MegiQ

RF Development Tools

VNA Sandbox

Measurement tutorial

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Connectors need special care.

Damage to connectors or wearing down do not fall under warranty.

So treat your connectors with care.

general practice

Vector network analysis is for electronic engineers and designers. The apparatus needs special care, it is by no means comparable to the robustness of most multimeter and oscilloscopes. If you are acquainted with the use of spectrum analysers you probably are on the safe side, since the vulnerabilities of spectrum analysers are in the same order as VNAs.

Misuse might damage the instrument or lead to nonsense results. Therefore you'll find a list below with suggestions to be on the safe side.

- Beware of the maximum input signals. With a VNA these are, just as with spectrum analysers, much lower then with e.g. an oscilloscope.
  There is often a difference between allowable AC and DC input. With the MegiQ VNA maximum DC input is 20 V and maximum AC input is +20 dBm (100mW into 50Ω -> 2.2V rms)
- Keep connectors clean and mate them carefully, not too tight or too loose.
- Be careful with cables:
  - If you use the 'real ones', the ones intended for measurement purposes:
    - realize that they are very expensive
    - that mating them too often will wear them down.
  - If you use inexpensive “standard” cables:
    - make sure not to move or bend them too much after calibrating the set-up. This way you can make good measurements with those inexpensive consumer grade cables.
    - check them before using them, specially look for good, stable contact.
    - throw them away every now and then, and use a fresh new one.
- Calibrate the whole set-up each time you make a change. Even if you change a cable with an other “same” cable. Most cables, although looking the same, are different, except the ones specially made to be the same. But those specials are very expensive.
- Use “SMA-savers” on the input connectors to the SMA, (a simple male-female adapter, or an adapter to an other standard, such as UFL).
  By using adapters, you (un)screw connectors at the “output side” of the adapter and not directly on the front panel. This way you make sure not to wear down the front panel SMA to much.
  The adapter itself is easily “calibrated-out”, so it will not spoil the measurement.

About this guide

This guide serves two goals. Because you might be new to vector network analysis, or you might be new to the MegiQ VNA models.

Learning a new instrument can be challenging, and although the MegiQ VNA has a very intuitive user interface, it still *is* a full blown VNA, with the many different features that make sense if you use them in the right way.

Therefore this Getting started helps you through both: getting used to the actual instrument *and* hands on training with vector network analysis.

Fore this you will use the MegiQ VNA-Sandbox, a PCB with several easy demo circuits, but well chosen in order to present you with *both* the many features of the MegiQ VNA *and* the use of vector network analysis in every day life of an RF-engineer / -designer.

In principle you can use the MegiQ VNA-Sandbox with other VNAs in order to get accustomed to vector network analysis in case you do not have a MegiQ VNA available. In that case the buttons to push on the VNA will be different. And several measurements will be unavailable, because the MegiQ VNA -how simple it may look- has a lot to offer other instruments don't.

Set-up

In this Getting Started we shall describe the set-up with the MegiQ VNA. You will need the following hardware / software:

- MegiQ VNA-0440 (standard or e-version) with USB cable and power adapter
- MegiQ VNA-Sandbox
- Windows PC with the MegiQ VNA software installed
- SMA (f) to UFL (f) converter (3 times)
- coaxial cable UFL(m)-UFL(m) (3 times)

We presume the MegiQ VNA software has been installed. If not so, please refer to the Installation Guide.

Note that for some measurements, the ones using the internal bias generator or the third port, you will need the VNA-0440e.

The use of getting started

You can start with circuits on the MegiQ VNA-Sandbox where you want in this document, but if you are new to vector network analysis, we suggest to follow the order of this measurement tutorial. In all cases you should always start calibrating the set-up.

Stored Sandbox measurements

The MegiQ VNA installation program installs a file with all Sandbox measurements. It can be found at :

..\Program Files (x86)\MegiQ\VNA\VNA Data\VSB Measurements.vns

These measurements can be loaded for a certain Sandbox circuit. However, when loading a measurement from the session manager you will have to recalibrate your test setup again.

Some of the preloaded measurements have particular graph settings to show some of the features of the VNA software.

Performing a VNA measurement

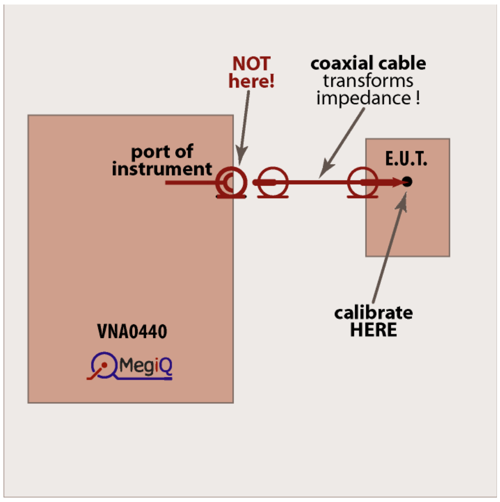
Performing a measurement with a Vector Network Analyser is not very difficult, as long as you do the right steps in the right order. These steps are independent of the kind of VNA measurement you want to do. It all just has to do with the use of the high frequencies, which makes it different from many other, lower frequency measurements.

- Think it all well over: what do you want to know, what do you want to do with the results, etc.?
- Choose the point where you want to measure. It is RF, so every millimetre counts: run length transform impedances, so choose this point carefully.
- Make sure you use the right cables, connectors.
- Power up the instrument and let it warm up. (the MegiQ VNA is very temperature stable, so in most cases you do not have to wait)
- Make the right measurement set-up (hardware) and the set-up of the instrument. (using the PC software)
- Perform the calibration. (see “calibration”)
- Perform the measurements.
- Interpret and save the results.

Using other brand VNAs

The VNA Sandbox can be used with other VNAs. Follow the VNA's calibration procedure to calibrate the Sandbox measurement setup.

Calibration

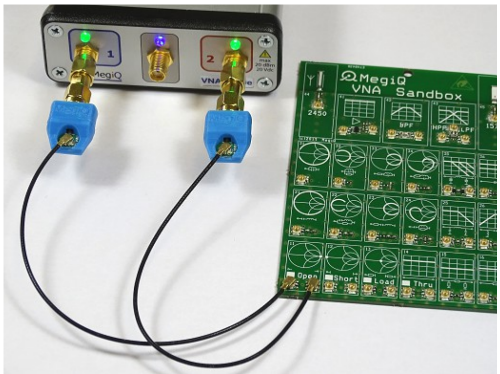


Point of calibration: at the EUT

In vector network analysis you are interested in impedances of components and circuits. At high frequencies almost any length of cable will act as an impedance transformer, thus altering the impedance you actually see. Furthermore at even higher frequencies many cables become lossy, which influences gain *and* impedance plots.

Luckily these cables act as linear elements and can be 'calibrated-out' by linear algebra. Do not be afraid, the instrument will do this for you, but it should be fed with some well known impedances for every frequency of interest before you start the actual measurement. Therefore before using the instrument you should perform a calibration on the whole set-up, including the cables, connectors, etc. for the frequency range you want to use in your measurement.

The instrument stores this set of calibration data, and since the MegiQ VNA is very temperature stable, you will not have to perform this calibration routine very often.



typical calibration setup

But, changing cables, connectors or frequency range means that you most renew the calibration. Avoid bending cables to much after calibration. (depending on the quality of the cable of course)

The well known impedances the MegiQ VNA uses for this are an Open Connection (O) a Short Circuit (S) a load resistor of 50Ω (L) a Through (T) and a “No Connection” in order to calibrate the insulation between ports (I).

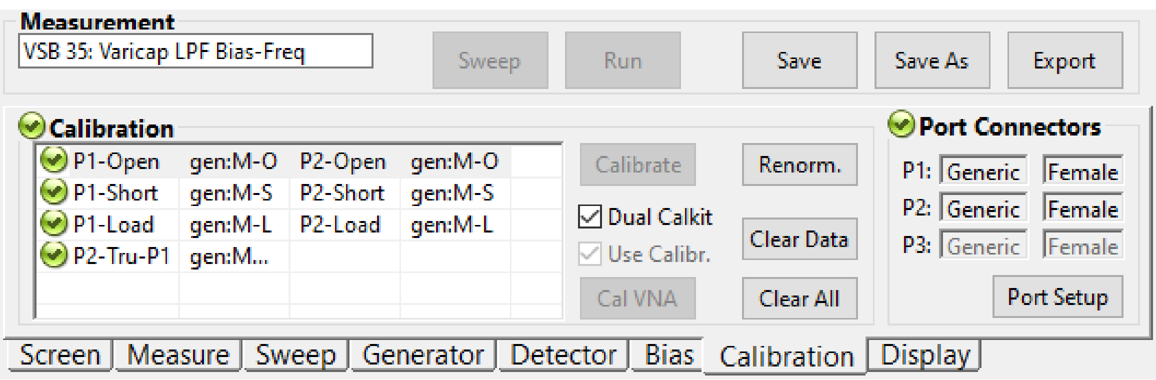
On the MegiQ VNA-Sandbox the calibration circuits are 11 (open), 12 (short), 13 (load and insulation) and 14 (through).

The calibrating process is straight forward, you will find it step by step below. You will find the process for the 1-port and the 2-port measurements. You will need cables with UFL connectors when using the MegiQ VNA-Sandbox.

Again: during the calibration process, use the very same cables and connectors you are going to use in the actual measurement! Not calibrating the whole set-up will lead to very confusing results!

The calibration pane

By selecting the calibration tab you get the calibration pane.



Calibration Pane

In the list "**Calibration**" you see what calibrations are needed. You can select a calibration you want to perform in this list and then press the button "Calibrate". Of coarse after you made the right connections to known impedances. (The OSLT-kit)
Green says the calibration has been done, red means there is no data.
Note that the instrument does not know whether or not you changed anything since you last calibrated the set-up, so green does not always mean you've got a valid calibration!

Check boxes

There are several check boxes.

- Dual Calkit: On the sand box, there are two of each calibration impedance (O, S, L,) This way you speed up calibration by doing two calibrations (both ports) at the same time, in case of a 2-port measurement.
- User Calibration: tells the instrument to use the calibration you perform with the OSLT kit.
  When this box is not checked the instrument will use the factory calibration at the SMA connectors of the instrument. You do not need to perform your own calibration now. But remember, the instrument will also measure any cable length, connectors, etc. that is in between the SMA of the instrument and your EUT. These will not be calibrated-out.

Buttons

There are several buttons in the Calibration Pane:

- Calibrate: The instrument will calibrate what you just selected in the list. (double clicking in the list has the same effect)
- Renormalize: The instrument will apply the last calibration you made to the measurement data in the graphs. You can use this when you want to calibrate *after*

you made your measurements, even on save data.

- Clear Data: This will clear the measurement data.
- Clear All: This will clear the measurement data and the calibration tables.

Single-port calibration (OSL)

If you are performing a 1-port measurement, you only need the O,S and L, because there is no “through” to an other port and also the “insulation” between ports is of no importance. First in the GUI, load the session file “VSB Measurements.vns” and select the measurement “VSB21/22:LCR series” This will pre-set the instrument and the display, which is handy if you are an new-comer to the MegiQ VNA-0440. Later on you can do all these, or different settings yourself, depending on the measurement.

1. GUI, Tab Generator: choose frequency range & generator power as appropriate.

open

2. Connect the VNA to the “Open” circuit on the Sandbox (*circuit 11*)
3. GUI, Tab Calibration: select P1-Open
   and press Calibrate.

short

4. Connect the VNA to the “Short” circuit on
   the Sandbox (*circuit 12*)
5. select P1-Short and press Calibrate.

load

6. Connect the VNA to the “Load” circuit on
   the Sandbox (*circuit 13*)
7. select P1-Load and press Calibrate.

Final check

Press Sweep. In the Smith chart all measurement points should now be close to the centre (50Ω) and in the Return Loss chart all points should be better then 45dB.
(50 is better then 40 when it comes to Return Loss)

You are ready to go now, but remember, after changing cables, connectors or frequency range you'll have to renew the calibration!

2-port calibration (OSLTI)

If you are performing a 2-port measurement, you need the O, S and L on both ports, *plus* the “*through*” (T) from one port to the other and the “*insulation*” (I) between both ports.

First in the GUI, load the session file “VSB Measurements.vns” and select the measurement “VSB25: CLC LPF” This will pre-set the instrument and the display, which is handy if you are a new-comer to the MegiQ VNA-0440. Later on you can do all these, or different settings yourself, depending on the measurement.

Instrument set-up

1. GUI, Tab Generator: choose frequency range & generator power as appropriate.

open

2. Connect *both* ports to the “Open” circuits on the Sandbox (*circuit 11*)
3. GUI, Tab Calibration: select P1-Open / P2-Open and press Calibrate.

short

4. Connect *both* ports to the “Short” circuits on the Sandbox (*circuit 12*)
5. select P1-Short / P2-Short and press Calibrate.

load

6. Connect *both* ports to the “Load” circuits on the Sandbox (*circuit 13*)
7. select P1-Load / P2-Load and press Calibrate.

insulation

8. The insulation between the two ports will be calibrated together with the load calibration above, so you do not need to perform any special action for that.

through

9. Connect *both* ports to the “Through” circuit on the Sandbox (*circuit 14*)
10. select P2-Tru-P1 and press Calibrate.

Final check

Connect both ports to the “Load” circuit on the Sandbox (*circuit 13*).

Press Sweep. In the Smith chart all measurement points should now be close to the centre (50Ω) and in the Return Loss chart all points should be below 40dB.

You are ready to go now, but remember, after changing cables, connectors or frequency range you'll have to renew the calibration!

Saving your calibration

You can press the button “Save As” and give your configuration a name. Specially the 2-port calibration is quiet some work. After saving the configuration, you also save the calibration tables and thus you'll have the saved configuration to go back to. Of coarse this only gives you a valid calibrated set-up as long as you change nothing.

Single port measurements

Now you are ready to start performing actual measurements on the MegiQ VNA-Sandbox. RF in real Life! You will find a description of every circuit on the Sandbox together with an explanation what you see on the VNA display, and more important: "*What does it mean*".

Real life circuits!

No, do not be afraid, these RF circuits are not "life" in the sense of dangerous voltages. No, the VNA uses low signal levels which are not dangerous. With *Real Life Circuits* we mean: circuits you are likely to encounter in your day-to-day work as an RF-engineer.

Experiment!

You can experiment freely with the circuits on the MegiQ VNA-Sandbox. Feel free to watch the effects of a loosely connected cable, of changing one cable by a slightly longer one without recalibrating. Also the effects of touching the circuit under test, or in case of the antenna experiments, just putting your hand in the neighbourhood of the circuit.

Using the sandbox

This is very easy. Every circuit has a number, one or more UFL connectors and a small graph of the expected results. Connect the instrument to the connectors of the circuit of your choice, do the right settings on the instrument and perform the measurement.

The circuits and the measurements on it are explained in this document, one chapter per circuit You can start with any circuit at will. But if you are a new-comer to vector network analysis, we suggest you start in the order of this manual.

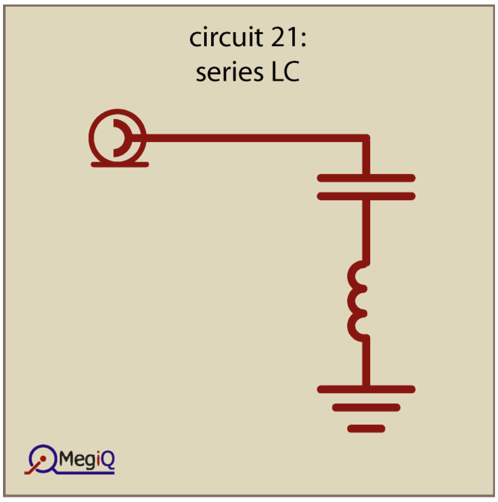
Calibration

Of course, you have already calibrated the set-up with connectors and cables you are going to use in the real measurements. If not so, see the previous pages under "calibration". The instrument is very stable, so once calibrated you can go on for quiet some time.

Enjoy!

It is not for an exam. So play around and learn, learn and learn. And do no forget to enjoy, because learning RF is fun!

Series resonant circuit (21)



schematic

An ideal series resonant circuit consist of a pure capacitor in series with an inductor and is therefore a pure imaginative impedance, except at resonance where the capacitive and the inductive part cancel each out resulting in a short circuit, which is a 'zero-vector' in the origin so you cannot define it being real or imaginative at resonance.

What do you see

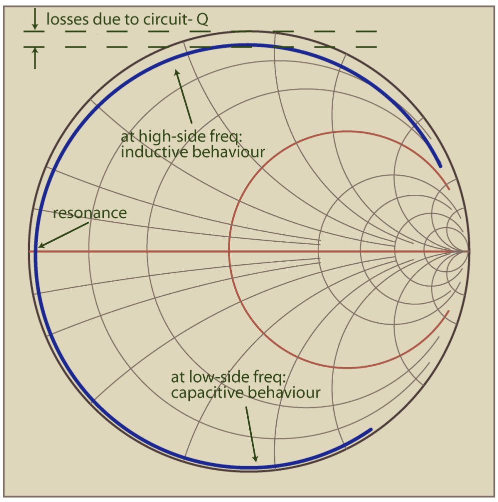
All pure imaginative impedances reside on the outer rim of the Smith chart. At very high frequencies the impedance is very high due to the inductor. on the low side of the spectrum it is very high due to the capacitor. In between the impedance goes from high through zero, to high again. As soon you see the graph of a series resonant circuit leave the outer rim going a bit to the middle it tells you that the circuit is not that ideal at all (which is with anything in real life)

Anything within the Smith chart is lossy, so there are pure resistive ('real') elements in the circuit. This has to do with the circuit-Q. Affecting this are resistance of the inductor (plus the skin effect), dielectric losses in the capacitor and PCB material.

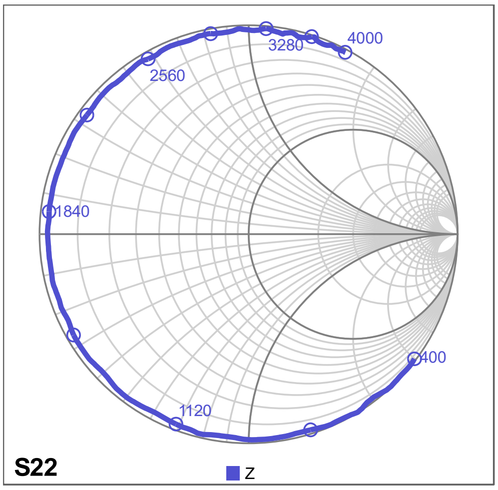
You also see that these losses increase at higher frequencies.

Note: losses in the cables are NOT contributing to this effect. You've calibrated these out.. (You *do have* calibrated the whole set-up including cables and connectors, haven't you?)

All points outside the graph indicate a negative real resistance, e.g. an active circuit, like an oscillator, but this is not the case with circuit 21.



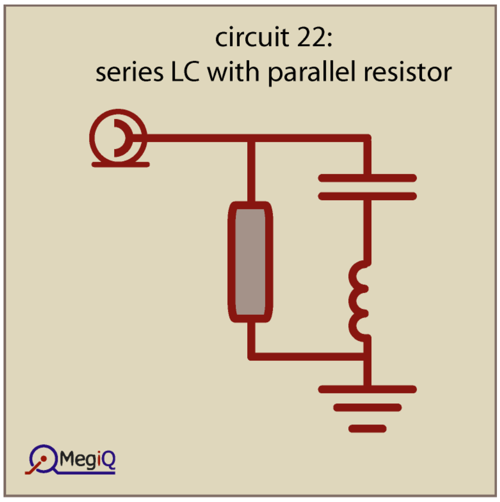
explanation of the display



typical measurement display

Series resonant circuit with parallel resistor (22)

Here the series resonant circuit is bypassed by a pure resistor, introducing a reel part in the impedance.



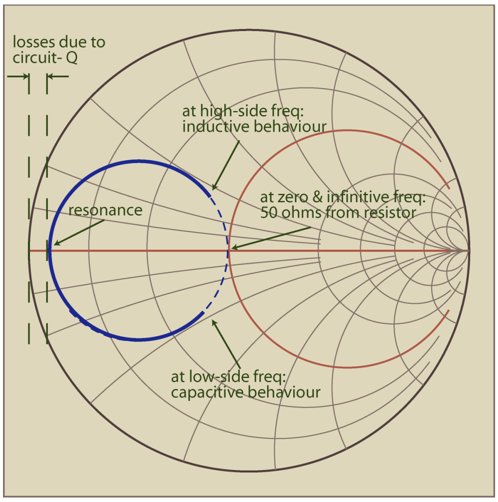
schematic

What do you see

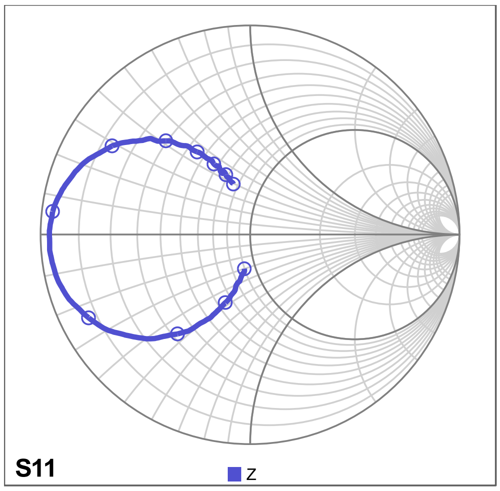
Near to resonance you will see about the same behaviour as with the previous circuit, because the impedance of the LC is very low at those frequencies, thus shorting out the resistor.

But, when you move away from resonance, the impedance of the LC will go way up and the influence of the parallel resistor will be greater, until finally, you only “see” this resistor (50Ω). Above resonance the circuit is more like a lossy inductor and on below resonance it looks like a very lossy capacitor.

Here the curve is much more to the inner of the chart, indicating a “lossy circuit”. Note that the word “lossy” only applies to the port you are looking into. It means there is less power “coming back”.

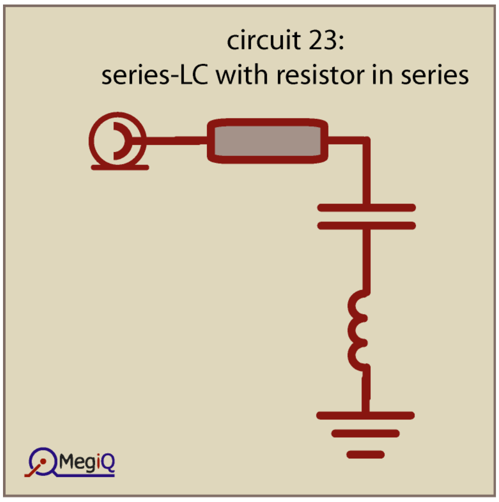


explanation of the display



typical measurement display

Series resonant circuit with resistor in series (23)



schematic

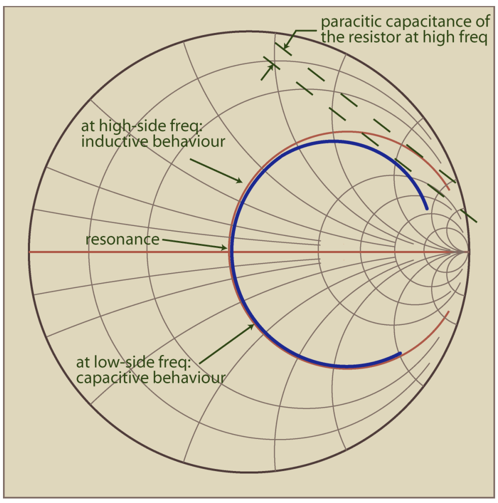
Now you find a resistor in series with the series LC-circuit, again introducing a reel part tot the imaginary impedance of the LC-resonant circuit.

What do you see

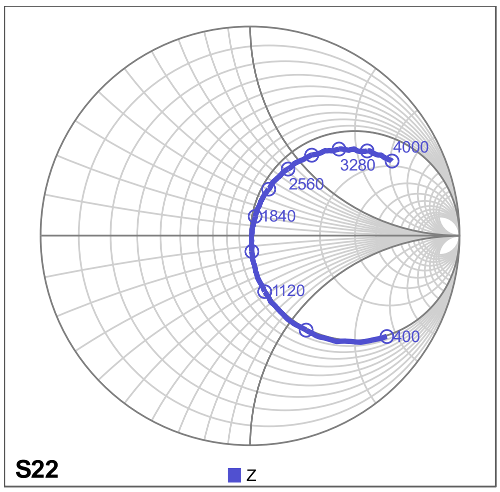
At very low frequencies the capacitor introduces the bulk of the series impedance, while at very high frequencies you will almost only see the inductor. In both cases the resistor does not contribute a lot to the total impedance. But around resonance the LC part shows very low impedance and then the resistor (50Ω) has a big influence.

The line does slightly go to the inner of the chart at very high frequencies. This is caused by the by the parasitic capacitance shunting the resistor and also by increased circuit losses at higher frequencies.

So way off resonance the circuit shows the same behaviour as the simple series LC-circuit (circuit 21) and close to resonance the circuit acts as a 50Ω resistor, yielding points very close to the middle of the Smith chart. (Yes, in this case very lossy *and* dissipative)

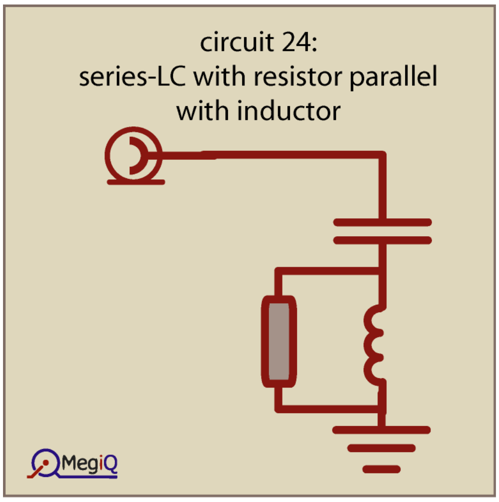


explanation of the display



typical measurement display

Series resonant circuit with resistor parallel with inductor (24)



schematic

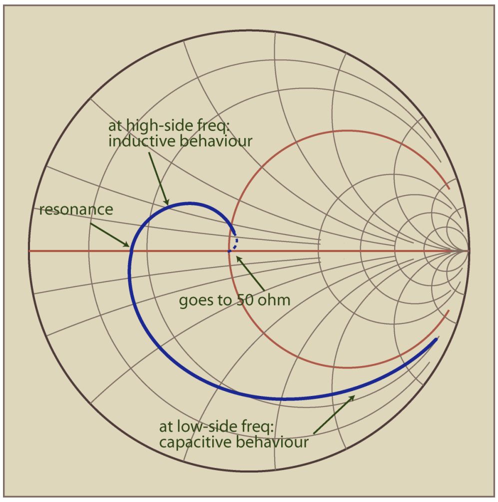
Again a series LC-circuit, but now with a 50Ω resistor parallel to the inductor. This simulates a very lossy coil at high frequencies.

What do you see

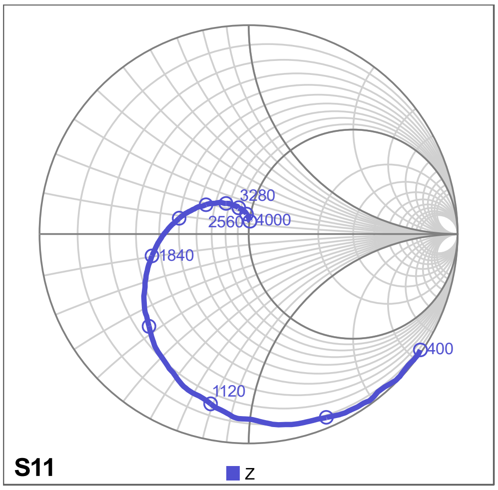
At very low frequencies the capacitor takes care of the bulk of the impedance: it shows a high capacitive impedance very alike circuit 21, the first LC-circuit. The resistor is of almost no importance. But when frequency goes up the capacitive impedance goes down and the RL-part gets more influence.

At resonance the line crosses the reel line (the horizontal line in the chart) much closer to the middle then in the case of circuit 21. Indeed, the circuit is much more lossy then the (almost) pure LC-circuit so the line *got to be* closer to the middle.

At very high frequency the capacitor has a very low impedance and the inductor a very high one, so the 50Ω of the resistor dominated the graph at high frequencies.



explanation of the display

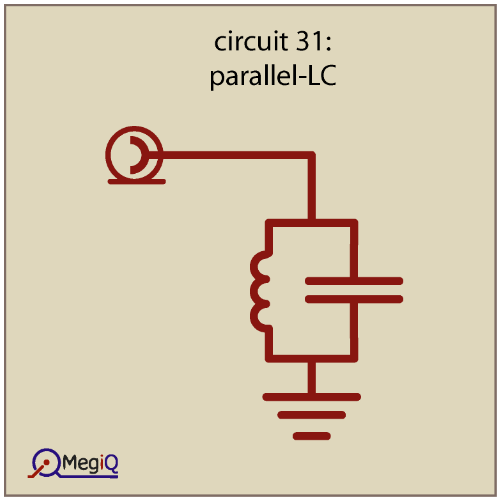


typical measurement display

Parallel resonant circuit (31)

An ideal parallel resonant circuit consist of a pure capacitor in parallel with an inductor and is therefore a pure imaginative impedance, except at resonance where the capacitive and the inductive part cancel each out resulting in *an open* circuit, which is an infinitely high impedance, so you cannot define it being real or imaginative at resonance.

Well, this is theory, let's look at the circuit in real life!

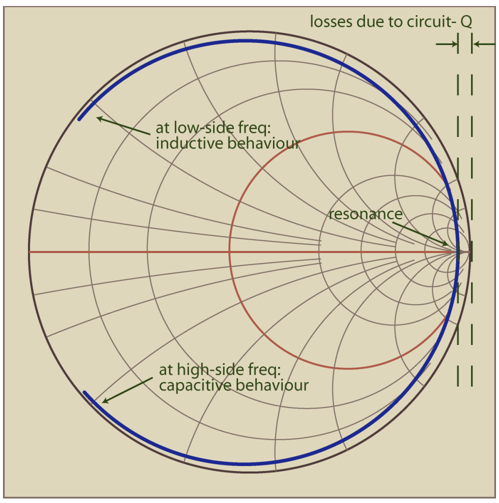


schematic

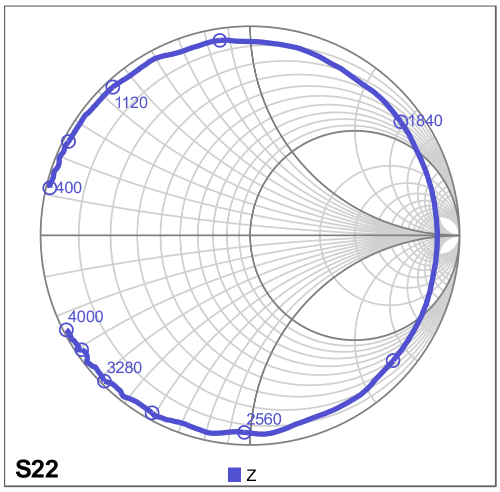
What do you see

Like with the (almost) pure series LC-circuit (circuit 21) the line almost lies on the outer rim of the chart, indicating very high reflections, and almost no dissipation. And also now in an ideal circuit the line would lie *on* the outer rim if it were really ideal.

Above resonance the circuit is capacitive, the higher the frequency, the lower the impedance. The same applies below resonance, but here the impedance is inductive. Around resonance the circuit has a very high impedance, but clearly *not* infinite. This has to do with circuit losses due to the fact that the Q is finite. At resonance you could think of a high ohmic parallel resistor shunting an ideal LC-circuit.

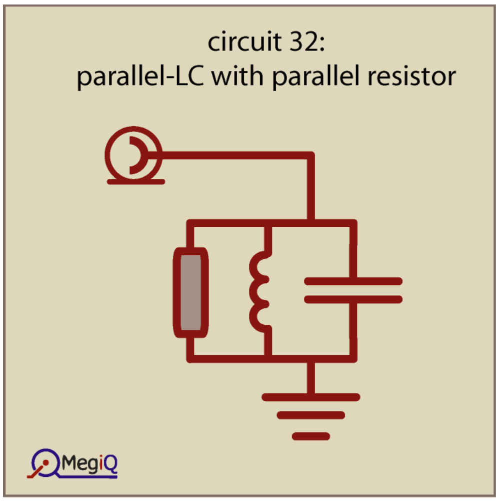


explanation of the display



typical measurement display

Parallel resonant circuit with parallel resistor (32)



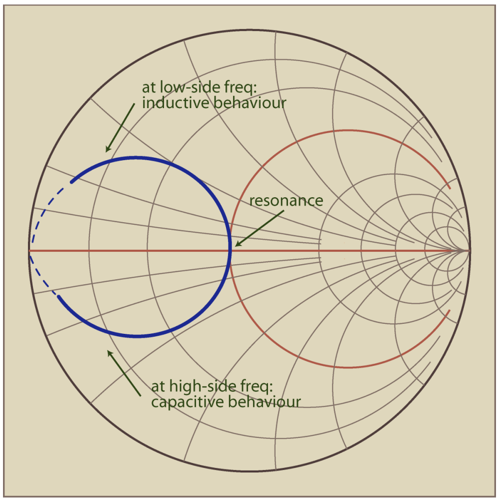
schematic

Now the parallel resonant circuit is indeed shunted with a resistor, but here the value is rather low (50Ω)

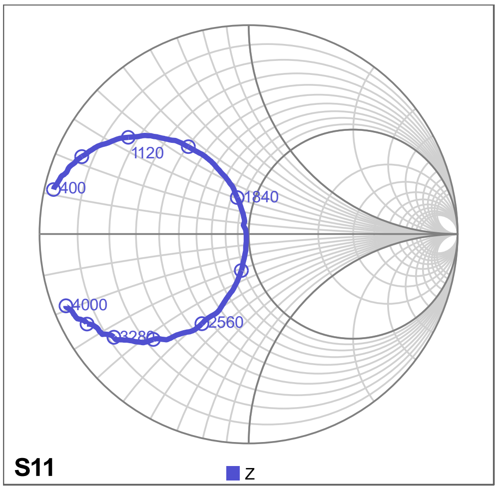
What do you see

Well, it does look a bit like the graph of circuit 31, the almost ideal parallel circuit, but now the imaginary resistor shunting the circuit is just only 50Ω, thus at resonance the graph crosses the 50Ω-point, the middle of the chart.

At very low and very high frequencies the graph is more alike the previous one, although the 50Ω in parallel seriously moves the line towards the middle, indicating a more lossy circuit.



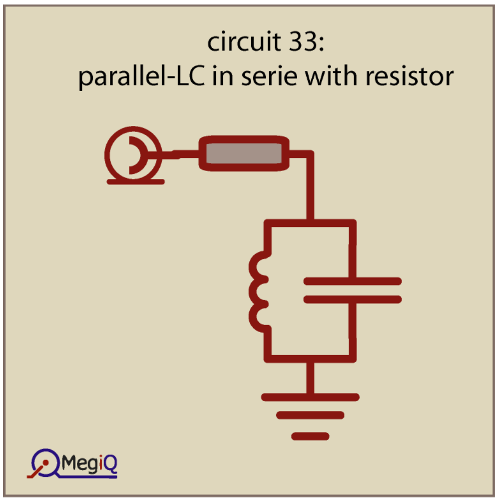
explanation of the display



typical measurement display

Parallel resonant circuit with resistor in series (33)

A parallel resonant circuit with a 50Ω resistor in series.



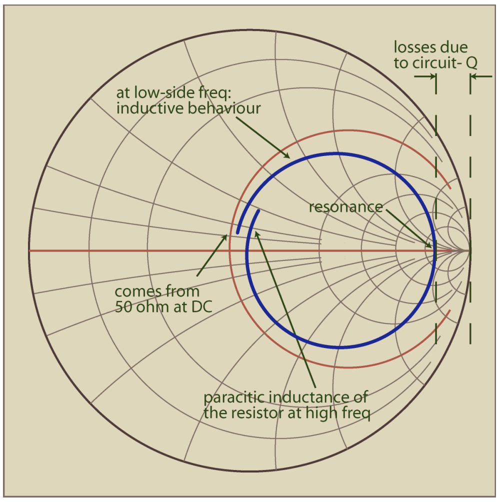
schematic

What do you see

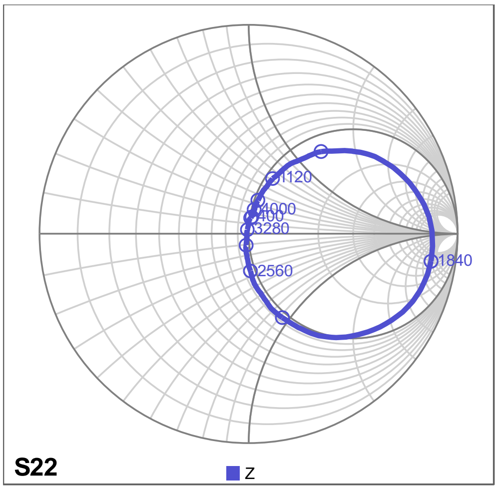
At resonance the impedance of the parallel LC-circuit is very high, so there will be no current flowing through the resistor. Ergo, the resistor has little to no effect around resonance.

But now, moving away from resonance, the resistor gains importance while the reactive impedance of the LC-circuit goes to zero. Both at very high and very low frequencies one would expect to see a mere 50Ω, so points in the middle of the chart.

But strangely enough the line "curves" further a bit at the high side! The explanation for this is the parasitic inductance of the 50Ω resistor at these high frequencies. This inductance makes the line move away from the middle: the extra inductance causes less dissipation in the resistor, thus more reflection.



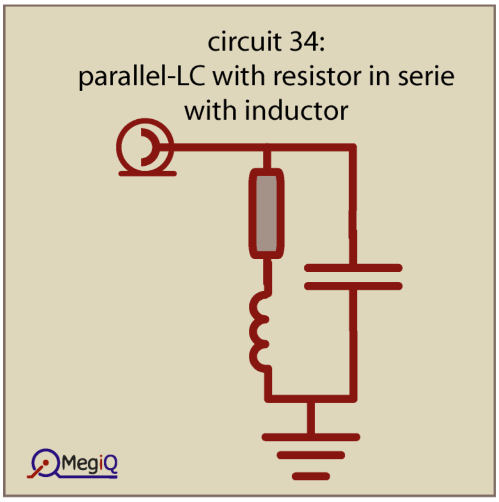
explanation of the display



typical measurement display

Parallel resonant circuit with resistor in series with inductor (34)

This is what you could encounter using good PCB material and a high-Q capacitor with a very lossy inductor: A parallel LC-circuit with a 50Ω resistor in series with the inductor.



schematic

What do you see

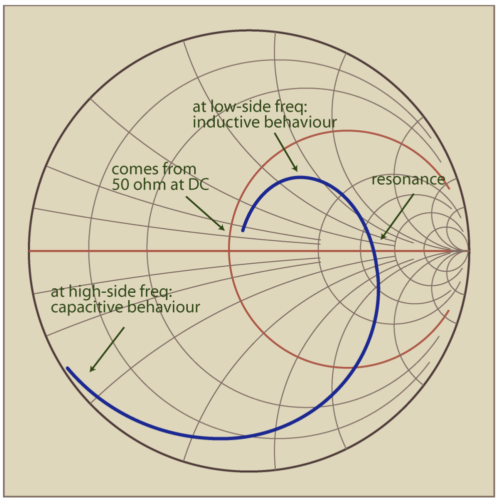
Again let's look at extremes and at resonance. That will explain a lot.

At very high frequencies, the capacitor acts as a capacitive short circuit, cancelling out the rest of the circuit. Therefore you will find the curve on the high side of the spectrum in the capacitive side of the Smith chart (lower half) close to the outer rim and close to zero (left)

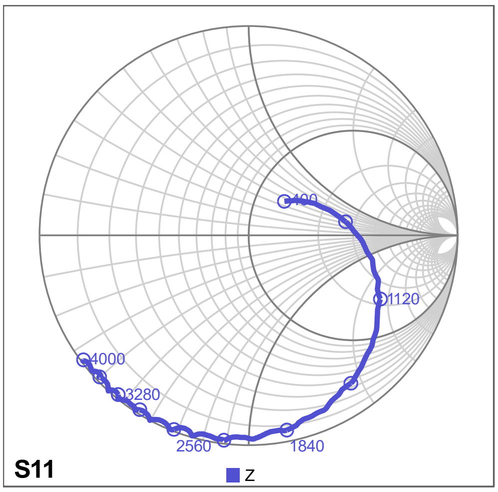
At very low frequencies the capacitor is almost a capacitive open circuit paralleled with the inductor (almost a short circuit) in series with the frequency-independent resistor. So you will see the resistor, which is close to 50Ω.

At resonance, the impedance is real thus residing on the middle horizontal line. Without the resistor, so with ideal (non-real-life) components it give you the out-most right point, i.e. infinite impedance. But here again, the fact the circuit is (very) lossy due to the resistor in series with the inductor, the point of resonance moves to the left over the horizontal, real impedance line.

Below resonance, the circuit is lossy inductive, above the resonance frequency the circuit is lossy capacitive.



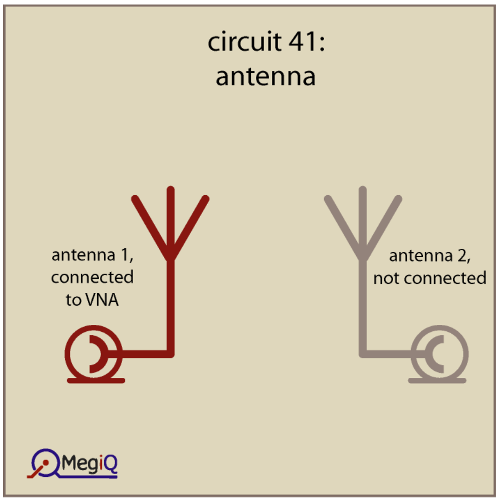
explanation of the display



typical measurement display

Antenna circuit (45)

A commercial chip antenna that has been implemented exactly following the data sheet. But though the antenna might look simple, there are a lot of parameters to be taken into account and a VNA will be of great help.



schematic

What do you see

With an antenna there is a lot more of interest. You probably are interested in:

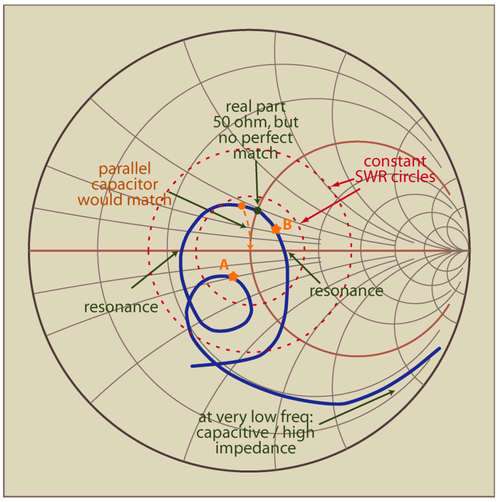
- impedance over a certain frequency range
- return loss (or SWR), with and without matching network
- matching to the receiver of transmitter
- influence of the surroundings

impedance

(Note: not all loads connected to an antenna will be pure resistive and 50 (or75) Ω. There is no reason for avoiding a complex load to be matched into an antenna with a matching (conjugate) complex impedance, as long as you have complete control over the transmission lines in between. In the example below we assume a real 50Ω-load)

constant SWR-circles

First we use a Smith chart and we will introduce the constant SWR-circles. SWR is a measure for the impedance mismatch and Return Loss is the quotient (in dB) of the amount of power you put into the circuit and the amount that is reflected back, due to mismatch. So both SWR and Return Loss tell you about the matching of a circuit, here the antenna.



Smith chart for an antenna

You see “constant SWR circles” in the Smith Chart. (red dashed circles) On these circles the SWR (and the Return Loss) will be the same. So if you must design an antenna with a Return Loss better then, let's say, 10 dB, you can use the SWR circle and make sure the points of the graph stay within the SWR circle corresponding to a Return Loss of 10dB.

showing SWR-circles

In the VNA software, right-click on the Smith chart to toggle SWR-circles on/off.

matching

With antennae, matching is important if you want put power into the antenna. In a well designed antenna, this power will be "lost" due to radiation. All the power you radiate will not be reflected back. How well it actually radiates or how much is dissipated in lossy conductors, a VNA cannot tell!

A line that curves around the middle (50Ω-pure resistive) of the Smith chart is a good candidate for a broadband antenna, since at many frequencies the SWR will be low.

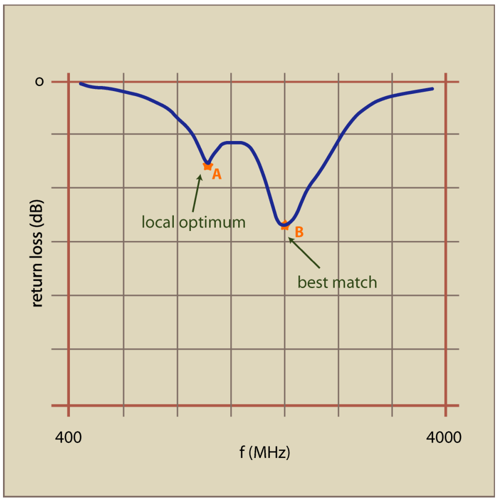
There is a lot of lore about antenna's. One of the lore is that an antenna should be in resonance. In this case you see very clearly that the SWR is not ideal at resonance (crossing the horizontal middle line)

Also the point were the real part of the impedance is 50Ω (were it crosses the 50Ω-circle) there is no perfect match.

It is often better to design the antenna to be not-resonant and match it with a simple matching circuit to a real impedance (here 50Ω). There are several ways for this matching circuit. Here you see a parallel capacitor. (orange dashed and curved arrow). Later you will see how simple you can use the VNA software to calculate the matching circuit for you.

return loss graph

The Return Loss graph shows Return Loss as a function of frequency. It is scalar, so does not give you information on the complex behaviour off the impedance, but just the magnitude of the quotient of how much power you put into the load and how much is reflected back (in dB). It is a handy graph, because as long as the Return Loss is high enough, you most probably don't bother about phase. So if you have 20dB Return Loss with a certain antenna over the bandwidth of interest, only 1% of all power you put into it will be reflected back. That is very good (in most cases), so don't look at the complex impedance (Smith chart) in that case.



Return Loss graph of an antenna

The Return Loss has reference with the Smith chart, it is a measure for the distance of the Smith curve from the origin (middle) of the Smith chart. So a horizontal line in the Return Loss graph will be a constant SWR-curve in the Smith chart.

Actual measurement

This is all theory, let's look at the results of the real antenna on the board, circuit 45

The graphs you will get will depend a lot of the surroundings of the antenna. That's is logical, an antenna has got to be sensitive for fields! So even the way you lay the coaxial cable connecting the antenna to the VNA, will be of influence. Well OK, that is one proof of the importance of being able to actually make VNA measurements.

This also tells you to control all parameters very carefully when measuring an antenna. Some ideas:

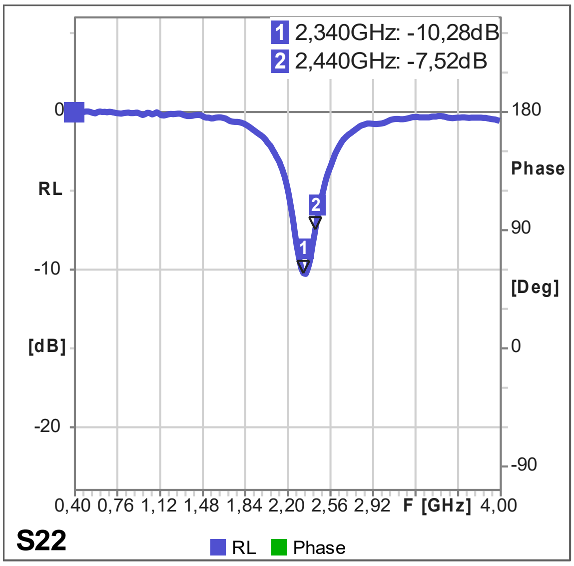
- Use a wooden table and e thick piece of polystyrene foam to support the Sandbox on this table. This removes a lot of the influence of the table. Make sure you are not just above a metal support below the table.
- Fix the Sandbox by taping it to the foam
- Fix the cable running to the Sandbox

influences

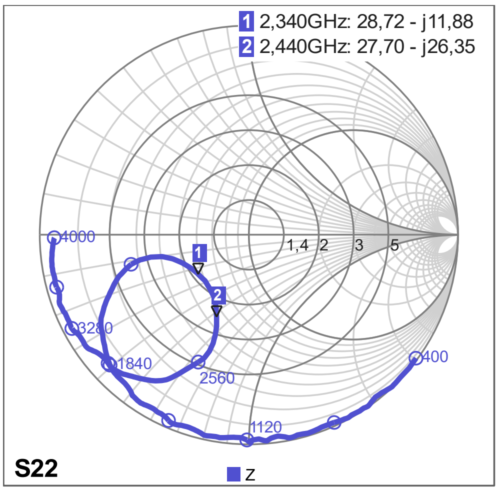
Feel free to play around with the position of the cable, plastic and metal parts near to the antenna, moving your hand over the antenna, etc.

We show some measurements below and assume you want to match the antenna in a frequency band of 2400 to 2480 MHz for Wifi use with at least 10dB return loss. You designed the PCB with the antenna on it, measure it with the VNA, and then choose the final matching circuit.

First the graphs of the unmatched antenna mounted and connected in the way that is typical for use in the final product. As you see the antenna is more or less matched at 2340 MHz, and has an unacceptable return loss of -7.5dB at 2440 MHz.



Return Loss. unmatched



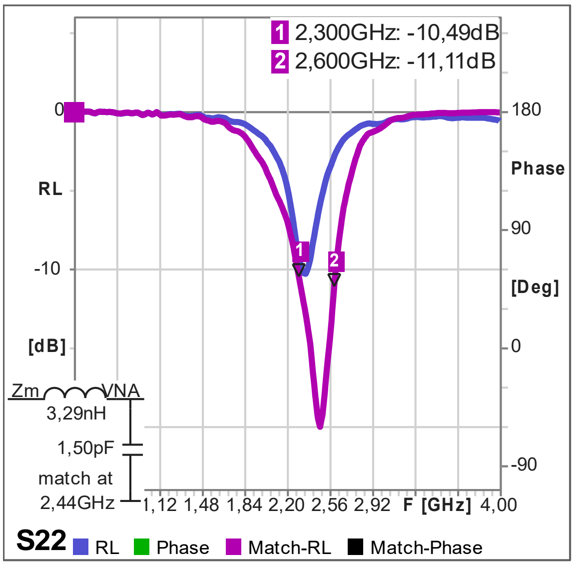
Smith chart, unmatched

The broadband match around the 5....6dB you find back in the smith chart, where the curve touches the SWR-circle of 2.

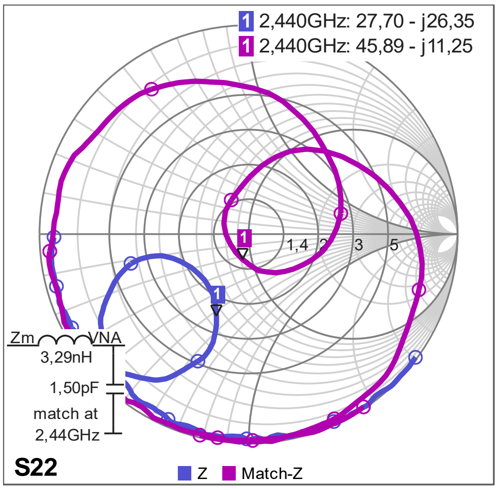
Matching

Let's say we want to have at least 10dB between 2400 and 2480 MHz, so we'll have to match the antenna. The VNA software has a very nice matching feature, easy to use.

- In the Smith chart, click on the frequency point you want to match, to set a marker.
- right-click on the marker, or the value readout of the marker, and choose “Match circuit” from the popup menu.
- choose the matching circuit you want to use by clicking the “select” button.
- Fine tune the components to have a wide band return loss better than -10dB.
- This will give an additional curve in the Smith chart, when you use the suggested matching circuit.
- Right click in the Smith chart and select “Copy match”. This will give you the results in the Return Loss graph.



Return Loss, matched



Smith chart, matched

As you see, in this case a shunt capacitor of 1.5pF and a series inductor of 3,33nH will give a very good match on 2440MHz.

The return loss is better than -10dB over a range from 2300 to 2600 MHz. This gives quite some room for the antenna to detune due to environmental factors (cabinet, hand effect) and still have an acceptable return loss.

2-port measurements

Until now, all measurements were single port and therefore about impedances, return loss etc. on a single port.

Now you are going to take a closer look at circuits with 2 ports. Many 2-port circuits are bi-directional, but there are also many circuits that have a specific "input" and "output", like non-symmetrical filters and amplifiers.

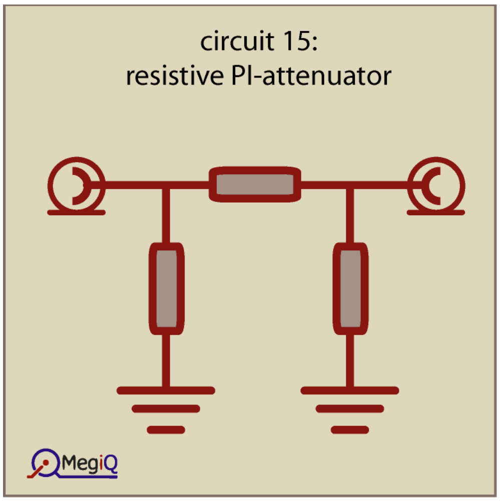
No there are much more things that can be measured:

- Impedance and matching of the input:
  This tells you how well the input will be matched, or what to do to get it matched, or how much power will be coming back,..
- Impedance and matching of the output:
  The same, but now on the output side
- Transfer of energy from port-1 to port-2, gain and phase. ("forward"):
  This is the gain of an amplifier, the attenuation of a filter,...
  You put a certain amount of power in the input, and measure how much you find on the output.
- Transfer of energy from port-1 to port-2, gain and phase. ("reverse"):
  If you put a certain amount of power in the *out*put (!), how much will you find on the *in*put (!)
  This is a sort of "reverse gain" and should be (much) lower on the negative side then forward gain is on the positive in order to maintain stability. An example explains a lot:
  An amplifier has a gain of 10dB. If you put -10dBm in the input the output will be 0dBm. If the reverse transfer is higher then -10dB, e.g. -5dB, the signal on the output (0dBm) will leak back to the input and give you a -5 dBm signal there....
  "Hey, that's more than the original input signal!"
  Yes it is, and if the phase is "right", the amplifier will oscillate. (Murphy's Law tells you that here the phase will most probably be right, unless you try to build an oscillator)

There are some "standard" 2-port circuits in the Sandbox, like a high- and a low-pass filter, attenuator. But there are also some special ones, like a voltage controlled low-pass filter and a current controlled PIN-attenuator (demonstrating the integrated bias step-generator with the bias-Tee's).

There are also two antenna's (each of course single port). But due to the fact that those antenna's are coupled, you can see them as a two port network. Be amazed how much influence an open or a short on one antenna has on the matching on the other antenna!

Resistive Π-attenuator (15)



schematic

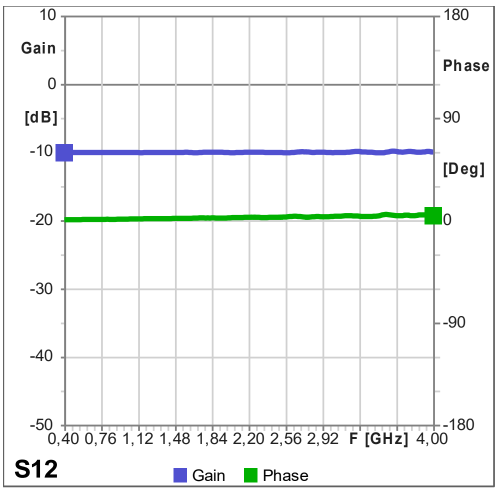
A resistive Π-attenuator consists of three resistors and should give good match on both ports, is fully bi-directional if is symmetrical and should give a fixed attenuation over the whole frequency range.

What do you see

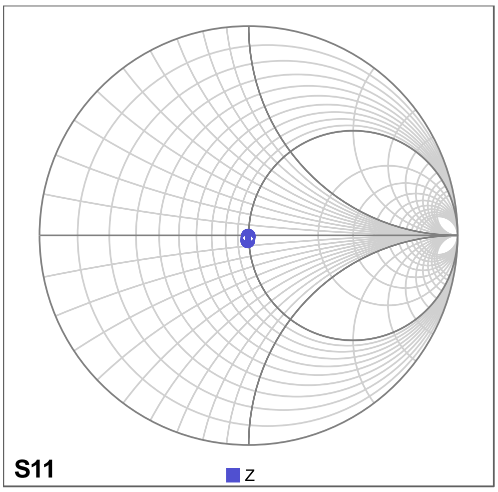
Main goal of resistive PI- (and also T-) attenuators is guaranteeing a good match, i.e. high Return Loss / low SWR and also attenuating the signal, although often the attenuation is not the main goal and even not wanted. But well, you get nothing for free...
Resistive attenuators should be broadband and should not exhibit any phase shift: they are not filters.

Well, from the gain/phase plot you can read that the attenuator is broadband indeed, doing 10 dB of attenuation and that phase shift is zero. There are some small anomalies at the high end of the spectrum, but for such a simple attenuator on epoxy and using standard components it is not bad at all!

As you would expect, in the Smith chart all measurement point are close to the middle,



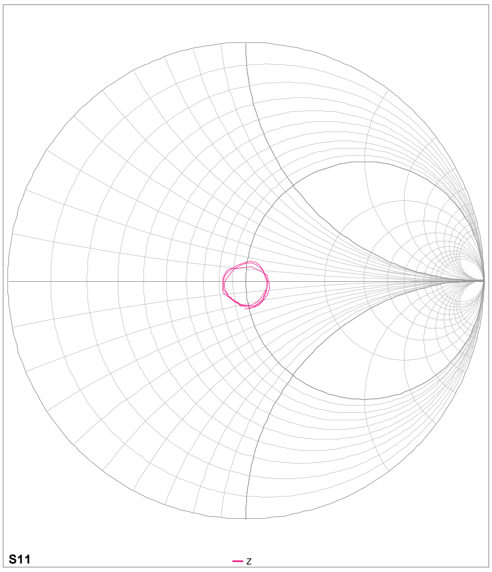
typical measurement display (gain/phase)



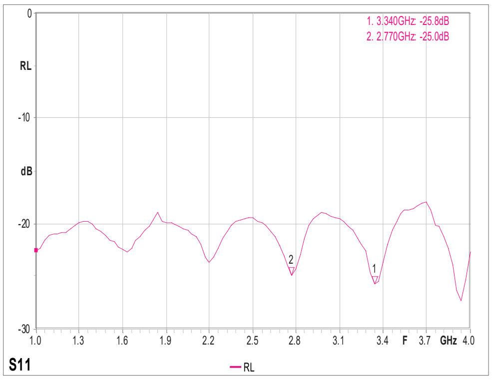
typical display: Return Loss terminated

indicating a very good match. there is some anomaly though, they all lie a bit below the resistive line, they are a bit capacitive. This is most probably due to parasitic capacitances of the components.

Now an interesting experiment: disconnect the output cable from the attenuator at the end of the VNA. You get a Smith chart with all points in a circle-like patten closely around the middle, and indeed, this is a SWR-circle, indicating a fixed (rather good) Return Loss. If you express this in a Return Loss graph in dB, you can look more into detail and see some wavelike patterns.



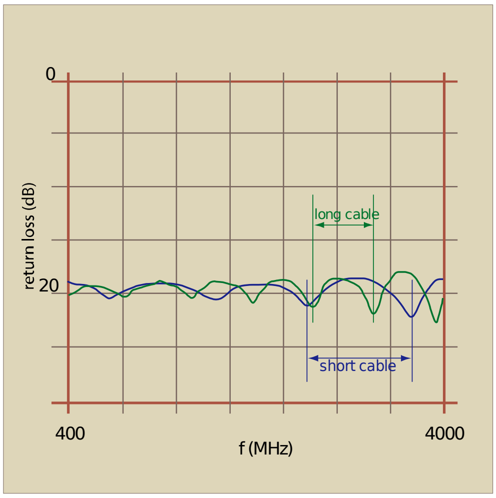
typical display: Return Loss terminated



typical display: Return Loss no termination

These wave are caused by reflections in the cable. You could try a long and a short cable and see the with longer cable the “wave-length” in the graph gets shorter. This has to do with the fact that the cable is in fact a transmission line transformer and that circles around the middle point of the Smith chart, thus transforming the mismatch at the far end of the cable in a repetitive way. A longer cable has a lower resonance frequency, i.e. it “turns around the middle” faster introducing more (and shorter) waves.

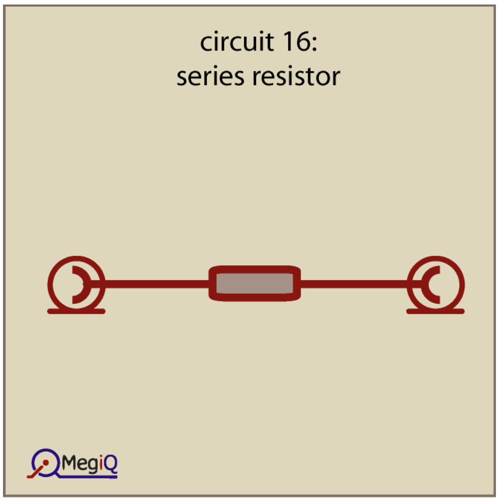
Furthermore the average of the Return Loss is around 20 dB, what you would expect from a 10dB attenuator.



explanation: reflections long and short cable

Series resistor (16)

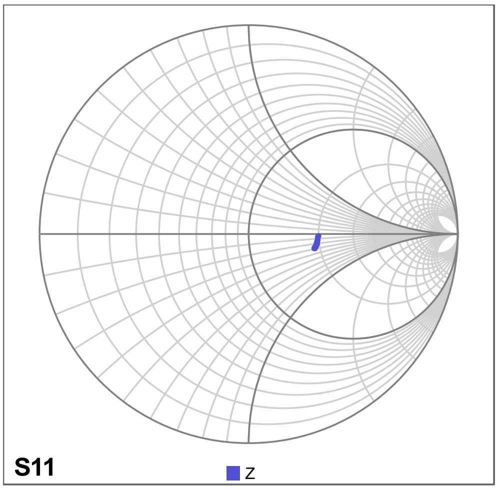
A mere resistor in series from one port to the other attenuates the signal, and should be broadband just as the previous circuit. But here there will be an impedance mismatch.



schematic

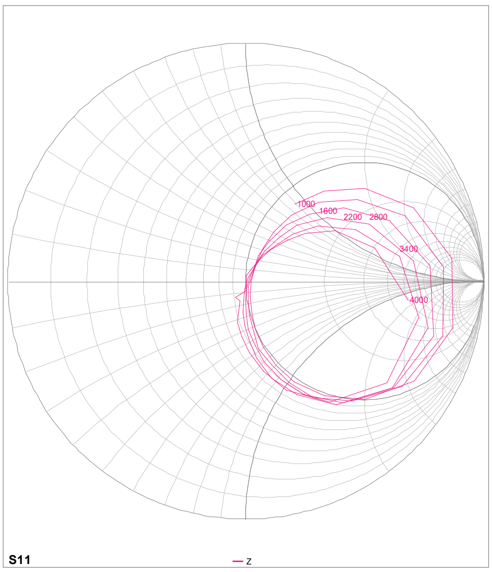
What do you see

Just a series resistor is not that a good idea when you want a good Return Loss. When terminated the points cannot lie on the middle of the Smith chart in both directions: it is a resistor in series with the characteristic impedance. Also, when you disconnect the 'output-cable' at the side of the VNA you see a Smith chart that shows you a lot of impedance changes over the spectrum.



typical measurement display (terminated)

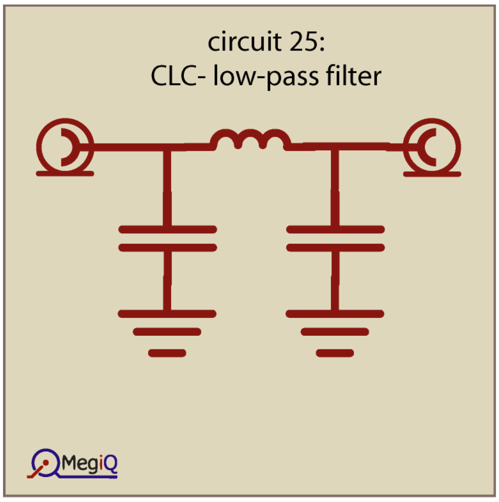
Here again, you see the transformation caused by the cable, but it is much more pronounced now. this is caused by the bad isolation (i.e. attenuation) between in- and output. Specially at high impedances (when the 'open' cable on the output is a multiple of ½ λ long) you see very high impedances, both capacitive and inductive.



typical display (Smith chart unterminated)

Low-pass filter (25)

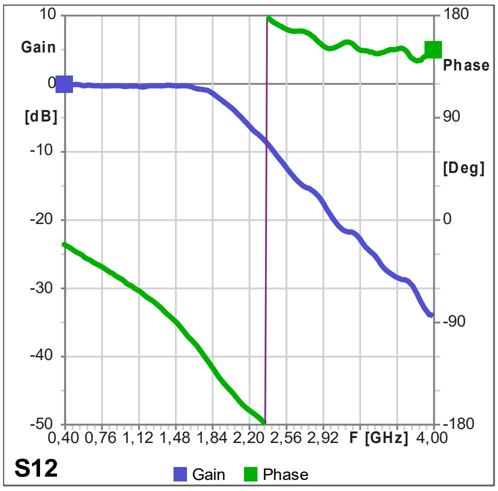
A simple CLC low-pass filter configured as a Π. Depending on the component values it gives you a certain roll-off, and impedance (mis)match. There might be pass-band ripple. Behaviour depends on termination.



schematic

What do you see

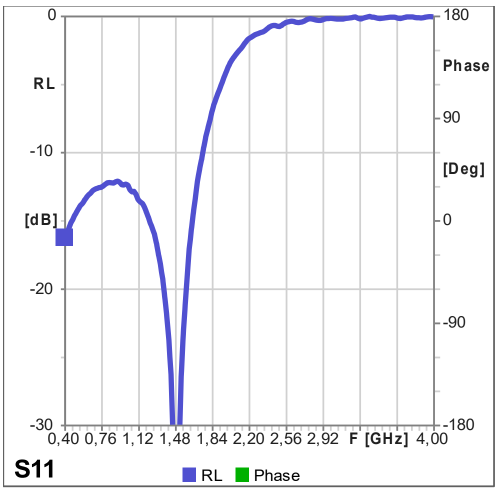
First look at the gain plot. That gives information on attenuation, insertion loss, etc. The picture you get is pretty straight forward, and looks like the picture you get when sweeping a filter with a Spectrum Analyser with Tracking Generator (SA/TG), except that the latter does not give you phase information.



typical measurement display (gain/phase)

Graphing the SWR or Return Loss, you can evaluate the matching of the input and/or output, (Note: this can also be done with a SA/TG together with a Return Loss Bridge / Directional Coupler. And though the set-up gets a bit bulky then, it is the way this is often done.)

You see now that, well below cut-off frequency, the matching is quiet OK, but gets rather bad at higher frequencies. At cut-off the RL is about 5dB. This is all “scalar” so just looking at magnitudes of gains and impedances.

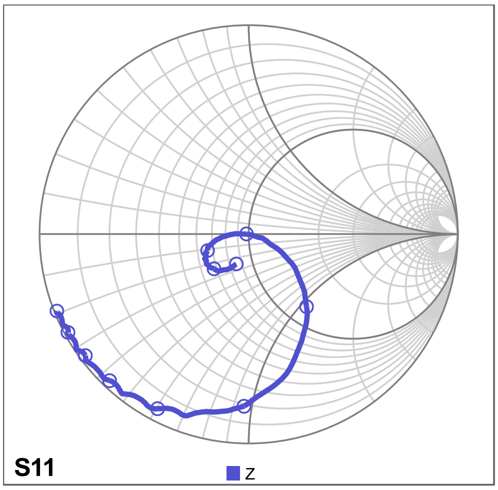


typical measurement display (return loss)

Things get more clear looking at *complex* impedances.

Again the Smith chart (next page) is a very nice tool for this. If you switch on the SWR circles, you get a good idea of how well the filter matches. As you see, at very low frequencies it matches quiet well (close to the middle of the chart), the filter looks transparent from input to output at those low frequencies. There is just a bit of a capacitive shunt paralleled with a small inductance and the output resistance in series. The total is not resistive, but well, the matching is quiet right as we saw before.

When the frequency sweeps over the cut-off frequency of the filter, suddenly the impedance gets very complex and moves quickly outside the inner SWR-circles, indicating a very bad match.

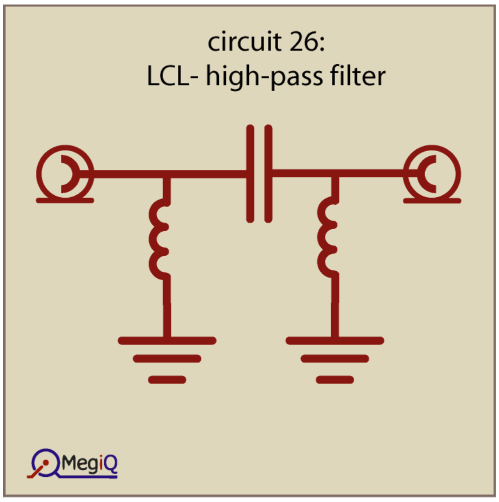


typical measurement display (Smith chart)

Now we see that the input impedance gets very capacitive and tends to go to zero. This is logical, the signal just 'sees' a capacitive short to ground, followed by a high impedance inductor in series.

If you would like to get a better Return Loss over the complete spectrum, you would be better off with e.g. a diplexer, i.e. a low-pass for the pass band and a high-pass that is terminated into the characteristic impedance.

High-pass filter (26)

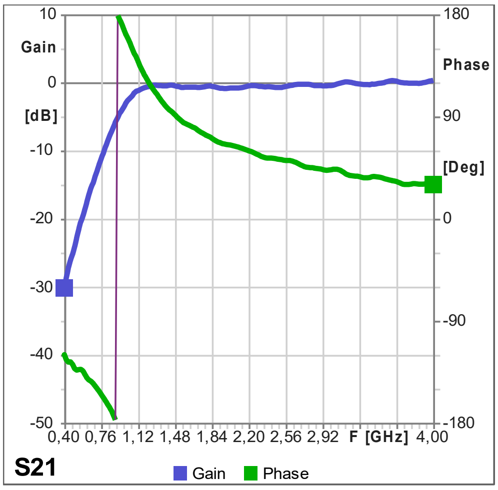


schematic

Again a filter, but now a simple LCL high-pass-Π. Depending on the component values it gives you a certain roll-off, and impedance (mis)match. There might be pass-band ripple. Behaviour depends on termination.

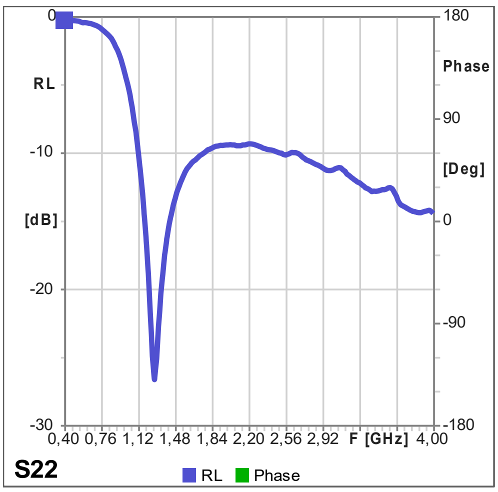
What do you see

Of course the idea behind the measurements are very similar to those of the low-pass filter. We present the different graphs below. The graphs look a bit more complex at high frequencies, but that has to do with line length at those frequencies and the fact that the Return Loss is not very high. This gives reflections in the cables resulting in a more bumpy RL-graph and spirals in the Smith chart.

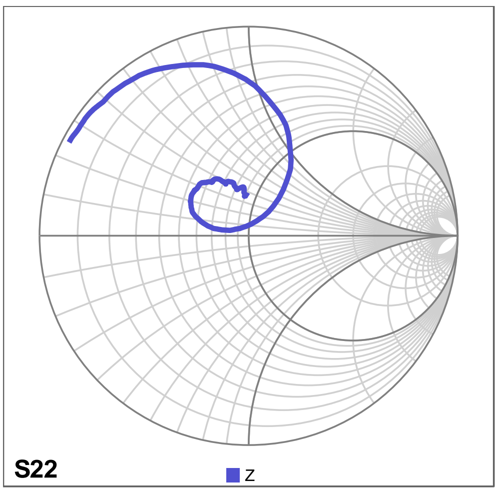


typical measurement display (gain/phase)

Now the circuit is a very low inductive impedance outside the passband, i.e. at very low frequencies.



typical measurement display (return loss)



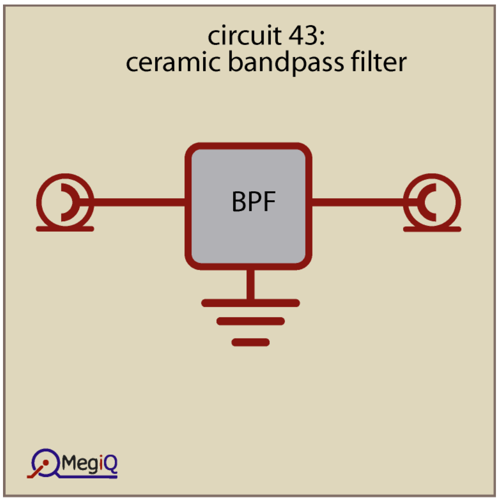
typical measurement display (Smith chart)

Band-pass filter (42)

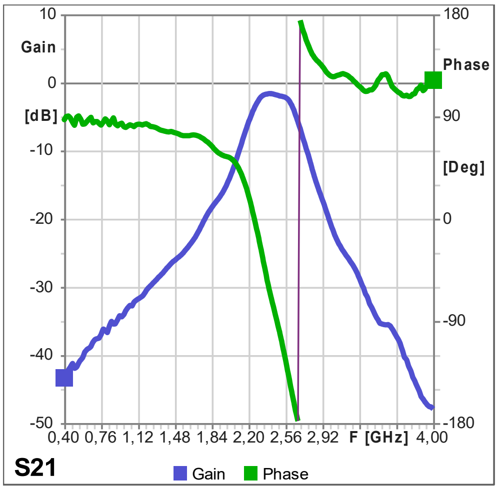
Now a band-pass filter.

What do you see

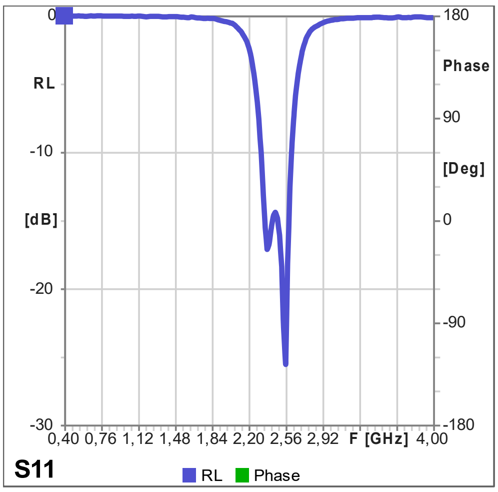
Again a filter; just plug it in, and look at the graphs. With the knowledge of the previous two filters it will be clear what you see.



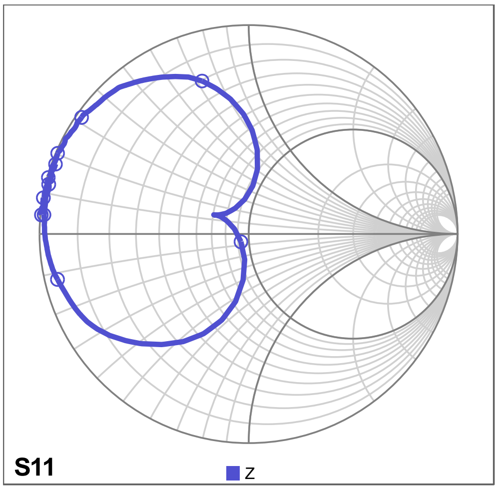
schematic



typical measurement display (gain/phase)

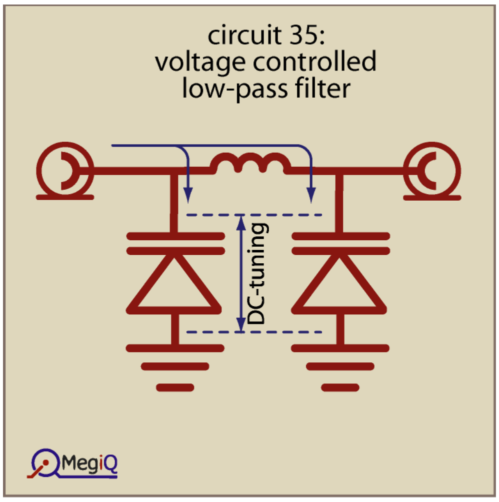


typical measurement display (return loss)



typical measurement display (Smith chart)

Voltage controled low-pass filter (35)



schematic

Again a simple CLC low-pass filter configured as a Π. But now the capacitors are varactor diodes, so you can adjust the cut-off frequency of the filter by applying a DC voltage on the varactors.

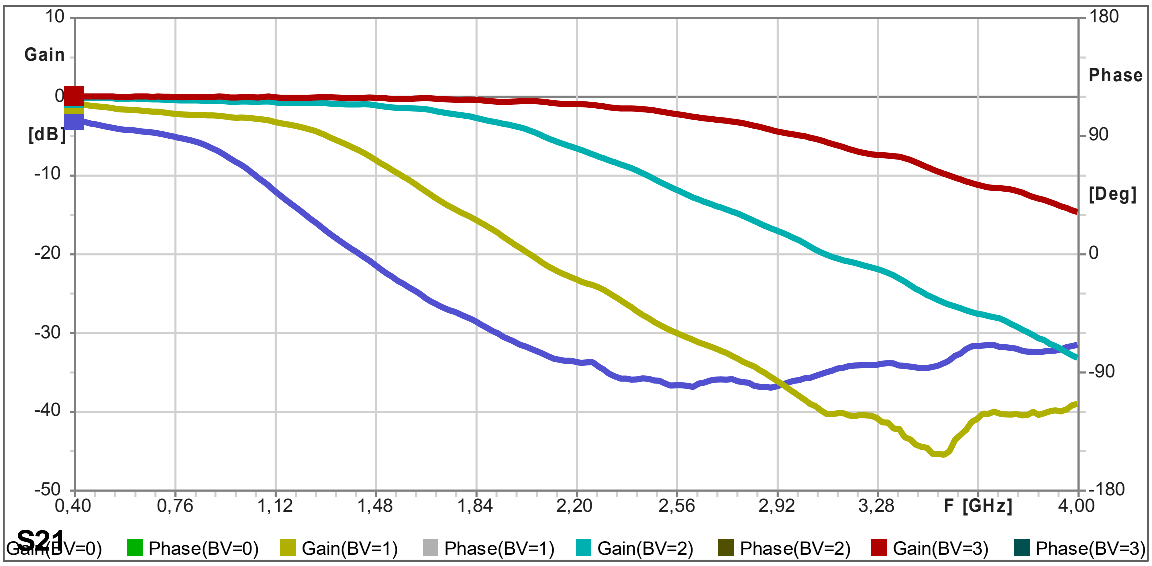
Here you use the internal bias generator and the internal bias-Tee's of the VNA as a programmable voltage generator. This is not incorporated in the standard version, you should have the extended version, the VNA-0440e. You recognize this version by the third SMA (generator output) on the front panel.

The bias generator

The programmable bias generator can make steps in voltage and in current. You can select on which port the bias generator acts, via a bias-Tee. You can also ground a port for DC or leave it open. In the case of this filter you can apply the DC tuning voltage to port 1 or port 2 as long as you leave the other port open, because you should apply DC-voltage across the varactor diodes.

You can choose to step the bias generator or leave it at a fixed level (I or V). You can also choose the order, so sweep the bias for each step in frequency, or make multiple frequency sweep with a different bias setting each. The latter is what we do here in this example.

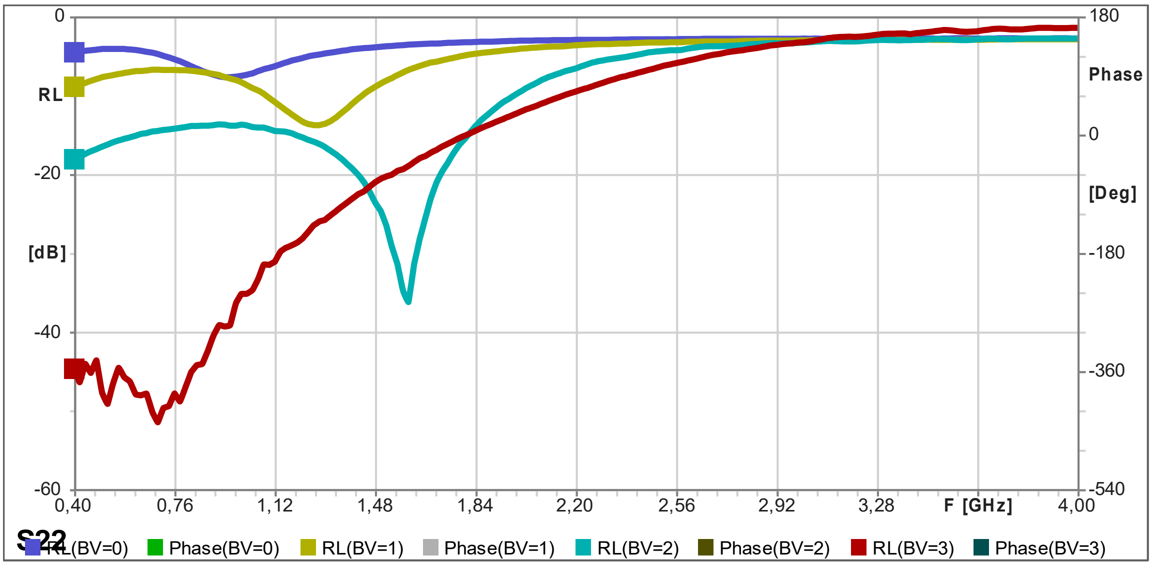
What do you see



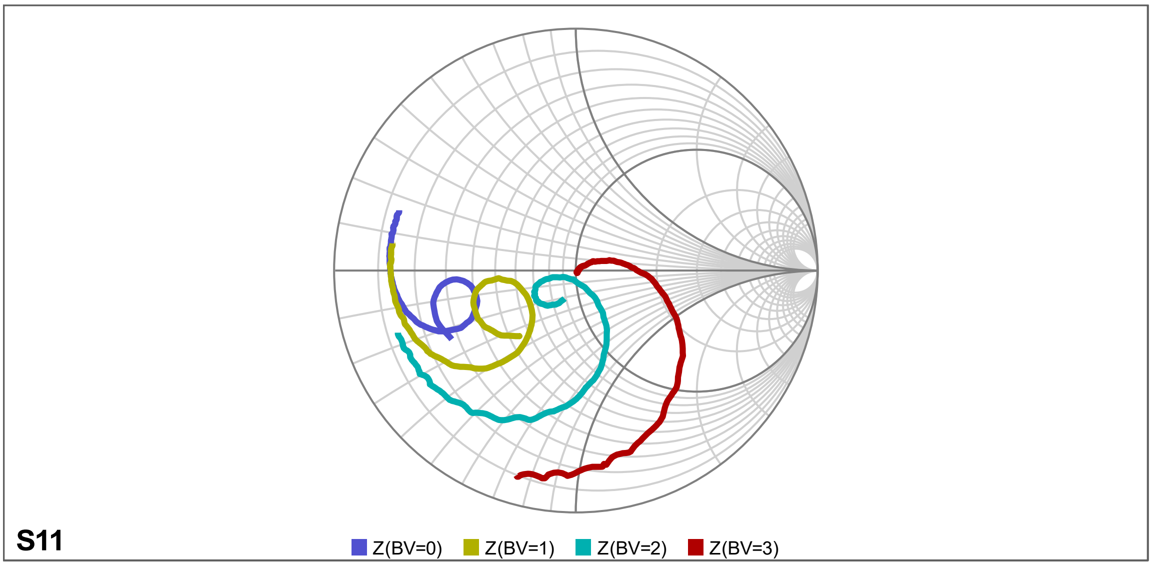
typical measurement display (gain)

In one overview you see the frequency response at different tuning voltages, and see how the cut-off frequency changes.

You can also draw the graph where you see the Return Loss at several DC-bias settings. Watch how the Return Loss is heavily affected by the DC-bias.



typical measurement display (Return Loss)



typical measurement display (Smith chart)

Amplifier (41)

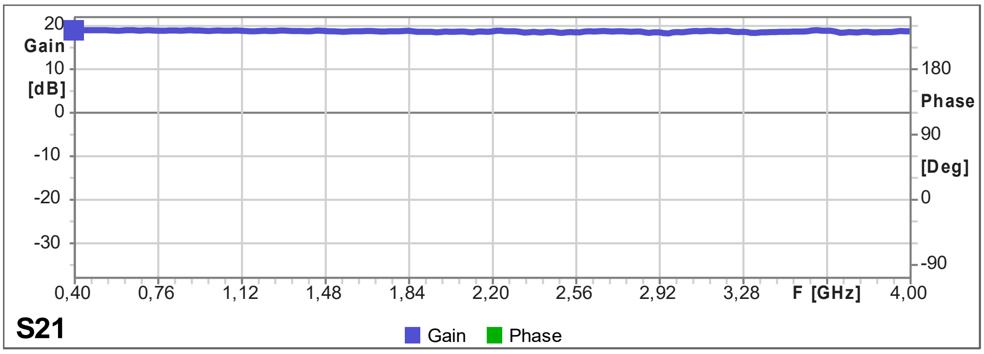
The VNA Sandbox contains an MMIC wideband amplifier chip. This amplifier needs a bias current of 70mA on its output pin as a power supply. The voltage at that current will be around 5V.

So we set the bias generator to 10V and 70mA. The bias generator will drop its voltage to provide a constant current of 70mA. The bias source should be switched on for the port that connects to the output pin in of amplifier.

Note: the measurements below were made with an (obsolete) amplifier with about 18dB gain. Newer Sandboxes are fitted with an amplifier with about 14dB gain (HMC311SC70E).

What you see

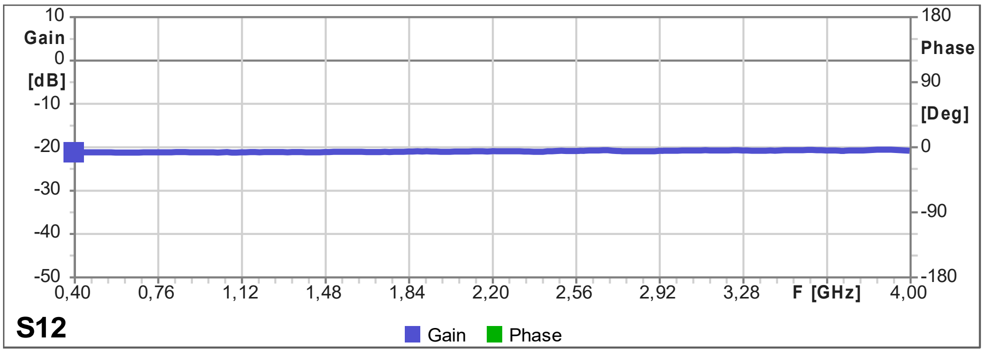
Forward Gain



typical measurement display (Forward Gain)

The gain in forward direction is nice and flat at about 18dB.

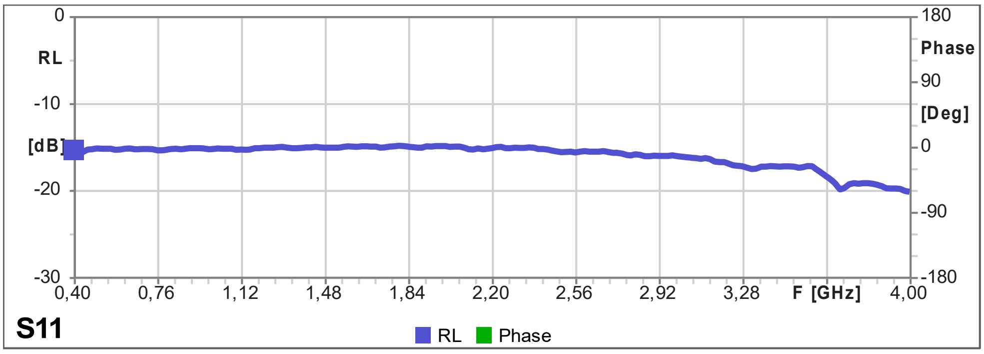
Reverse Gain



typical measurement display (Reverse Gain)

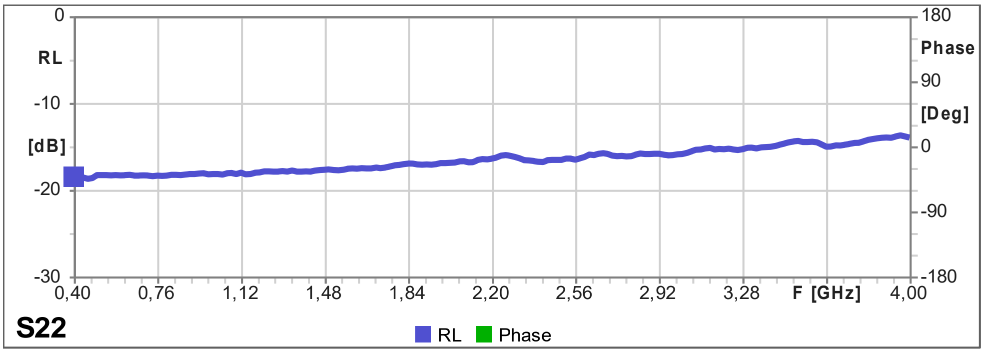
The gain in reverse direction is -20dB. This loss in reverse direction must be higher than the forward gain to avoid oscillation of the circuit.

Input Return Loss



typical measurement display (Input Return Loss)

Output Return Loss



typical measurement display (Output Return Loss)

Both input and output return loss are better than about -15dB over the whole frequency range. These are quite acceptable values for a wideband circuit.

Note that the above measurements are done purely on the amplifier chip. All other effects of the PCB and bias generator are (mostly) calibrated out of the measurement. In real life the chip needs a bias circuit that will affect the overall performance of the circuit and most likely degrade the performance to some degree.

The Sandbox amplifier circuit contains the footprints to solder and connect a bias circuit to an external (current) supply. This allows measuring the circuit with a real bias circuit. The bias generator of the VNA must of course be switched off for this measurement.

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