Receiver construction using 50 ohm modules (gain blocks)

Example Application: a low noise 2m receiver using a DVB-T stick

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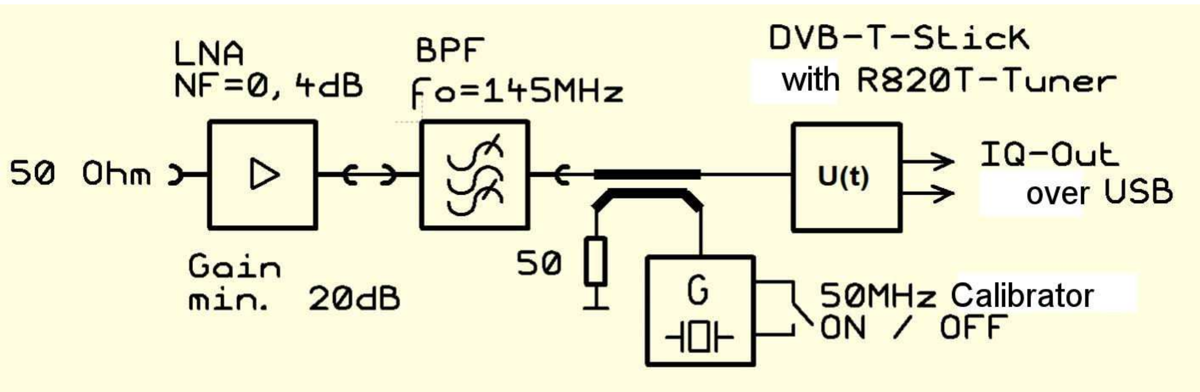
1. Introduction

Professional technology has used this technique for a long time. Initially for expensive measuring instruments and then at higher frequencies using devices in the GHz range. The principle can be seen in the practical designs: very similar building blocks connected to each other by Teflon or semi-rigid cables using SMA connectors. Each building block is described by a precise set of parameters and most importantly have an input and output resistance of 50 ohms (small reflection S11 and S22) giving good power transfer. Thus, the stages can be connected in series without problems and the overall behaviour can usually be estimated without major difficulties with simple calculations. In this way, special requirements can be fulfilled quickly or changes can be made to a different frequency range or the cable lengths adjusted.
It is not a big problem any more if the "design properties" are changed. It no longer requires a complete re-design – this saves time and money.

I now have my latest toy: A Vector Network Analyser VNWA3 by Tom Baier, DG8SAQ. It is right beside my notebook PC ready for development and measurement up to 1300MHz. This makes the whole exercise a pleasure.

2. The project: a 2m SDR receiver



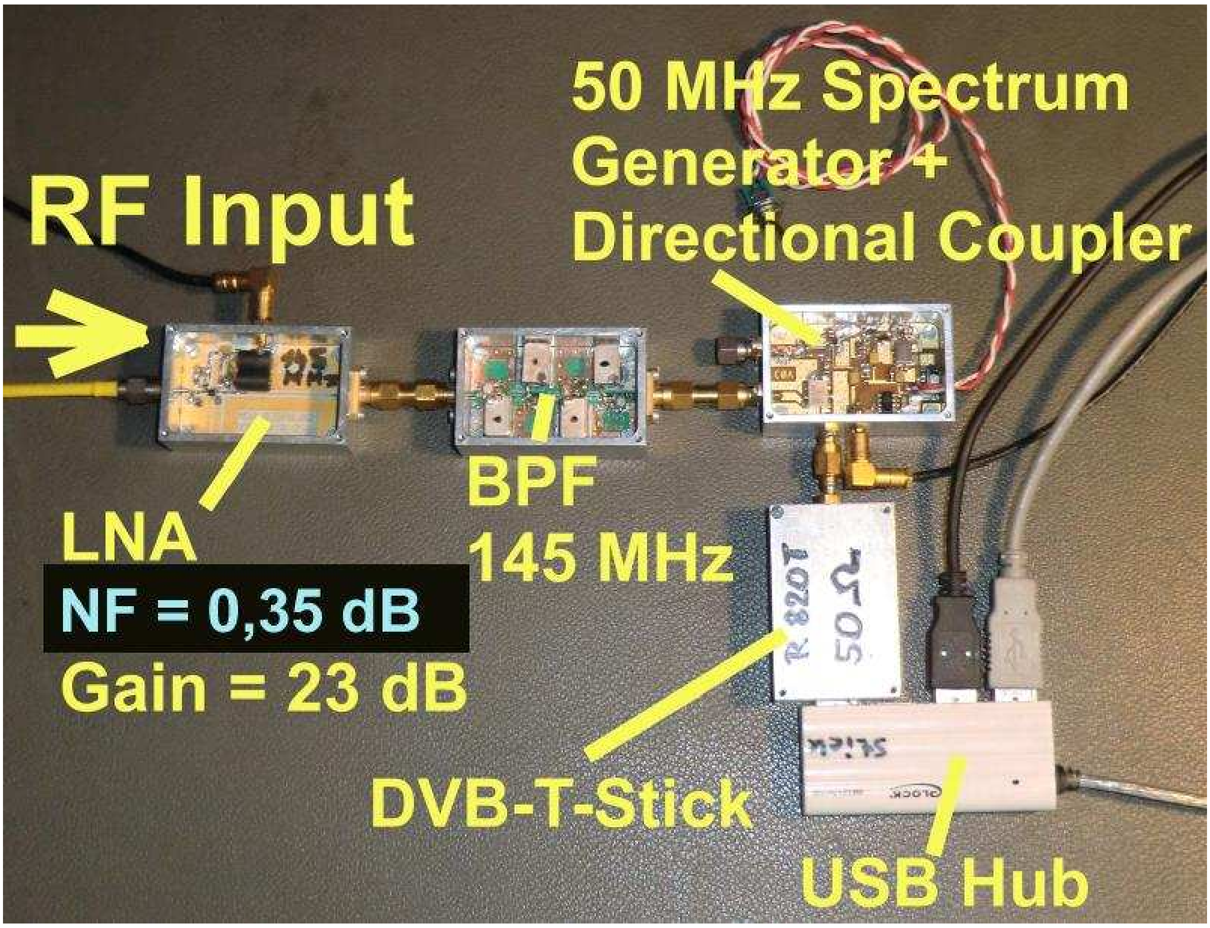
It starts with a low-noise preamplifier (noise figure no more than 0.4 dB between 100 and 500MHz). Its gain in this range should be more than 20dB and the values of S11 and S22 of less than approximately -13dB.
This is followed by a fourth order narrow bandpass filter; the passband loss at 145MHz should be small and only a few dB. This is very difficult to achieve because the skirts are quite steep - we will deal with this in more detail in Chapter 4.
A special feature was required between the bandpass filter output and the input of the DVB-T stick. It is a directional coupler with 10dB reverse coupling factor used to feed a 50MHz calibrator signal from a precision crystal generator with a harmonic spectrum up to 500MHz. When the calibrator is switched off the receiver operates normally, it's sensitivity is not affected. If the calibrator is switched on the tuning accuracy can be considerably increased on the PC using the "SDR frequency

fine calibration in 1 ppm steps". The 50MHz calibrator accuracy can be checked using DCF77, GPS or a good frequency counter.

Finally there is a DVB-T stick with an "R820T" tuner and the IQ decoder: "RTL2832". This is a familiar item that can be purchased for less than €20 from China using Ebay. The sampled IQ signal is passed on to a PC via USB and decoded with the software such as "HDSDR". This is also popular - but the way it is used can decide the outcome.

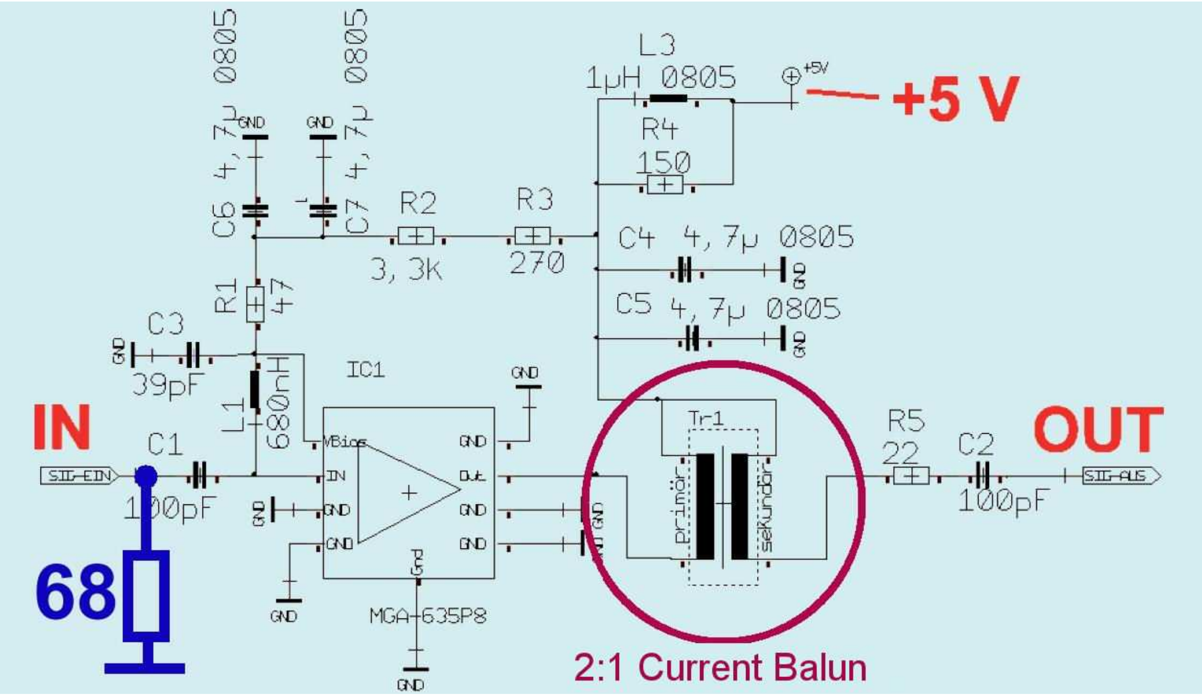
The reflection of the antenna input is designed to be best in the range from 100MHz to 500MHz. A prototype receiver inside the DVB-T-stick has a board size of approximately 20mm x 20mm using SMD 0402 components. It operates from +5 V that is supplied from the USB connection or, if necessary, fed in to the module via an SMB socket. All the building blocks are mounted in the same size milled aluminium housing with a cover. The size of the PCB for every building block is always 30mm x 50mm. An "SMA" connector is used for the RF input.

This is how the finished, ready-to-run receiver looks:



The 50MHz calibrator spectrum can be activated with the toggle switch and fed to the USB stick input via the directional coupler. It has a usable spectrum up to 2GHz.

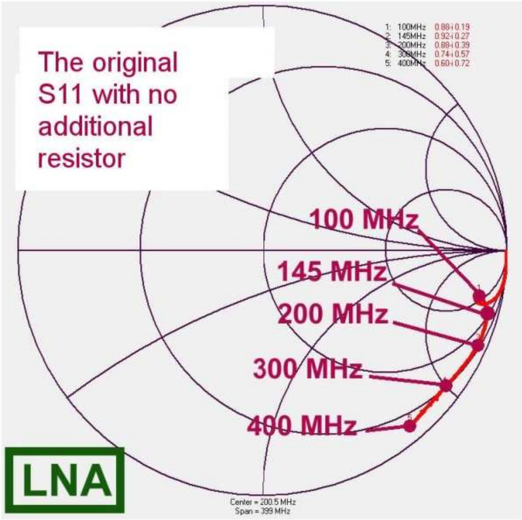
3. Designing the LNA

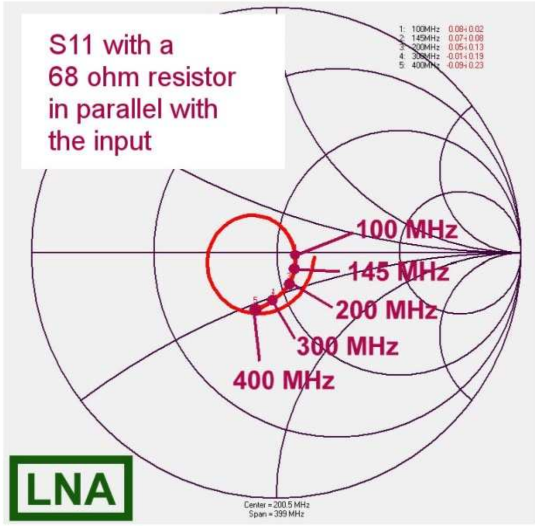


It has been some years since I wrote the first version "very low-noise preamplifier for the range of 1 ... 2 GHz" [1]. It is a cascode circuit using PHEMTs, which have low noise but need a high quiescent current (55mA). Since this worked very well with low noise, there is a version for 70cm with minor changes [2] and the last version for the 2m band [3]. For all three versions, the noise figure NF was between 0.3 and 0.4dB and the main differences were not the necessary changes in the component values, but small layout and circuit changes on the output side, in order to change the value of S22 to approximately -20dB. A broadband 2:1 current balun performs this task in the 2m LNA.

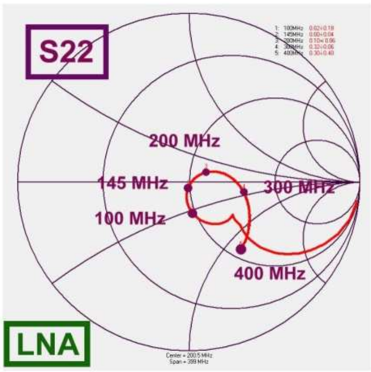
This 2m version is of course used for our receiver, but its input reflection has a very bad value (S11 at f = 100MHz of only about -2dB and at 500MHz only about -4dB). This can be significantly improved, a job for the new VNWA3 Network Analyser.

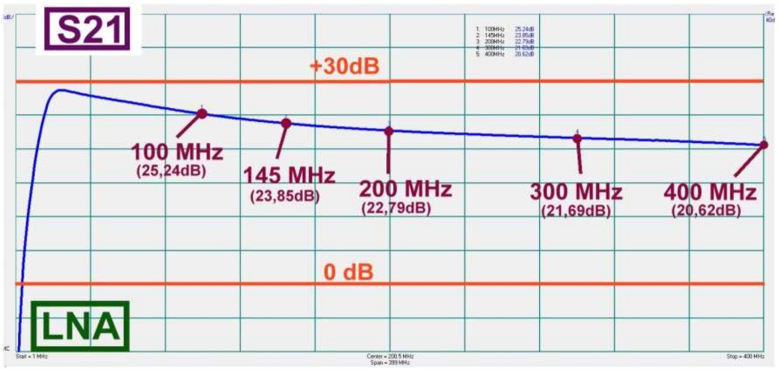
On the left side of the circuit one can see the original cause of the input reflection S11. It is quite logical because it goes directly to the gate terminal of the HEMT transistor in the MMIC, which is high resistance. There is the simple remedy: with a simple parallel resistor of 68 ohms directly across the input socket the problem is solved.





My new toy, the VNWA3 toy had to be used immediately; the plots of S21 are shown above with the plots of S22 below.





The values obtained for S22 = 0 - j0.4 with |S21| = + 23.85dB at 145 MHz which is a good result. S12 was far below -40db and is therefore not listed here.

An investigation of the noise figure NF showed that it had deteriorated from "slightly larger than NF = 0.3dB" before the change to "just below 0.4dB" with the change. That's still OK

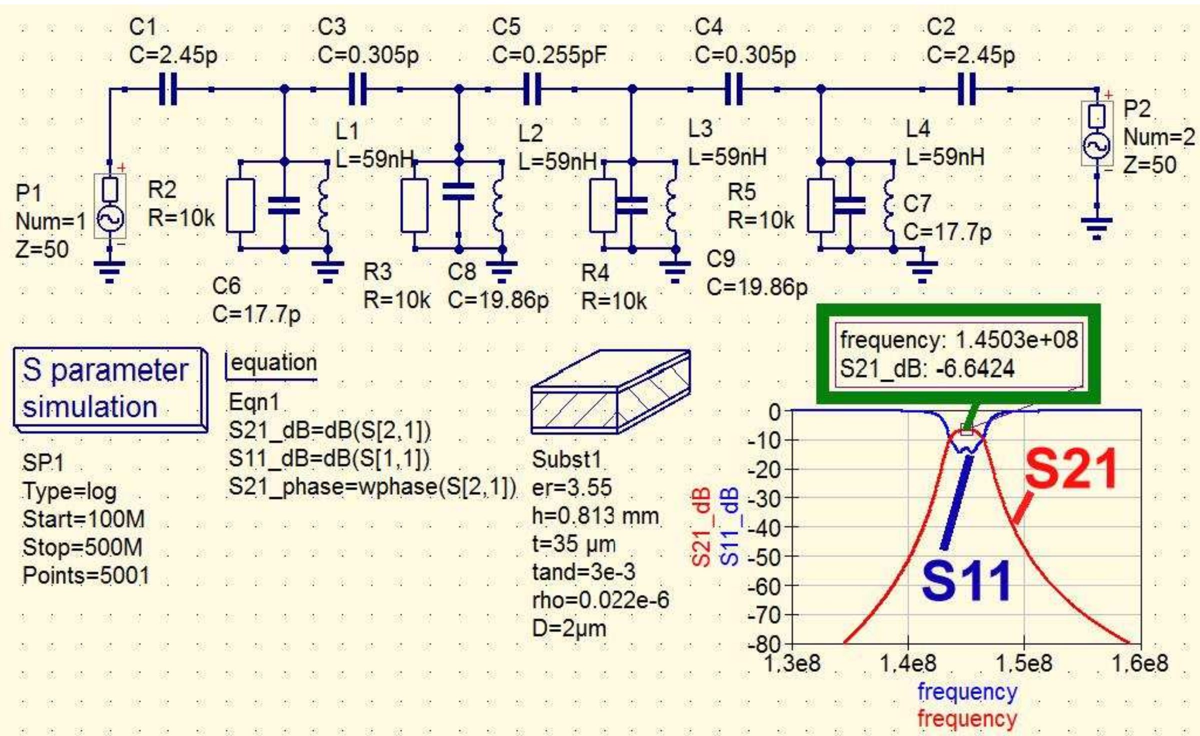
4. The narrow bandpass for 145MHz

The Chebyshef type of filter has been used for "Narrow Bandpass Filters or Coupled Resonator Filters" for years. If you design a "normal" bandpass filter for 50 ohms with a filter calculator it is done by "transformation of a unit low-pass filter". In this case that transformation gives abnormal component values that cannot be used to realise a filter (for example, a combination of 1 Henry and 1 picofarad for a resonant circuit).
The "Coupled Resonator Filter", on the other hand, specifies a practical and identical value of the inductance for every circuit which must be chosen by the designer (a guideline value: reactive resistance at the centre frequency between 50 and 100 ohms). The capacitors required will be given for the circuit depending on the filter specification. However, such a filter has a typical system resistance of more than 1K ohm and therefore "transformers" are applied to the input and output of the circuit to reduce that to our desired system resistance of 50 ohms. These transformers are very

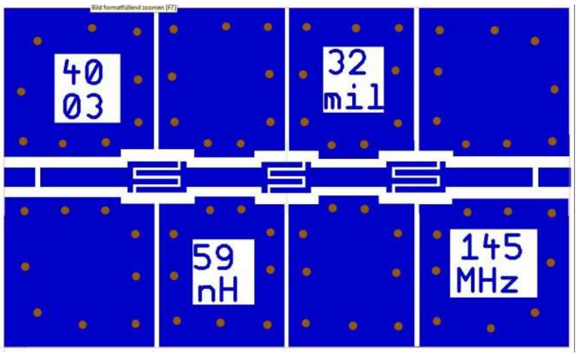
simple small coupling capacitors ... and suddenly everything is very simple! Luckily, there are excellent free filter calculators on The Internet that will do all the heavy work. I personally come back to "fds.exe" again and again - a DOS program. It can be used under Windows 7,8 and 10 with the help of the programs "dosbox" and "dosshell", it works perfectly and provides very precise results. The method of using it with "Dosbox" and "dosshell" can be found in German on my homepage (www.gunthard-kraus.de). There are similar instructions to install “dosbox” and “dosshell” in English in the installation instructions for the CAD program PUFF21 for Window 7.
The design is done in few self-explanatory steps. With L = 59nH (Neosid type 10.1 commercially available filters in silver plated screening cans with the adjustment core removed)
This gives the result:

```
                              Narrow BandPass Filter
What is the value for the inductors? (in nH)
59                               Resonating caps are:
Coupling caps are:               C(1) = 20.11 pF
C(1,2) = 0.305 pF                C(2) = 19.86 pF
C(2,3) = 0.255 pF                C(3) = 19.86 pF
C(3,4) = 0.305 pF                C(4) = 20.11 pF
The characteristic impedance of the filter is 4065.91 ohms
Match to a lower rs/rl? (Y/any key)
Default impedance is 50.00 ohms.  Type 'D' for different src and load
or hit any key to match to default.
Add 2.449 pf to the source end, and 2.449 pf to the load end.
Then change C(1) to 17.695 pf and C(4) to 17.695 pf.
(S)ave to file (P)rint or (C)ont?
```

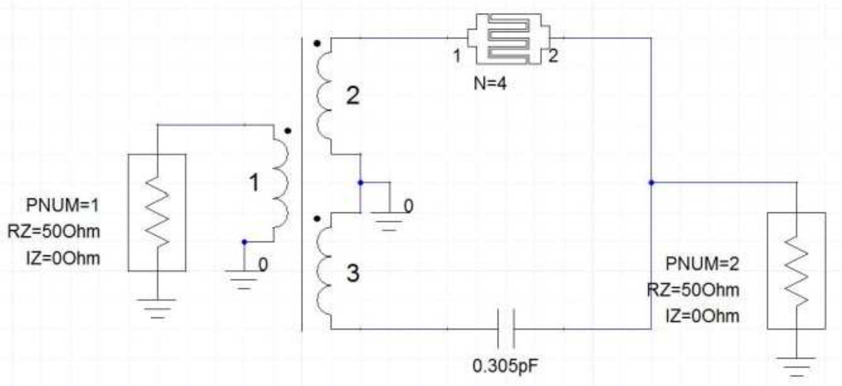
Now for the test, a "qucsstudio" simulation, taking into account the leakage resistance (measured with a Boonton RX meter) of each coil at 10k ohms at f = 145MHz: (the qucsstudio CAD software can be downloaded free from The Internet in German or English. My huge and free qucsstudio 200 page tutorial in English, German or Russian is hosted on my homepage (www.gunthard-kraus.de)



The problems with this circuit are the very small coupling capacitors of 0.255pF and 0.305pF between the resonant circuits. These can only be realised as "interdigital capacitors".



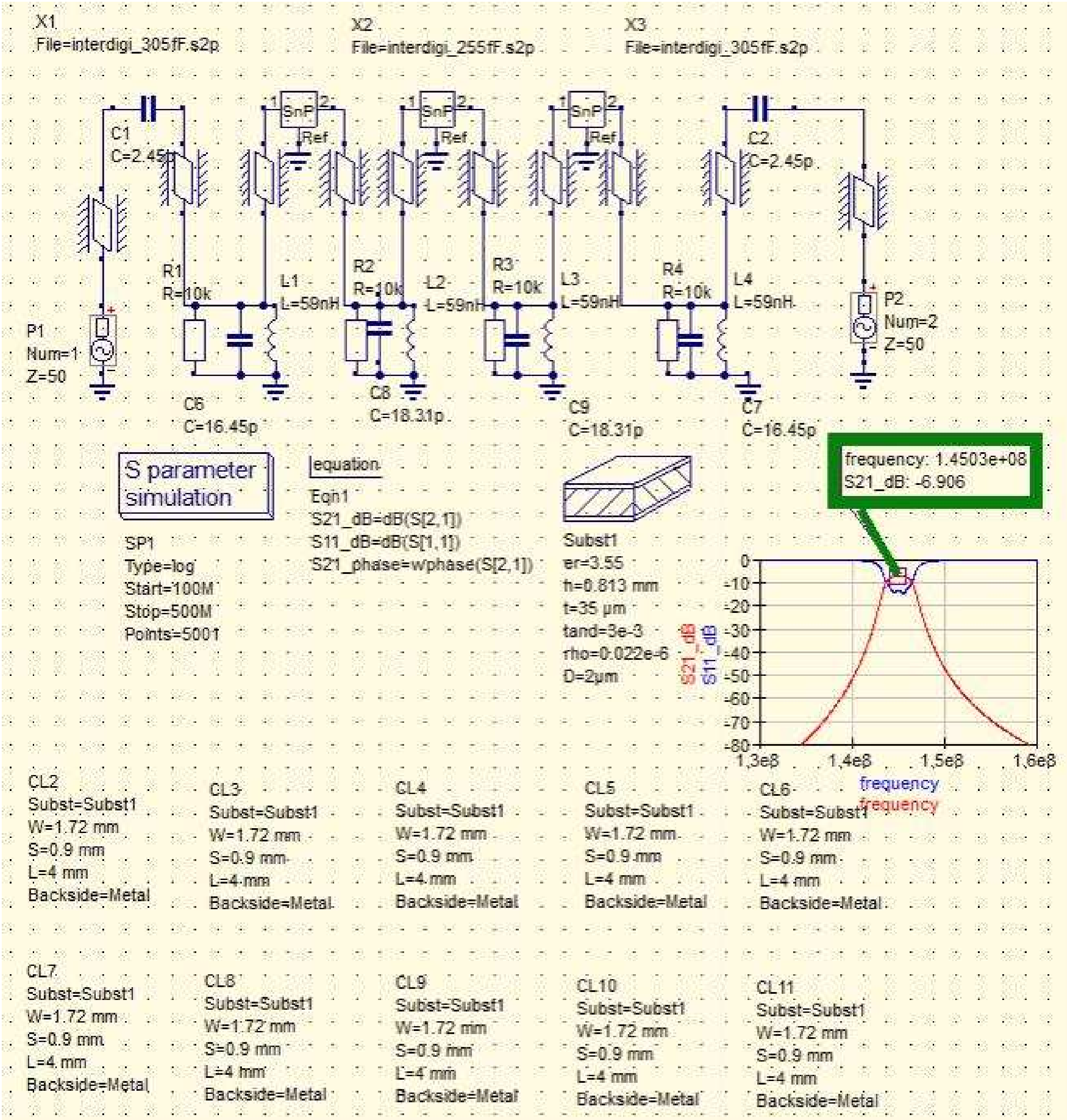
The board layout shows how this can be achieved. The capacitors are a "finger structure" where the numbers of fingers, their width, distance apart and their length determines the value. These are "individually designed" very difficult to do and "qucsstudio" doesn’t contains a model (yet). So you have to use the free "Ansoft Designer SV", which contains all this and many other things in a finished model. This software is no longer officially available on The Internet, but I have received permission from Ansoft to continue to provide it free for those who are interested. You can find this together with my tutorial in German or English in my homepage (www.gunthard-kraus.de). A comprehensive tutorial is available in German under the heading "Alle meine Veröffentlichungen in der Zeitschrift "UKW-Berichte" seit 1995”. The article “Ansoft Designer SV project: Using microstrip interdigital capacitors” is available in English from VHF Communications Magazine Issue 2-2009



The design is not quite as simple as it sounds, because the Ansoft Designer can only perform the analysis of a circuit that it is given! The solution is to use a "half-bridge", and adjust the finger length, If the rest of the capacitor (number of fingers, finger width, finger distance ...) has been defined, the finger length is adjusted until S21 of this arrangement has fallen below -60dB. Then the capacitances in both bridge branches are the same (here: 0.305 pF). The S parameter file of this capacitor is generated by the analysis. The procedure for the second capacitor is repeated with 0.255pF to generate its S parameter file.

These S parameter files are now inserted into the bandpass filter circuit diagram instead of the "original" coupling capacitors. In addition, the simulation circuit is changed to include the continuous "50 ohm Grounded Coplanar Waveguide" which can be seen in the circuit. This leads to additional capacitances in the circuit at these frequencies. Similarly, physics says that the interdigital capacitors represent not only a coupling capacitance, but also a parallel capacitance on each side connected to ground. So after these components are added the resonance curve will be significantly shifted towards lower frequencies and there is still a lot of work required to correct that: the four capacitors must be slowly decreased in value until the centre frequency of 145MHz is correct PLUS the transmission and the reflection curves look beautifully symmetrical! The inductors remain unchanged.

Here is the result of this sweaty work ..



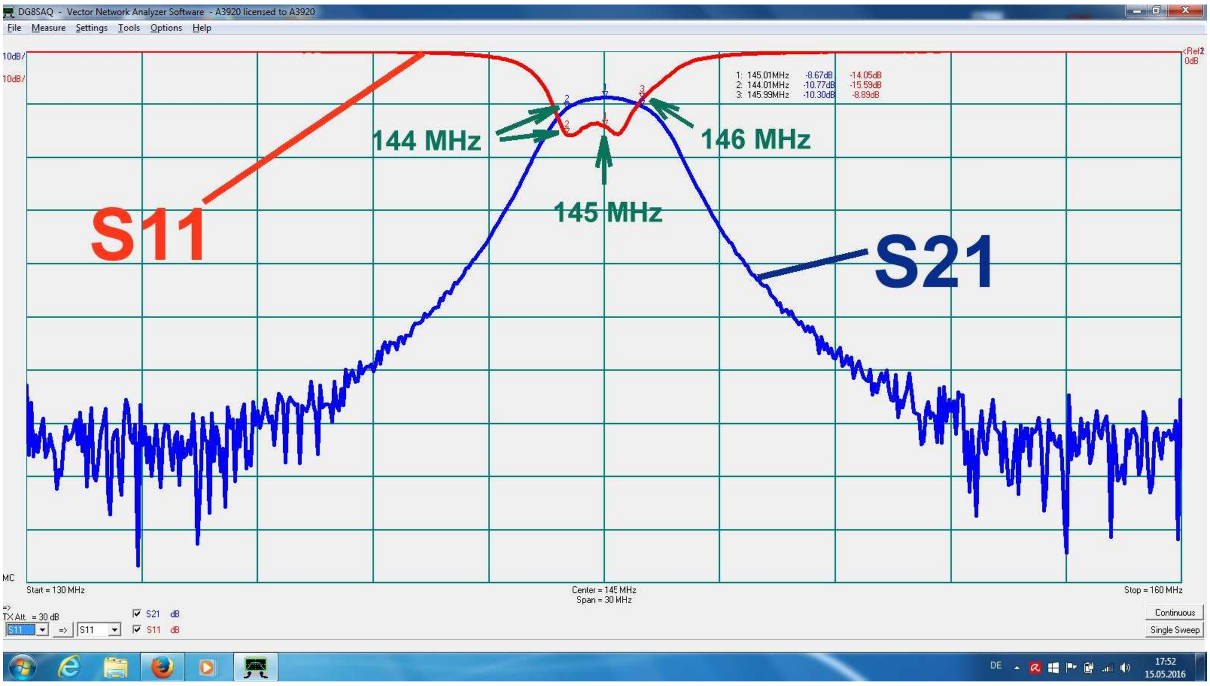
The attenuation at the centre frequency of 145MHz is approximately 6.9 dB, but only the coil losses are taken into account in the simulation. The printed circuit board used was: Rogers R = 4003 / thickness = 0.813mm = 32 mil / both sides coated with 35µm copper. The parallel capacitors were made from 4 trimmers (1.5 pF .... 3 pF) as well as a total of 16 SMD 0603 COG/NP0 ceramic capacitors. The capacitance values were realised by parallel connection of suitable standard values from the E12 series!

The damping values measured on the finished board are all the more interesting:

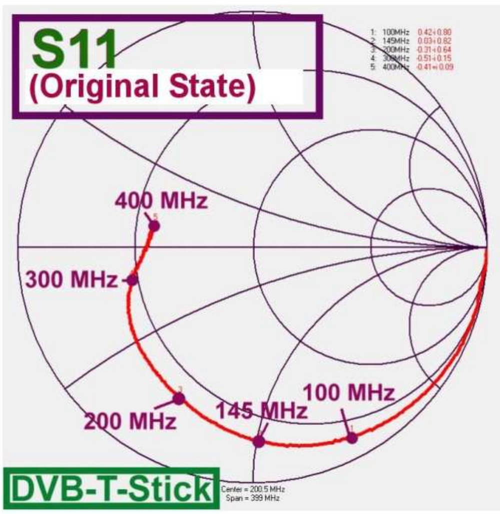
At 144MHz = 10.77dB
At 145MHz = 8.67dB
At 146MHz = 10.3dB

This is an increase of the attenuation compared to the simulation of about 1.75dB which is not bad.

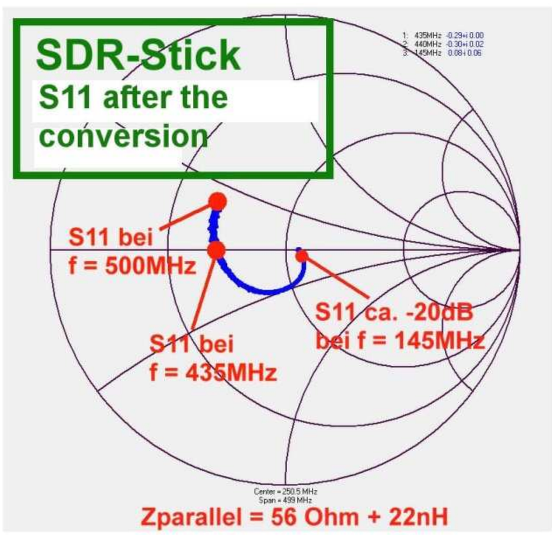
Here is the measured curve (vertical division = 10dB / Div. measurement with VNWA3).



5. The change to the DVB-T stick



This was about the input reflection S11 but first the original state had to be determined. It looks like a PHEMT at the input of the tuner IC "R820T", but the stick manufacturer uses some compensating components in front of the gate of the FET. They lead to the curve approaching the centre of the circle at about 1GHz therefore the change to the correction looked somewhat different.



For frequencies up to about 200MHz a 56 ohm resistor in parallel with the input socket gives the required improvement and reduction of the reflection. Above that frequency the effect of this additional resistor must be reduced more and more (because of the compensation components used by the stick manufacturer).

This is achieved by adding a 22nH SMD inductor in series with the resistor.

And that was a complete success ...
(Small Private Note: The whole receiver is only about 2cm x 2cm and the assembly consists of 0402 SMD components. You need some spare sticks to practice until you get hang of the change ....).

Other important things are:

A) Installation in a milled aluminium enclosure with screwed-on cover

B) Conversion of the MCX antenna input to an SMA plug connector as used for all devices

C) Filling of the complete enclosure with nonconductive heat transfer paste because the power dissipation of the stick is approximately 1W. You can burn your finger on the antenna input of the stick after one hour.

6. The calibrator module

The basic idea was actually quite simple:
Take one of the small commercially available 50MHz SMD crystal oscillators and change its output signal (fairly symmetrical rectangle) to something like a needle. In practice it is simple to obtain a short pulse by differentiating the rectangular signal and clipping the negative half by a comparator circuit. The remaining positive pulse is amplified by an MMIC and fed into the signal path between the bandpass filter output and the stick input via a small directional coupler. Its harmonics range is then up to 2000MHz and with nice frequency values (50MHz / 100MHz / 150MHz ...) to display on our SDR Receiver. This calibration spectrum can be switched off (using a toggle switch on the tristate input of the crystal oscillator) and a directional coupler was used at the output of the MMIC so the signal path does not notice this additional device. A small additional circuit with a red LED indicates when the calibrator is in use.

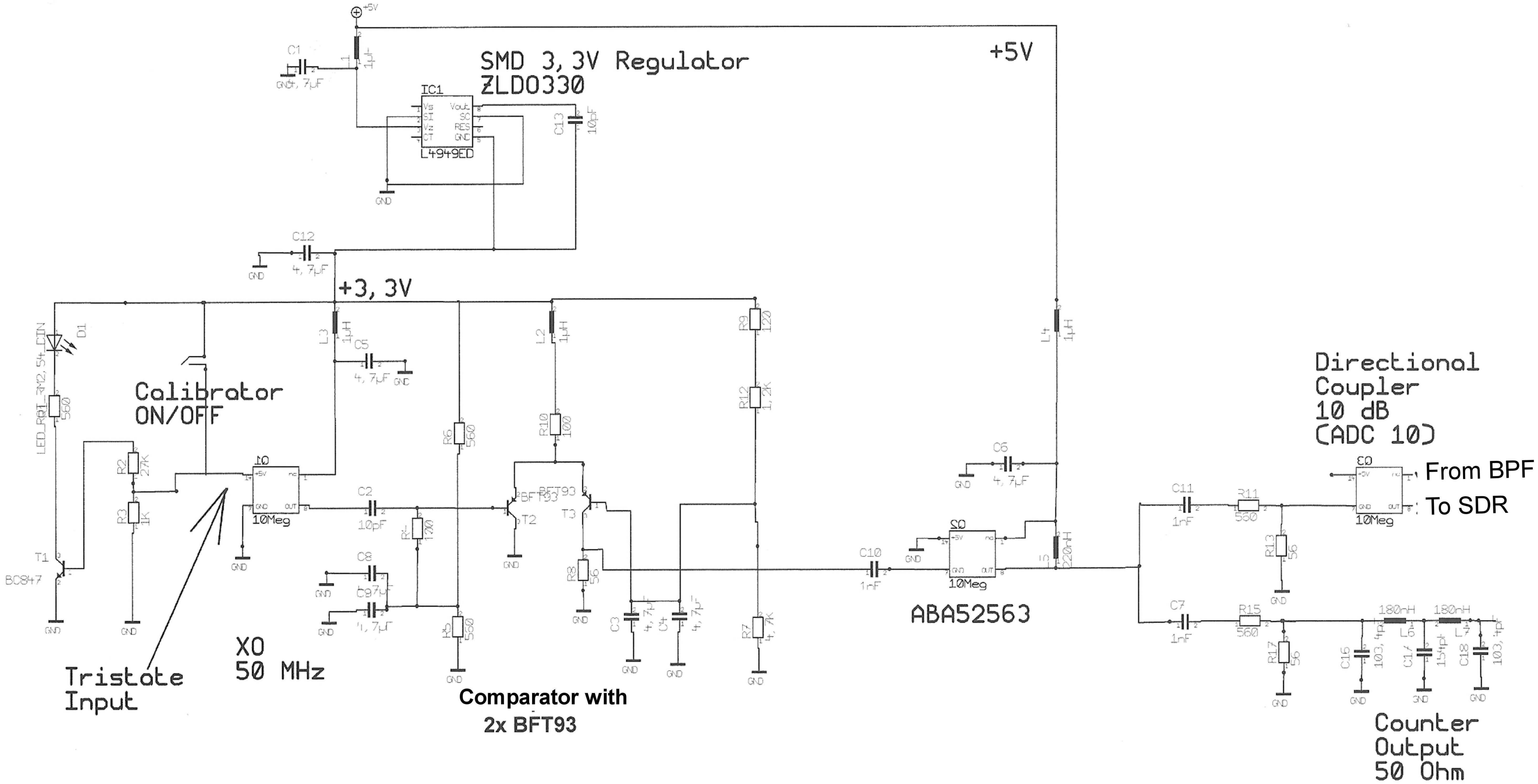
In order to achieve the desired high accuracy of the calibrator a "counter output" was added. Now you can adjust the frequency accuracy of the 50MHz crystal oscillator with a high precision frequency counter (calibration via DCF77) and check for deviations with the next "calibration mark" in the spectrum. Since most SDR display programs have a display frequency shift in "1 ppm steps" you can quickly see on the screen how far it deviates from the calibrator and correct it.

By the way:

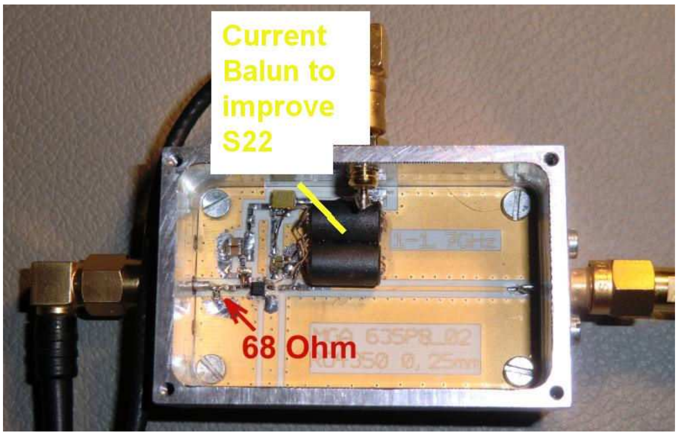
A frequency counter connected to the counter output of the first circuit (tested without the low pass filter on the counter output) did not show the frequency. After a little puzzling the solution was found:
The counter input was not happy with the short pulse. Therefore a Chebyshev lowpass filter with N = 5 and a cut-off frequency of 55MHz was inserted in the output circuit to give to a "sinusoidal like waveform".

Success:

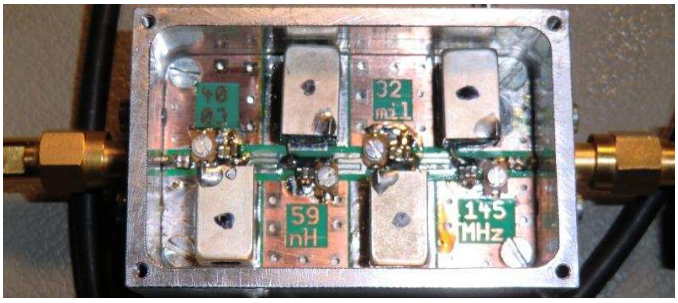
Immediately after switching on 50,000.020Hz was displayed on the counter.


SMD 3,3V Regulator
ZLD0330
+5V
+3,3V
Calibrator
ON/OFF
Tristate
Input
XO
50 MHz
Comparator with
2x BFT93
ABA52563
Directional
Coupler
10 dB
(ADC 10)
From BPF
To SDR
Counter
Output
50 Ohm

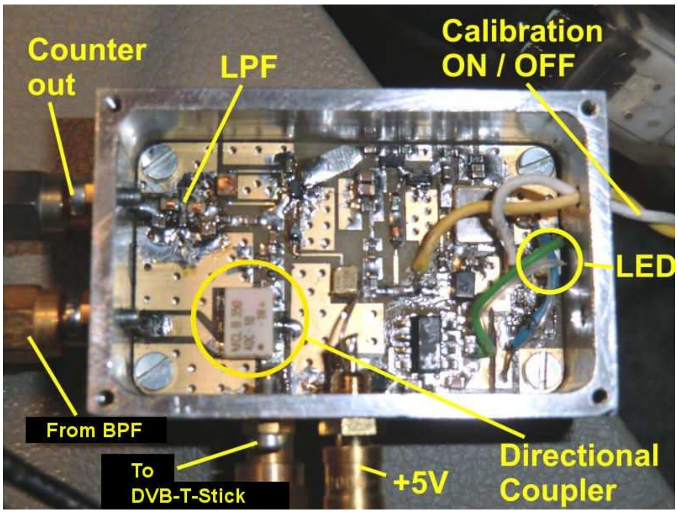
7. A look at the finished building blocks



First the LNA



Next the bandpass filter



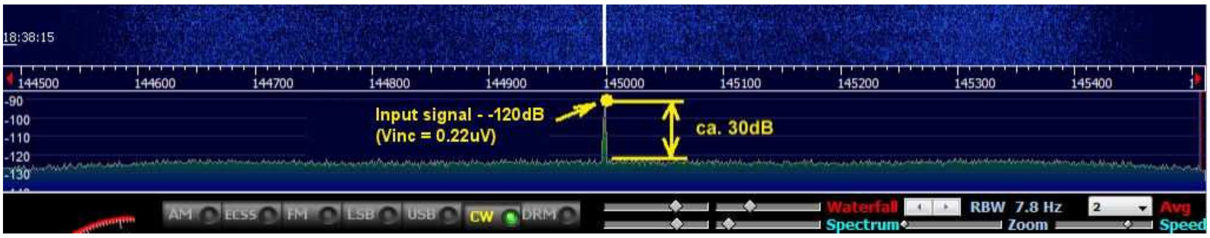
A great deal of effort went into the Calibrator module

And here we have the DVB-T stick (with and without thermal grease)

8. Results and experiences

To complete the receiver, the program "HDSDR" was downloaded from The Internet and installed together with "ExtIO-RTL2832.dll". Studies have shown that it is superior to “SDR#” especially at a low sampling frequency and a small Resolution Bandwidth “RBW”. But you will also need "zadig.exe" to install the correct USB driver for the Stick to operate. Once this is setup it should be straightforward to use (full instructions can be found under [4]).

You will be able to see the smallest input signals (f=145MHz):

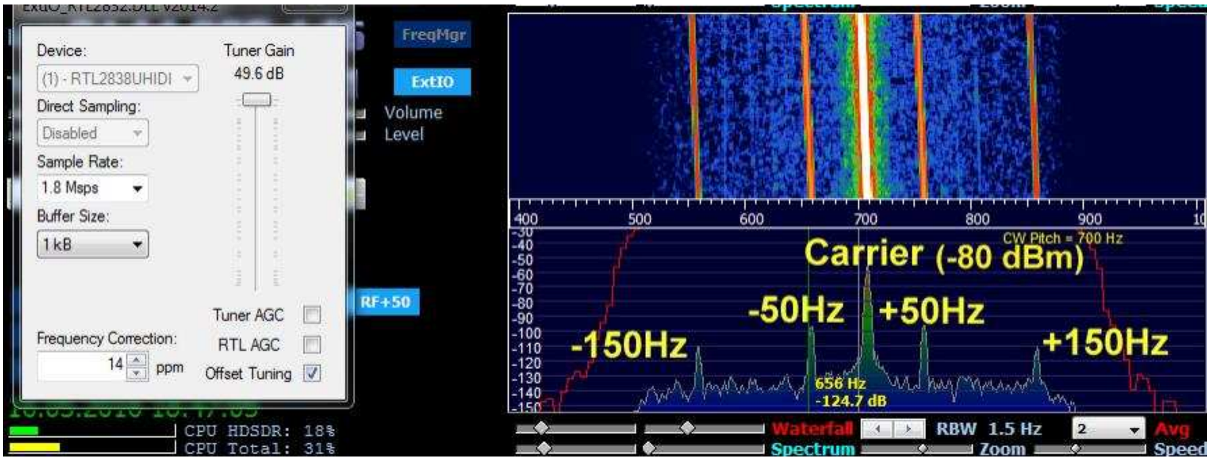


At an input level of -120dBm (Vinc = 0.22µV), a signal-to-noise ratio of 30dB can still be achieved at approximately 8Hz bandwidth. The amplification ("Tuner Gain") was set to full and the "Tuner AGC" switched on (gives a further 10dB more gain).

Remark:
The RBW = resolution band width is NOT the actually used receiver's bandwidth! RBW is calculated by this formula and means:

RBW = resolution band width = minimal frequency spacing between two lines in the spectrum =
1 / time for collecting samples in the time domain

Example:
If you wish a frequency resolution of 1 Hz in your spectrum then you must sample for 1 second....and if you have a time distance of 1 µs between two adjacent samples you get a million of samples in 1 second in the time domain. Reflect the result file size and the necessary computation speed for the conversion to the frequency domain by the FFT and for a greater circuit...



Then the input level was increased to -80dBm (Vinc = 22µV) and the Tuner AGC switched off. There were some initially unexplained additional spectral lines in the displayed spectrum. Riddles, a frown, and the question, "What is that?"

It takes a while to reach the solution because you have to analyse the individual frequencies. Then it becomes clear: the high quality, but already somewhat mature, precision signal source (an"HP8640B") has some mains supply modulation on the signal.

The work never ends ... and the development of the 70cm and 23cm versions are already in progress

Literature

Everything is available in German on my homepage www.gunthard-kraus.de under the heading "Alle meine Veröffentlichungen in der Zeitschrift "UKW-Berichte" seit 1995"

Some articles are also available in English on the VHF Communication Magazine web site – www.vhfcomm.co.uk

[1] UKW Berichte Issue 4-2012: "Development of a preamplifier for 1 to 1.7GHz with NF = 0.4dB". Also available from VHF Communications Magazine Issue 2-2013

[2] Issue 2-2013: "A low-noise preamplifier with NF = 0.4 dB for the 70cm band". Also available from VHF Communications Magazine Issue 4-2013

[3] Issue 4-2013: "A low-noise preamplifier with NF = 0.35 dB for the 2m band"

[4] Issue 1-2015: "The program HDSDR for the operation of DVDB-T-Sticks as measuring receivers and SDRs"