 LC circuits. I designed this filter to be used in a 50 ohm environment. But it is nice to demonstrate some miss-match effects through using the the matching tool the other way around.


DG8SAQ Vector Network Analyzer Software   Version: Beta 32.18 / 2010.04.14 09:02:30

5/19/2010 2:42:43 PM   90 MHz low pass mem1/2 50 ohm mem3/4 is 29 ohm S21/11 is 100 ohm

1: 17.1MHz	-0.78dB	2.31	1.67	-0.36dB	-4.97dB	9.82
2: 80.9MHz	-0.58dB	1.50	5.37	-3.32dB	-9.97dB	28.56
3: 56.5MHz	-1.79dB	3.61	1.60	-0.38dB	-4.00dB	7.23
4: 143.5MHz	-99.34dB	41.61	36.27	-98.25dB	-102.18dB	57.85
5: 160.3MHz	-66.22dB	36.40	38.10	-67.06dB	-72.58dB	70.98

What is important ? A low insertion loss. You do not want the bandpass signals to be attenuated. You also want a steep roll-off so you reach the maximum attenuation as quick as possible. And you want a low VSWR in the bandpass section. Each section you add (so you make a filter with a higher order) adds some extra steepness. This is expressed in dB/octave.

The blue trace is the filter as it is. The insertion loss, caused by the bandpass ripple is a bit high here . I found out one of my cables was not optimal any more, causing some extra loss and vswr. Normally this is below 0.1dB. The roll-off is steep and stopband attenuation is high. -100 to -50dB

Now the purple one, Mem3 (and 4). I told the vna the filter is supposed to see 20 ohms. So if we would use this filter at 20 ohm we see a very high bandpass ripple and almost 5dB insertion loss. That is huge. The good thing is the stopband attenuation is also better but with this VSWR and insertion loss you do not have a use for this. It is just to demonstrate the importance of matching. Remember, I did not change the filter a bit.

The pink one, Mem2 and 1, This looks rather good and was for me the sign there was something wrong. That's why I did not make a new measurement after repair. This is just to show you, never trust your gear, always test it. I did a through measurement for each cable and the rx cable gave the unwanted loss because a connector was not crimped firmly enough (by me) . So always, no exceptions, start your sessions with measuring a open, short, load and through. The first three needs to give a dot in the right place in smith. The through a zero insertion loss. If that is OK you are ready to have some fun. Part 5 will probably be about (antenna tuners) and matching.