Chapter 2 inductors

Inductors are components we often use in radio design. We measure them with our LCR meter and build a circuit with them, only to find out the resonance is way off from the calculated value. The reason for this has to do with things I showed in chapter 1 but also with some sneaky characteristics of inductors.

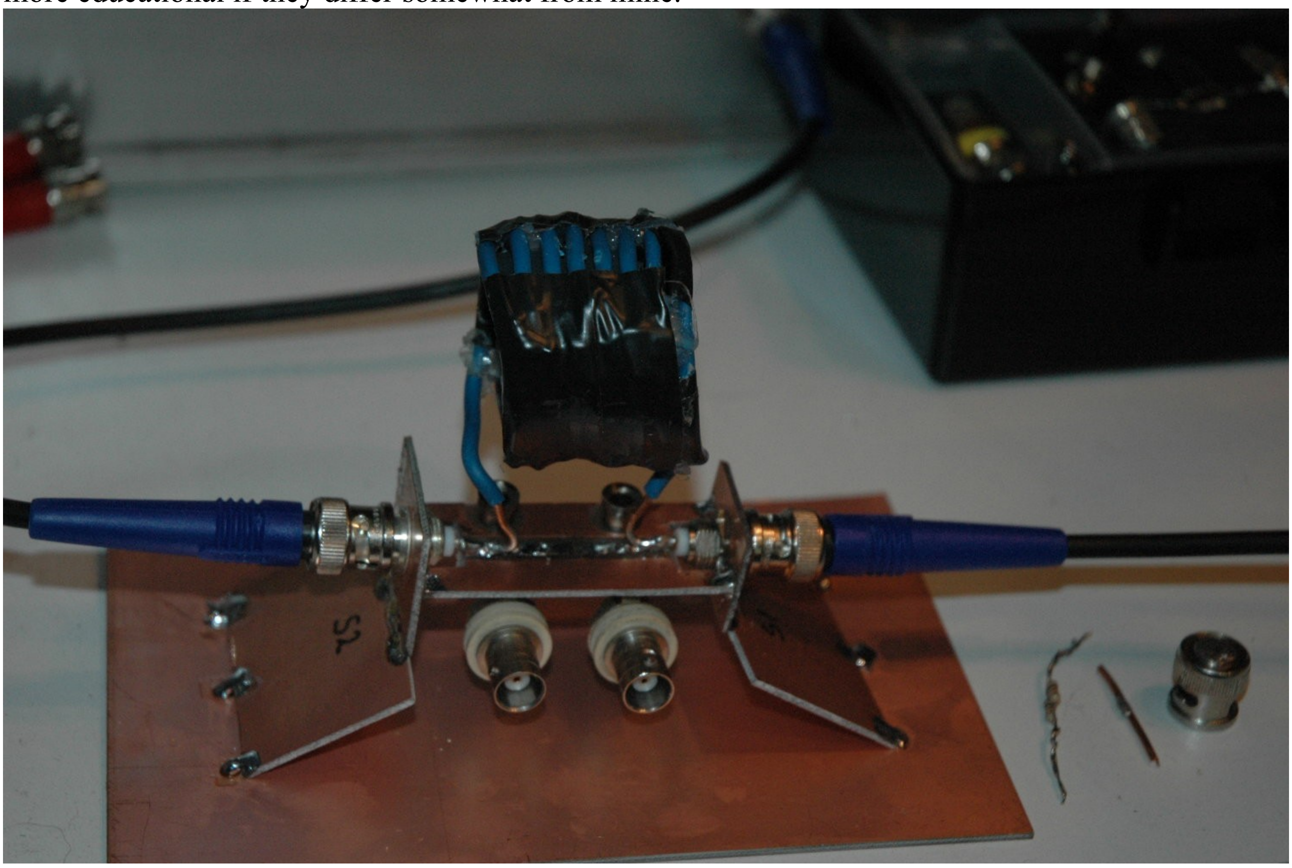
The first thing that goes wrong, is that an inductor does not have a “fixed” inductance. This is phase related and because of that it is also frequency related. Scientists have made the agreement to measure the inductance between +45 and +60 degrees. This has to do with the current/voltage behaviour. First the current flows and then the voltage rises. The difference is 90 degrees and this is the “moderate” in between. Between 45 and 60 the self induction differs only a little so the precise degree is not important.

Our LCR meter just measures at one or two frequencies. This measurement is most times rather correct because the phase changes relatively slowly at this low frequency. But the inductor has characteristics that make it behave differently at other frequencies.

But this is about practical experiments so lets find out what an inductor is all about.

Set up

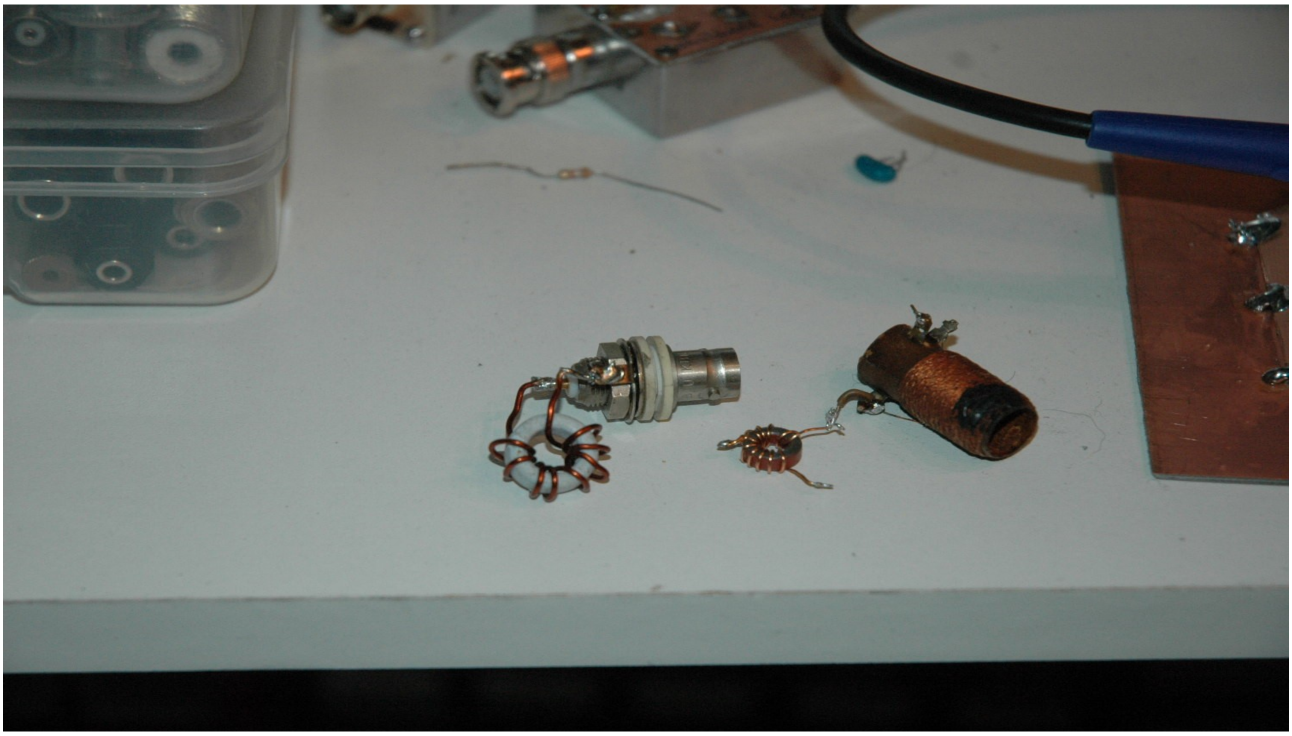
We take our DUT-holder and we are going to make 4 completely different coils. The first one is a theoretically perfect air coil. At the first picture you see coil A. The second one , B, will be a toroid coil wound around a small 4C65 toroid and the third, coil C, will be wound on a T32-2 like toroid. The last one, D, is a multi-turn air coil from an old BC radio. Do not worry about the sort or type of material. Build them with the stuff you have. The values/results will be somewhat different but the idea and effects they show will be similar and you will be able to “translate” them. It will be even more educational if they differ somewhat from mine.



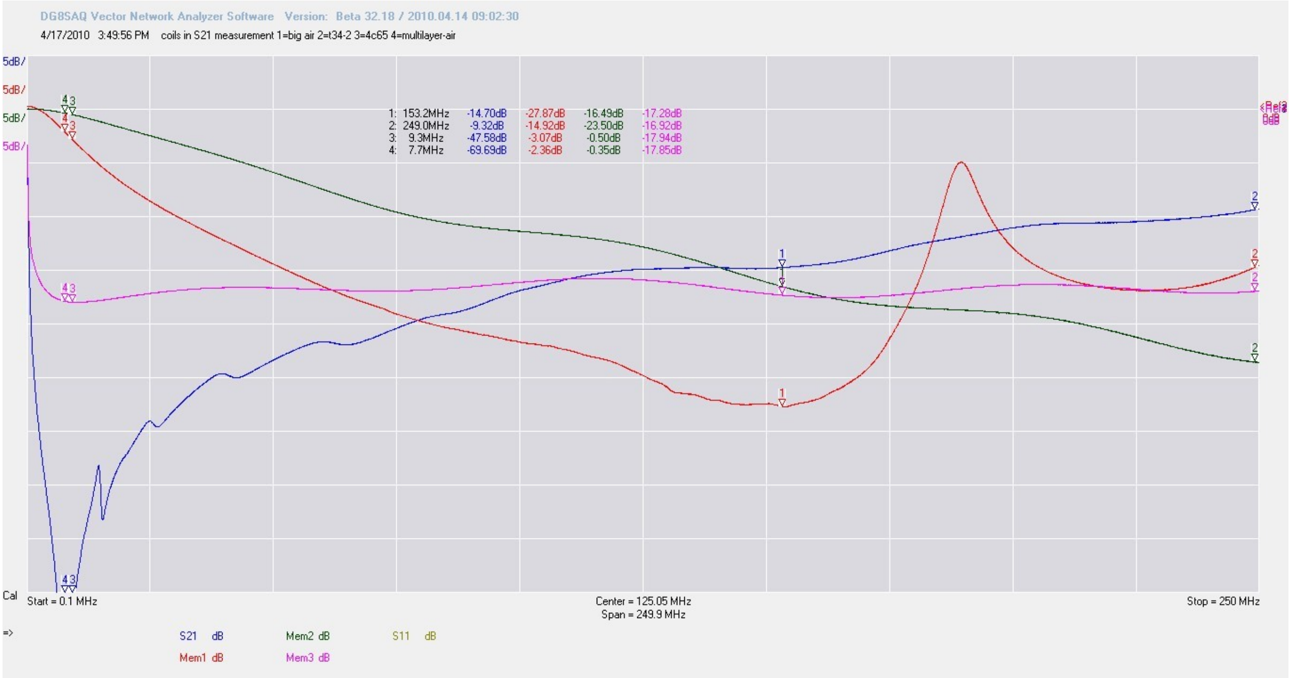
Here you see coil A, a wire wound “spaced” between the turns, big air inductor set up for S21 after

calibration.
First we are going to see what an inductor does.
An ideal inductor is a pure reactance, a resistance for AC. The complex notation R+xj for it's impedance will be, for instance 0+100j. That is a 100 ohm reactance There should be no real resistance (the R part) and as the frequency goes up, so does the reactance. So we expect to see an attenuation that becomes bigger at higher frequencies. The S21 trace should drop linearly. Lets see if the books are right.

First we take coil D. We set up the DUT holder for an S21 measurement. (the one on which we solder, like in the picture with coil A) so the DUT holder is between the TX and RX port. We do a true calibration of our DUT-holder like in chapter 1 with the piece of wire, on the picture right from the holder (save this calibration for example as dutholderS21_250MHz, we are gonna use it a lot)



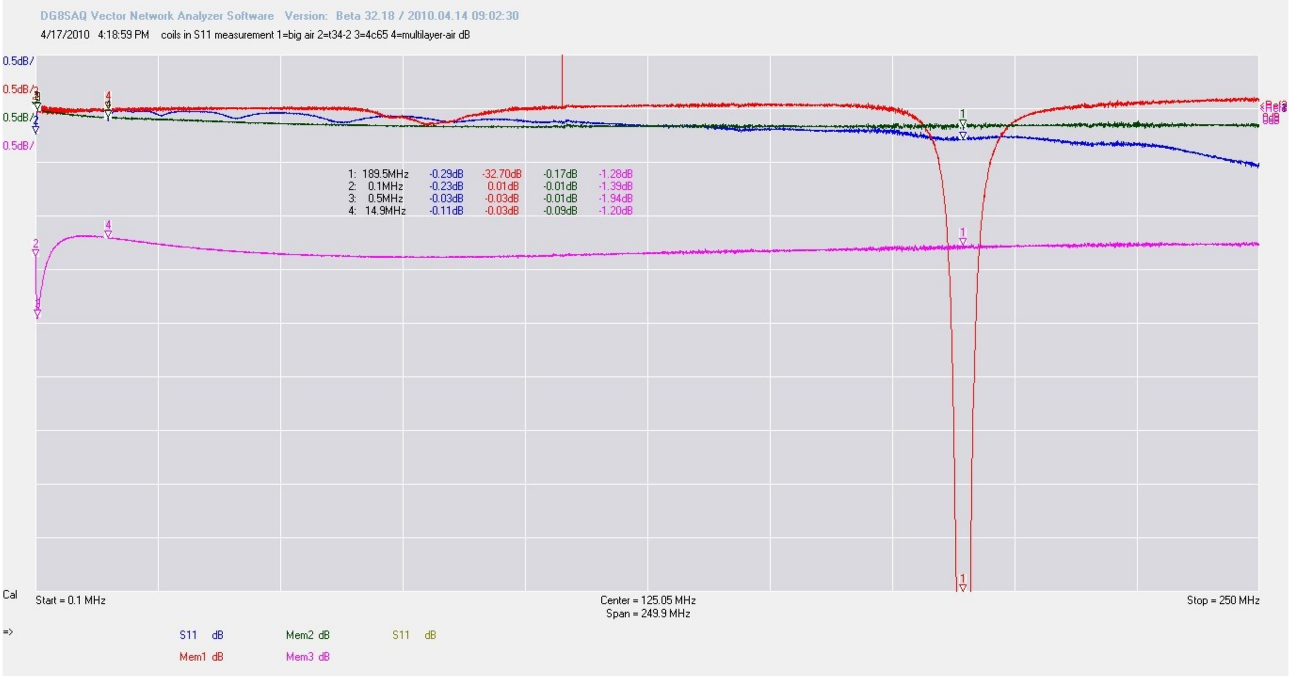
These are from left to right, coil B on 4C65 (the BNC is for later tests), then a smaller variant C on iron powder T34-2, just as an example, and coil D from an old radio where it was on ferrite.



Trace mem1(red) is coil A, mem2 (green)is coil B, mem3(pink) is coil C and S21(blue) is coil D
We select S21 in dB and a do a sweep over 0.1 to 250MHz. Scary sight isn't it. Meet coil D alias coil-zilla. It is the blue trace S21. It dives down and then slowly goes up while we expected it to go down all the way. There must be some dark forces at work. Before we hunt them down, we test our other coils

You see, the coil that behaves the most like an ideal one, is coil B. Later we see it is not the best. This means that there are some characteristics involved that are not easily discernable. The two coils look similar but behave differently.
Coil A in mem1, the red trace, goes very well up to 153MHz, from there the trace goes up again. The same effect we see at D, S21 blue. Only this one dives down to find it's bottom at 7,7MHz and steep up again from there. Coil C, the pink one in mem3, also dives down to 9.3MHz but does not really go up again. Weird, 4 coils and 4 different reactions.
To find out why we have to explore the hidden characteristics. To do that we make the second experiment. Welcome to the world of parasitic behaviour.

S11 measurement:
We first calibrate our DUT- holder for S11, like in chapter 1. So, we disconnect the RX port, place a short on it and then do the open calibration, solder the piece of wire for short and do a short calibration and solder the two 100 ohm resistors in stead of the wire for load calibration. Save this calibration too. For instance as “dutholder_S11_250MHz”. We are also gonna use this a lot.
An alternative method is to use the toroid mounted to the BNC (left on the picture). This is also an easy way . In this case the calibrating must be done by soldering on the connector. Do not measure on a metal surface. I did not use the BNC method this time. It was only there for use in other demo's.



This is a S11 return loss measurement. Because there are a lot of parameters I will give every inductor a separate picture and take you by the hand in exploring the hidden facts.
The return loss picture however gives us some clues. The red trace shows us a big dip in return loss. Return loss is related to impedance. A return loss around 30dB is almost 50ohms. A return loss around zero means the impedance is really high or is really low. A pure reactance (a impedance without resistance) wil give 0dB. So we see the red trace bottoms at 50 ohms. The dip here is related to the bump in the S21 picture. You see the same effect. The impedance becomes lower instead of going up. The reason is resonance. Such a dip often shows you there is a resonance at that point. But be careful. It can also be a measuring fault or calibration fault. If the trace is not zero dB it indicates losses.

But how do you find out what is this phenomena. The VNA has a lot of different options to look at these inductors better. If there is resonance, there must be a phase jump and the trace must leave the inductive part of the smith chard and enter the capacitive part. Resonance itself is the point where the trace crosses the line and the inductive part is as big as the capacitive part and they cancel each other. What remains is a pure real resistance value. (To look at this we can also use the S21 measurement.)

You see the zero degree reference in the middle. Here you see two phase jumps and a not so sudden crossing. The blue one at 7.8Mhz and the red one at 188Mhz. The pink ones also cross the zero degree line but this is no jump. For resonance we normally use a network made of an inductor and a capacitor. So this means there sneak in a hidden capacitor in those coils.

But it did not sneaked in. It was there right before our eyes all the time. The coil forms a reactance for the signal. This “resistance” rises with frequency. But the windings are next to each other. There is a rising voltage drop over the coil. So there is also an electric field between the windings. This is the thing that forms a capacitor. A capacitance gets a lower “resistance” as frequency rises so there comes a point where the (parasitic) capacitance between the windings becomes a easy way for the signal to skip the coil. The point they are equal is the resonance point.

Now look at the inductors one at a time:

To make it a bit easier to read, I use one page per inductor.

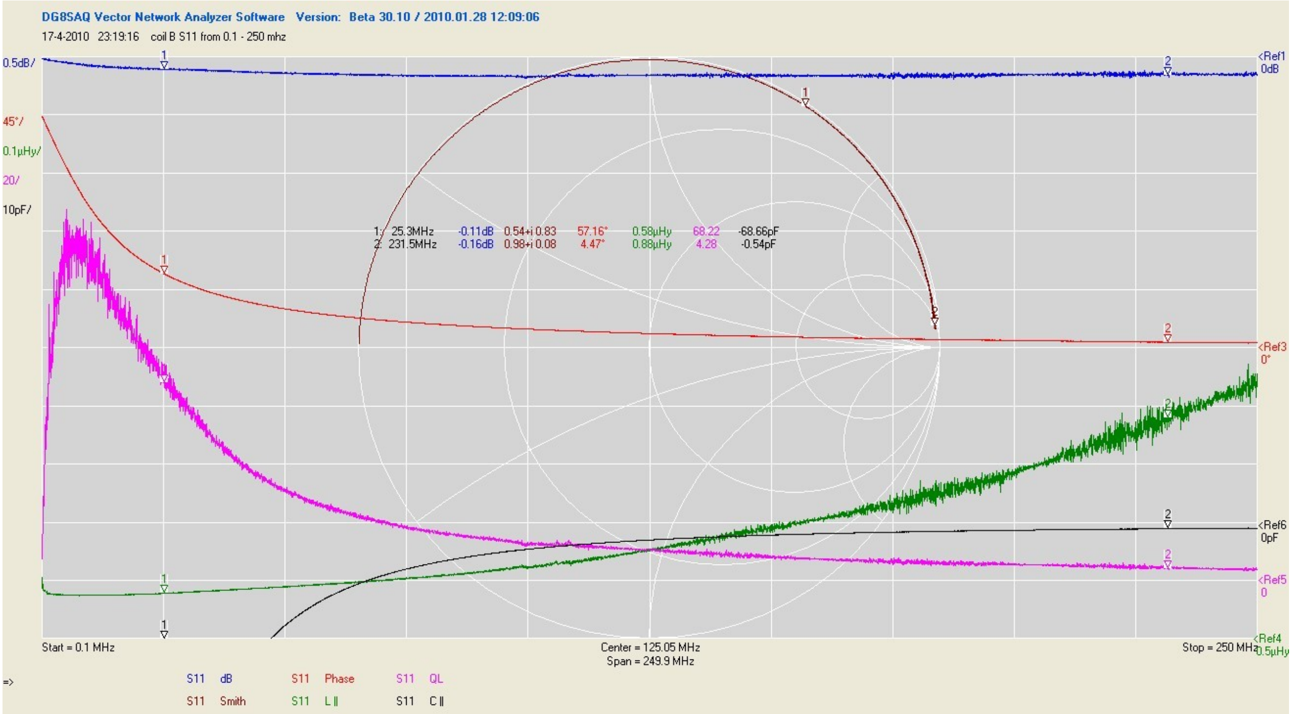
Coil A:

Coil A is the air coil. It's windings are spaced about the same size as the wire is thick. What can we tell about it looking at the picture? We see 5 traces. S11 in dB as a reference, phase in degrees, L|| the parallel inductance in uH, the Q, or quality of the coil and a trace in the smith chart.

Remember this is a reflection measurement. So the phase behaves differently here.
The red trace is the phase. This trace is very handy for finding the place where we measure inductance. We do this at a point between 45 and 60 degrees. I have taken a point at 52 degrees. The inductance is 1.77uH. I measured the coil with my digital LCR meter and that told me it was indeed 1.77uH/1KHz . But it shows more, S11 goes through zero at two points. Around 90 and 186 MHz. The first one is a little one. It is accompanied by a little dip in S11. Not so serious looking but look at the Smith and self-induction trace. The self induction goes sky high and a moment later the trace in the smith chart goes over to the capacitive section. But at a higher frequency it goes up again towards inductive. Only at this time, you see the smith trace rotating inwards and go up to the inductive section, again exactly through the middle at the 50 ohm point as we predicted in the S21 picture. This means that beside capacitance there is also a lot of resistance(loss) involved. This is the resistance of the copper and the skin effect loss because the waves like to travel on the outside of the conductor. There are some added losses because the dielectric of the insulation. If you use this coil above 86 MHz you are going to lose power in this coil. Normally a pure inductor does not dissipate power. However if you use it at HF this will a great coil with a high Q. The losses are small there, it is a close to perfect coil, with a Q of 160 at 9MHz. The inductance trace seems rather flat through HF but it is 10uH per division so around 30MHz this coil is already about 4uH. This will give you a (serious) problem in a filter or tuned circuit at that band. The Q trace is placed outside the screen because it goes very wild around 80MHz so it will block your view. But you can see it at the marker text.

Is this a meaningful measurement? Yes, it tells you not only the inductance at the working frequency but also if it is still an inductor and the quality, so you know if there are losses and it can tell something about bandwidth.

Coil B:

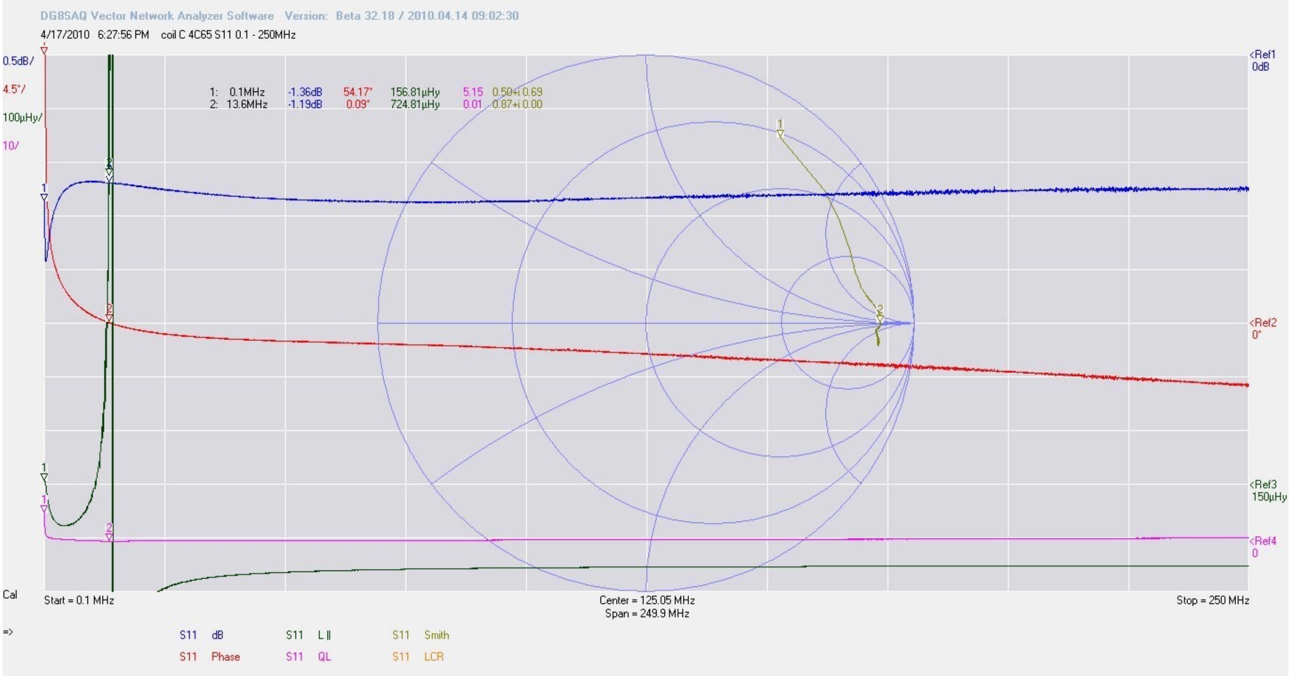


This inductor is made from 12 turns on a T34-2 iron powder toroid (I think :-)) The little brother of the T200-2 some people like for using in current chokes or baluns. You need a lot of self inductance for that. You see this picture is a bit different from the others. That is to show an other handy function of the VNA. I saved this measurement as a SP2 file and reworked it later on an other (linux) computer. All data you forgot to measure (within S11) is still there. But back to the coil; In the S21 measurement this was a very good looking coil. Indeed there is no resonance up to 250Mhz but you see it will come soon after that. The self inductance is rather small. It is 580nH and there is not much room for more windings because then the capacitance takes over.

If you take a good look at the smith chart you see the trace moving on the inside of the outer circle. Remember that means we have a real resistance here. This also is seen in the Q, that is 112 at 9Mhz. Coil A was 160 at that frequency and that coil had much more wire. I also placed the C|| trace inhere . This shows the capacitance. Under 50Mhz that is a large negative number, that is good. But at higher frequencies it is just a few pF from becoming inductive. So it is a very thin balance. Place this coil to close above an earth plane and this almost perfect coil can quickly change.

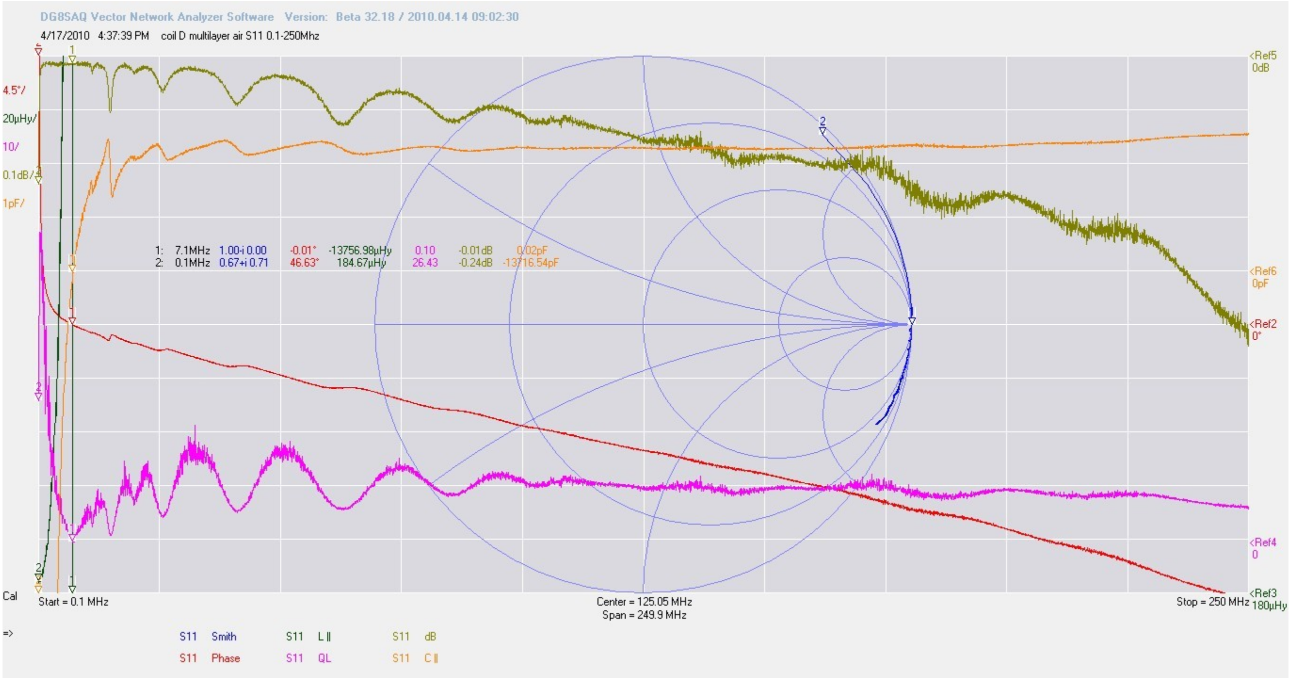
But this type of toroid is made for lower frequencies and there it will make a nice but small coil, for instance in a bandfilter.

Coil C:

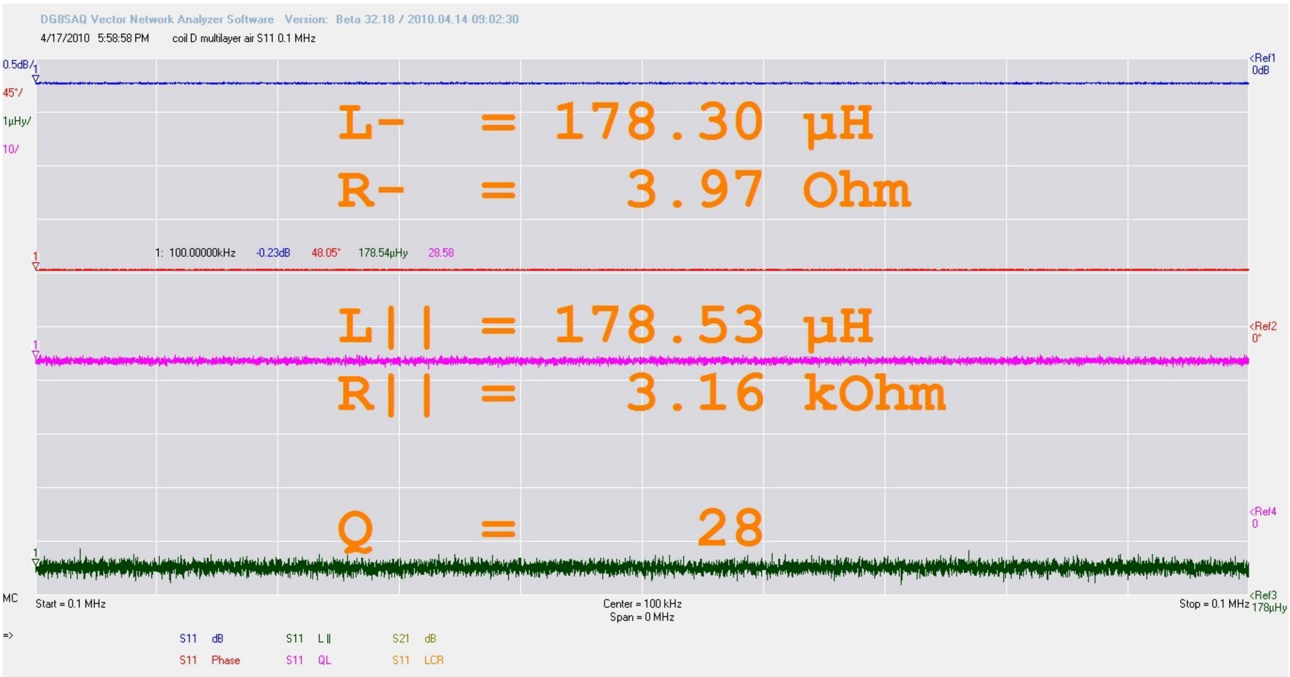


This is a small brother of a 4C65 material sort of toroid. It has a huge self induction with 9 turns. You see it is 156uH at 100KHz. But there is a huge down side. The losses are as huge as the induction. You even see it in the S11 dB trace and of cause in the smith chart. This results in a very bad Q of only 5. This is not good for use in some applications but it is a good toroid for making a broadband common mode choke. You have a lot of self induction the whole HF band. This is the small one with rather a lot turns. That last thing shows that it is self resonant at 14Mhz. You do not need 160uH but still have the benefit of only a bit of wire and so even less capacitance. For common mode current choke that is not a problem but as an impedance match or voltage balun this is a bad thing.

Coil D:



Wow, that is a scary picture. Here we have coil-zilla again. But is this fair? We have an 50 year old coil made out of the finest materials. Real multi strand wire with each strand isolated. It is made for use as an antenna coil at long and mid waves. So this measurement is a bit cruel. But it shows not every inductor is suitable for all frequencies. If you would make a coil like coil A with 184uH it will fill up your radio by itself. Remember this is already 184uH without the ferrite in it. The Q is still 26 and that is not bad if you compare it with the 4C65 but at 7MHz it's over. First inductance goes skyhigh and then drops so fast and deep.



As a bonus, use a zero span and S11 LCR and you have a wonderful LCR meter. (this was done using the mastercal while soldered direct on a BNC like on the picture, so you see a very small difference) So this iss my introduction to the wonderful world of coils. The opposite of a coil is a capacitor. The next chapter will be about these little critters by many people considered as almost ideal components. Will they be......? We will see.