BACHELOR THESIS

Design of a low-cost 1 GHz Active Probe

conception, construction and evaluation

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Abstract

At any given time, a RF-Engineer may have to probe an unknown signal and use a high input-impedance active probe instead of a passive one. In aim of minimizing potential risks for high-cost equipment or not having access to such devices at all, probing via a low-cost device, such as a homebrew 1 GHz active probe, may be sufficient for a first impression of the signal. This can be archived through various circuits. In this case, one based on a double-gated Fet and another based on a high-speed opamp have been investigated and are compared throughout this work. As for many RF-related measurement setups, it is imperative to minimize adverse effects on the circuit under test. It is addressed how to design and to build such a device, and what performance one can expect in comparison to an off-the-shelf high-end product. Here we show that the Fetprobe performs much better on some linear and nonlinear measurements of its characteristics than the opamp-based Opvprobe. In the end, since the results of the Fetprobe are in some ways quite compareable to its commercial counterparts, it may be usable as a low-cost measurement tool for basic use.

Kurzfassung

Als RF-Ingeneur wird man ein unbekanntes Signal eher mit einem hochohmigen aktiven Tastkopf untersuchen als mit einem Passiven. Um potentielle Risiken für teures Equipment zu verhindern (bzw. falls überhaupt Zugang besteht), könnte das Messen per selbstgebautem, aktiven 1 GHz Tastkopf ausreichend sein um einen Ersteindruck des Signals zu erhalten. Das kann durch unterschiedliche Schaltungen erreicht werden. In diesem Fall basiert eine auf einem double-gated Fet und die andere auf einem high-speed Opv, welche in dieser Arbeit verglichen werden. Wie bei vielen Messaufbauten ist es notwendig Beeinflussungen der zu messenden Schaltung zu minimieren. Es wird erkläutert wie man so ein Gerät designen und bauen kann und welche Performance im Vergleich zu einer high-end Kauflösung zu erwarten ist. Weiters wird gezeigt, dass die Fetprobe sowohl bei linearen als auch nichtlinearen Messungen ihrer Charakteristika besser abschneidet als die Opvprobe. Letzenendes sind manche Ergebnisse der Fetprobe relativ vergleichbar mit kommerziellen Lösungen, weshalb eine derart günstige Lösung durchaus für einfache Zwecke verwendet werden könnte.

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1 INTRODUCTION

Firstly some basic information on passive and active probes, as well as existing homebrew active probe projects are being discussed. As for a probe being the link between the device under test and the measurement instrument, it has to have certain characteristics.

1.1 Overview

For troubleshooting circuitry, one approach is the analysis of the occurring signals, via the use of a so called probe to pick up the waveform.

A probe effectively has to both tap off signals without causing too much influence on the device under test, as well as transforming that quantity into something the attached measurement instrument can work with.

It is effected with both linear frequency-dependent effects as well as nonlinearities, such as variable attenuation, harmonic distortions and clipping.

Such devices are grouped into either the category passive or active probes. In context of RF-signals active probes are superior but they are also very expensive and hard if not impossible to maintain and repair. Therefore, a high input impedance homebrew active probe would be very handy because it can be

- cheap
- simple
- easy to build and maintain
- suitable for low-level field or student use

1.2 Passive Probes

For measuring a signal line, directly hooking up test leads or a coax cable (i.e. x1 probe) is usually not a good idea. It acts as a load, which in turn changes the behaviour of the signal. In contrast, an attenuated passive probe acts as an impedance converter, which means the low impedance of the measurement instrument is converted to a higher one[1], effectively preventing too much power from being pulled away whilst still providing insights about the relatively unaltered signal.

Firstly, the input characteristics of the measurement instrument, i.e. an oscilloscope, have to be considered. Therefore, a possible equivalent circuit diagram is being presented.

As shown on the right side of Fig. 1.1, it merely consists of a RC parallel element.
In aim to give a probe some attenuation for reducing the load on the device under test, one simply could add series resistance. However, when one looks at the transfer function of the whole system (the parasitics of the cable and probe-tip[2]), it becomes obvious that this system would be frequency dependent[3].

$$G(j\omega) = \frac{U_a(j\omega)}{U_e(j\omega)} = \frac{Z_a(j\omega)}{R_t + Z_a(j\omega)} \tag{1.1}$$

$$Z_a(j\omega) = R_s || \frac{1}{j\omega(C_s + C_{tip} + C_{cable})} \tag{1.2}$$

Moreover, it may either act as a low-pass or high-pass filter, effectively reducing the frequency range drastically. To get rid of that, the attenuation resistor has to be replaced with an impedance: Because if it was to be chosen as a factor of the oscilloscope's RC element, the transfer function would be frequency independent, with the attenuation factor n.

$$R_t(j\omega) = Z_e(j\omega) := (n-1) \cdot Z_a(j\omega) \tag{1.3}$$

$$Z_e(j\omega) = R_{comp} || \frac{1}{j\omega C_{comp}} \tag{1.4}$$

$$G = 1/n \tag{1.5}$$

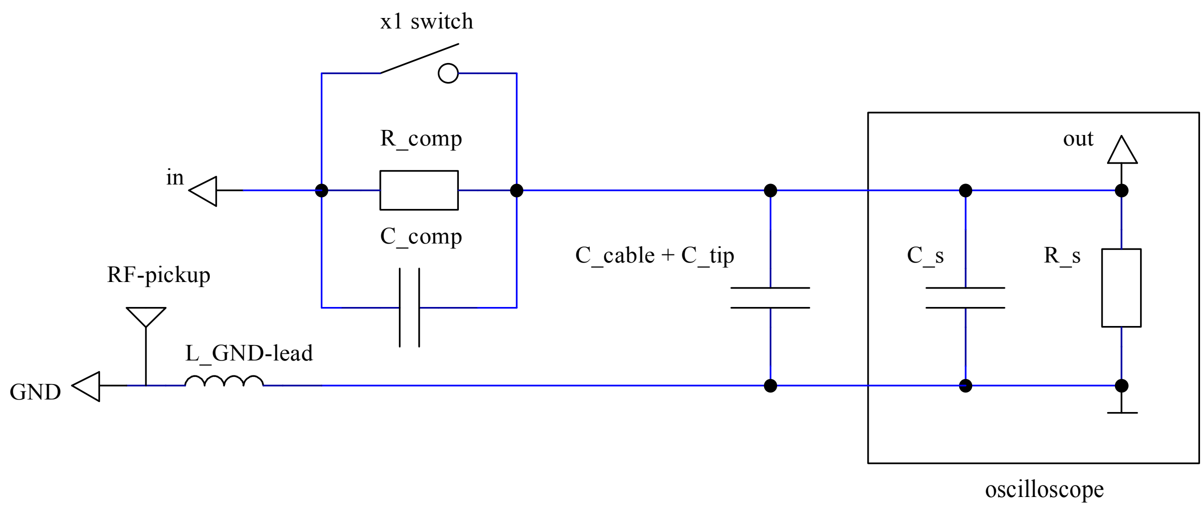

Figure 1.1: equivalent diagram of the oscilloscope-probe system

In practice, a passive probe has an adjustable C_{comp} for frequency compensation, since the input capacity of measurement instruments slightly varies amongst different devices (tough usually being around a few

[1] for good measure at least one magnitude higher than system impedance
[2] the ground-lead will be addressed separately lateron
[3] concentrated resistances however are thought to be sufficiently non-frequency dependent in our application

pF). The resistor R_{comp} has to be selected according to the desired gain. This method of probing and compensation however only works as far as the probe's elements act as if they were lumped-elements (as shown above), which tends to break down around 200-800 MHz.

As represented in Fig. 1.1 as well, it has to be kept in mind that the ground lead may add both inductance and RF-pickup too. That can't be modelled as easy, because it's highly dependent on the individual measurement setup. Here, the approach is to not use a ground lead at all, which may impact flexibility a bit but provides a more stable measurement environment.

1.3 Active Probes

To get around the issues of passive probes (especially for higher frequencies), active probes have to be used.
As higher frequencies come into play, passive elements are no longer able to compensate the transfer function on their own. Hence, active components, such as transistors and opamps etc., are needed.

Main prerequisites of an active probe are:

- high input impedance
- stable transfer function
- good pulse response
- little harmonic distortion effects (THD)

Firstly, because the active probe must not have too much parasitic influence on the device under test it has to have a relatively high input impedance (Z11). For this project it was decided that ten times the typical termination impedance of $50\,\Omega$ is sufficiently high.

As any output signal has to represent its input signal accordingly, a stable transfer function (S21) is needed so that no undesired attenuation occurs in the desired frequency band.

For not getting an alteration of any pulse (or waveform) passing through the probe, its pulse response has to stay about the same as its corresponding input pulse. To a small magnitude, however, effects like ringing, overshoot and undershoot are to be expected.

Last but not least, by utilizing an active component the probe will show some nonlinear behaviour. In order to be a practically useful tool the nonlinear contribution needs to be quantified for expected input power levels, which usually is done through so-called THD-measurements. The Total Harmonic Distortion is a quantity which tells about how the device may produce nonlinear frequency components in respect to the base output frequency.

1.4 Related Work

Preliminary research included the finding of a forum-thread on [1], where a 500 MHz Active Probe had been built utilizing the OPA659 opamp.
Also, a published article about a 1 GHz BF998 dual gate Mosfet (metal oxide field effect transistor) active probe in [2] has been examined, which has been used as a template for this project. Interestingly, when observing the drain-current of the Fet, it became clear that the article's proposed 5.3 V bias voltage cause it to operate well outside its power specifications. Thus, a safe range of 0-2.4 V has been determined and used, where the lifespan of the Fet is not being threatened.

Concerning commercial solutions, one of the simpler designs includes a Fet in source-follower configuration with a bootstraped gate bias resistor and drain (Fig. 1.2), as used in the Tektronix P6201 active probe. However, it has been found unsuitable for this application because simplicity dictated only having a single active component, if possible.

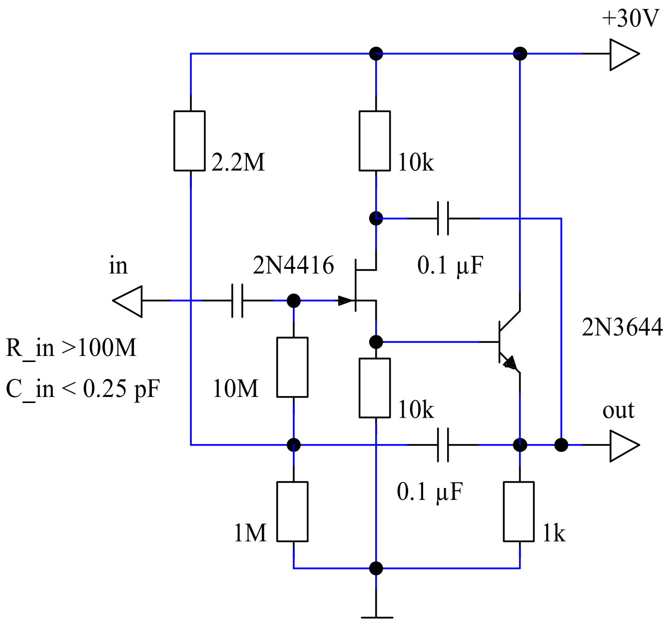

Figure 1.2: schematic of bootstraped Fet

2 Circuit Design

In this section possible active components, their corresponding topology-setups and the PCB-design will be investigated.

2.1 Overview

Previously, a short introduction on what passive and active probes do, has been given. It was shown that a homebrew active probe can be more than adequate if it's cheap, simple and easy to use. Then, related work in this field has been examined and sure enough, some of its topology was used.

First of all, the main device, an impedance converter (an Opamp or a Fet), will be selected. After having found some elements, initial testing occurs and schematics of how to make active probes around them are shown. Following, the simulation results of the circuits are presented. Lastly, some PCB-design considerations will be explained.
Using the state of the art RF simulation software NI AWR [3], design, simulation and graphs can be kept under a single hood.

2.2 Selection of Impedance Converters

For picking a suitable device, the understanding of its characteristics is key.
When parsing through stores and datasheets, features to look for are:

- high input impedance (i.e. low gate capacity)
- low price
- RF-application rating
- high gain(-bandwidth product)/unity gain stable, etc.
- low noise/harmonic-distortions
- high bandwidth [1]

[1] best seen on S21 graphs, as the term tends to be used quite loosely

In terms of simulation estimates, a good approach is to have a look at the most basic configuration for getting to know its theoretical limitations; at least for Opamps (opa659, ths4304). As for the Mosfet (bf998) however, an analysis of that nature (without bias resistors or an input cap) does not yield comparable results, so the complete (but untweaked) circuit has to be considered.

In Fig. 2.1 and 2.2 the results of the spice simulation are shown.

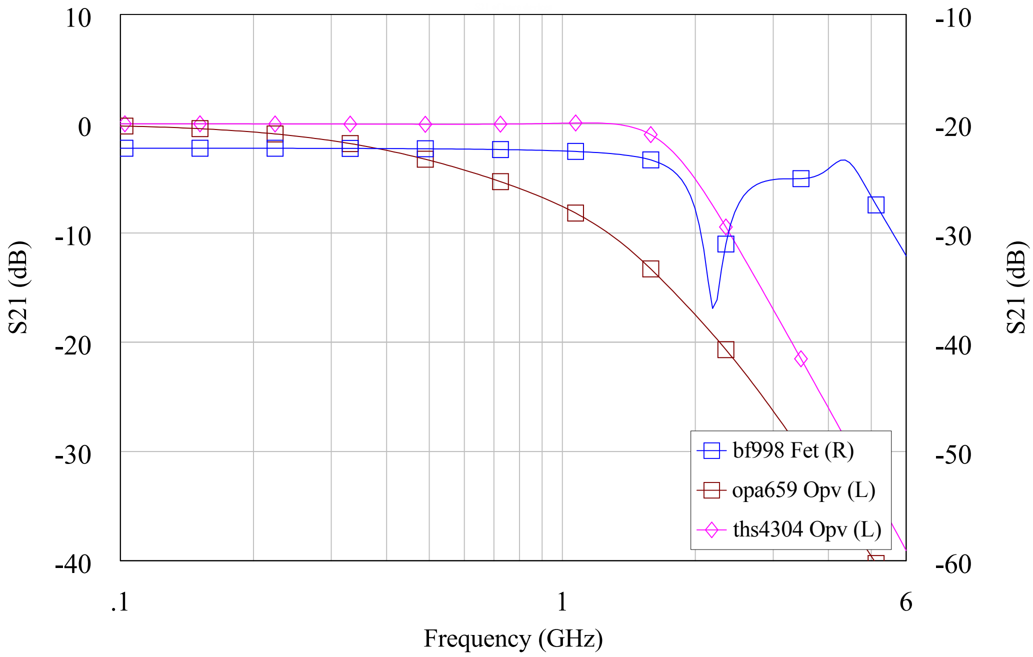

Figure 2.1: S21 of bare devices

Clearly, opa659 already performs less-than-ideal, so it will subsequently be omitted from further analysis. As for the input impedance in Fig. 2.2, the Opamp[2] clearly needs an input resistor to get closer to the mark of 10 times system impedance at 1 GHz.

The devices are supposed to be used in 50 Ω Systems, so they have been set up with an equal resistance to ground on their inputs in the S21 setup accordingly for simulating an ideally terminated transmission line (see also: Section 3).

[2]Opv is the german term for Opamp

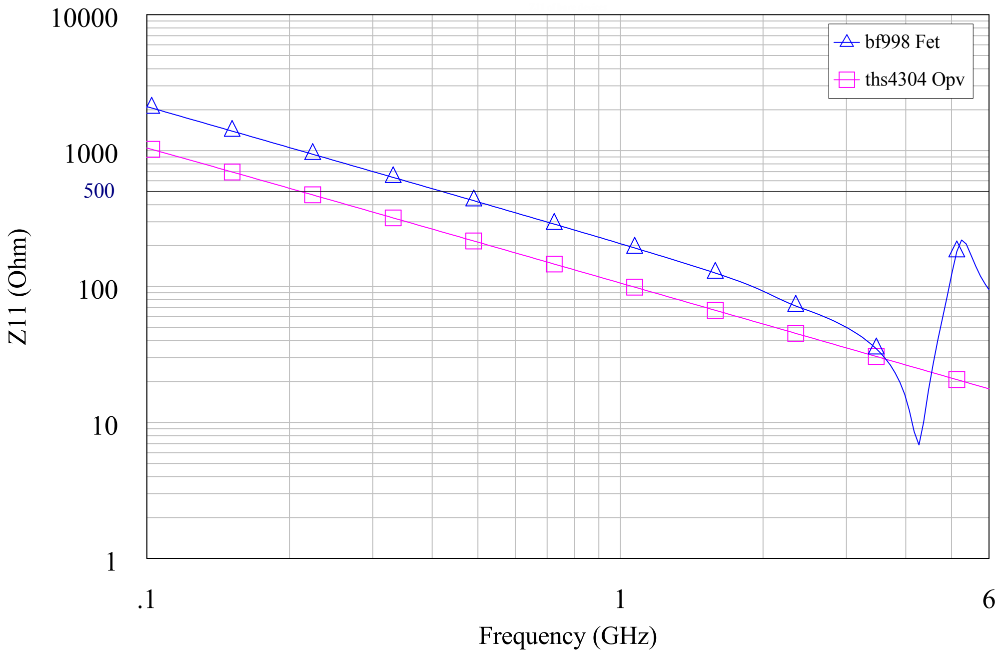

Figure 2.2: Z11 of bare devices

2.3 Fetprobe

The bf998 Fet operates in Source-follower configuration [4], which means it acts as an voltage buffer or impedance converter. The input capacitor C_{in} really needs to be as small as shown in Fig. 2.3, as a test with 5 pF[3] had shown that the input reflection coefficient S11 had risen above the target of -10 dB). The 2nd gate (top one in schematic) stabilizes the Fet by being subjected to voltage-feedback: As drain-current I_D creates a voltage drop over R1, the gate2-source voltage V_{GS2} drops and that in turn regulates the gain. In general, it can be approximated via eqn. 2.1, but for that the conductance S has to be approximated via a measurement from the hardware implementation. The gain of the Fet hasn't been touched in the course of the main measurements and only will be addressed shortly in one graph and the Addendum.

$$V = \frac{SR_1}{SR_1 + 1} \tag{2.1}$$

The $10\,\mathrm{M\Omega}$ bias-resistor R_{bias} is to block RF from reaching outwards while applying the DC working-point. This is required as the Fet needs to work in the positive input voltage range, and without the DC-offset it would handle negative voltage transitions significantly worse[4]. The Fetprobe's bias voltage was tuned to 2.4 V, where the current is on the edge of its datasheet limitations but still within specs. That altered its working point and makes it act in a more linear area of its input-output function. This of course has a positive effect on its harmonic behaviour as well (Fig. 3.4). On the output-side, R2 raises the resistance to compensate the low-impedance of the Fet's output.

Also, in the output path there has to be a $150\,\mathrm{nF}$ cap (C_{out}), for blocking off the DC working point and a $33\,\Omega$ resistor (R_2) to improve matching.

[3] because it was believed that the gate capacity of 2.1 pF might be the limitation anyway
[4] since the selfbias of the device has been proven to be insufficient

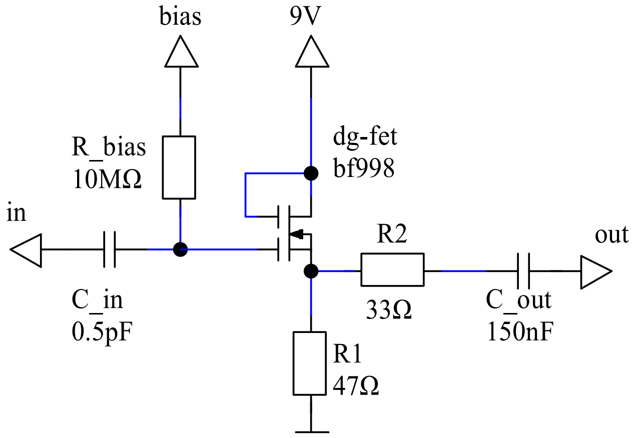

Figure 2.3: schematic of Fetprobe

To enable external control, the bias voltage of the Fet can be set from (0-2.4 V) on prototype boards by utilizing a designated pad and removing the voltage divider resistor which usually would provide the bias. The probe is being supplied with 9 V, since it is below the maximum rating of 12 V and changing it around had no immediate effects on S21, as the gate2-feedback kept the gain stable.
In the output path of the hardware-version a filter has been added (Fig. 2.4) to get rid of the main resonance around 850 MHz, with the values of $C_1 = 1.8\,\text{pF}$, $C_2 = 1\,\text{pF}$ and $L = 22\,\text{nH}$ (all RF-rated). These values originated from a maximally flat Butterworth LPF calculator and were then tuned in the simulator to dampen the resonance. It has to be noted that the soldering quality on the filter is crucial, and was not perfect in this project[5].

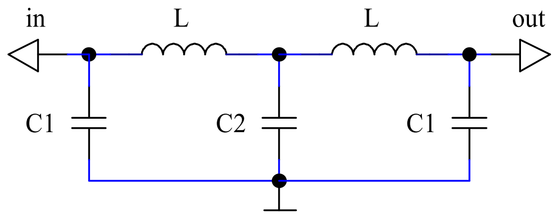

Figure 2.4: Fetprobe output filter

2.4 Opvprobe

The ths4304 Opamp is being utilized as a non-inverting amplifier in the Opvprobe[6], which acts as a voltage buffer or impedance converter as well. The way it tries to adjust its output-current is to minimize the difference across its input terminals, which causes the input potential to be present between R_f and R_{f2} (Fig. 2.5). In this arrangement, the gain can be calculated via the voltage divider across said resistors, as the inverting-input (as well as the noninverting one) is of high-impedance.

[5] the used ATC-caps were designed to be reflow-soldered, not hand-soldered
[6] Opv is the german term for Opamp

Unfortunately, the device requires more input current and needs a substantially larger input series cap ($C_{in} = 170\,\mathrm{nF}$) than the Fet, which results in a worse S11. Also, R_{gnd} of $10\,\mathrm{k}\Omega$ had to be added to improve the transfer function flatness, perhaps preventing a charge-buildup at the device's non-inverting input. A $300\,\Omega$ input resistor (R_{in}) has proven to be necessary for reducing the load on the testline, as indicated in Fig. 3.1. That results in a RC-element, which consists of the input resistor and the opamp's input capacitance, acting as a parasitic low-pass filter. Although the datasheet claimed unity-gain as favourable ($R_f = 0, R_{f2} = \infty$) for the best frequency-bandwidth product, a gain of 1.5 has been proven to be most suitable for a flat transfer function ($R_f = 120\Omega, R_{f2} = 240\Omega$). This archives a relatively flat frequency response, being at the same level as the spike of a resonance around 1 GHz and thus limiting its impact.
C_{in} has been implemented as parallel circuit of a smd-cap and a trace-cap, which can be seen in Fig. 2.17. However, since the value has proven to be not that critical, lateron a glued-on, relatively arbitrary sized piece of copper-tape was put in place.

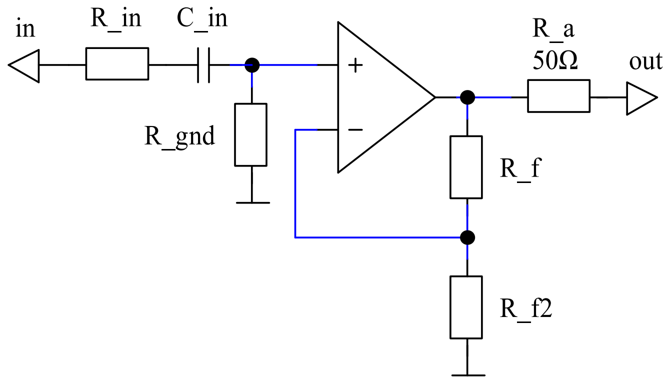

Figure 2.5: schematic of Opvprobe

As the ths4304 had specified to remove the groundplane underneath it, that has been implemented as well (Fig. 2.17). It is being fed with a dual supply of 2.5 V.

2.5 Simulation Results

With respect to the goals defined in Section 1.3, the transfer function is of first interest. In Fig. 2.6 we see that both versions perform well over 1 GHz, which is a good start.

While the output matching in Fig. 2.7 seems pretty spot-on, the input impedance of the Fetprobe barely misses the target of being one magnitude higher than the system impedance. This was to be expected, as the gate capacity of the bf998 has been thought to be less than the input capacity of the ths4304.

At first, when using $500\,\Omega$ as R_{in} (Fig. 2.5), S21 seems to buckle down (Fig. 2.8). In the end a $300\,\Omega$ resistor has been proven to be suitable, as already stated.

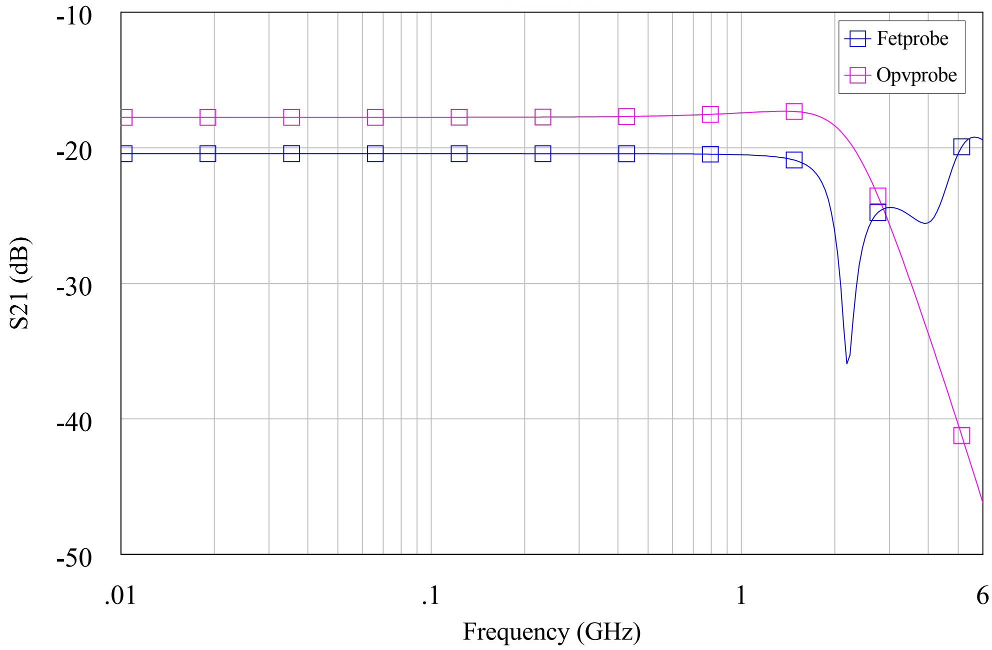

Figure 2.6: S21 of Fetprobe and Opvprobe

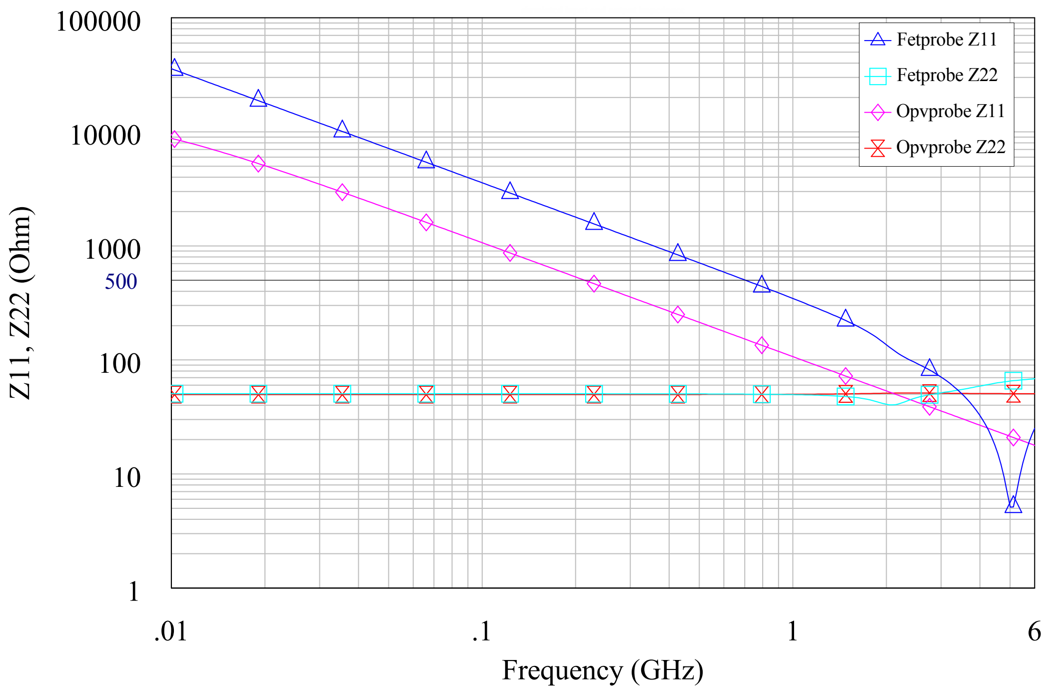

Figure 2.7: Z11 and Z22 of Fetprobe and Opvprobe

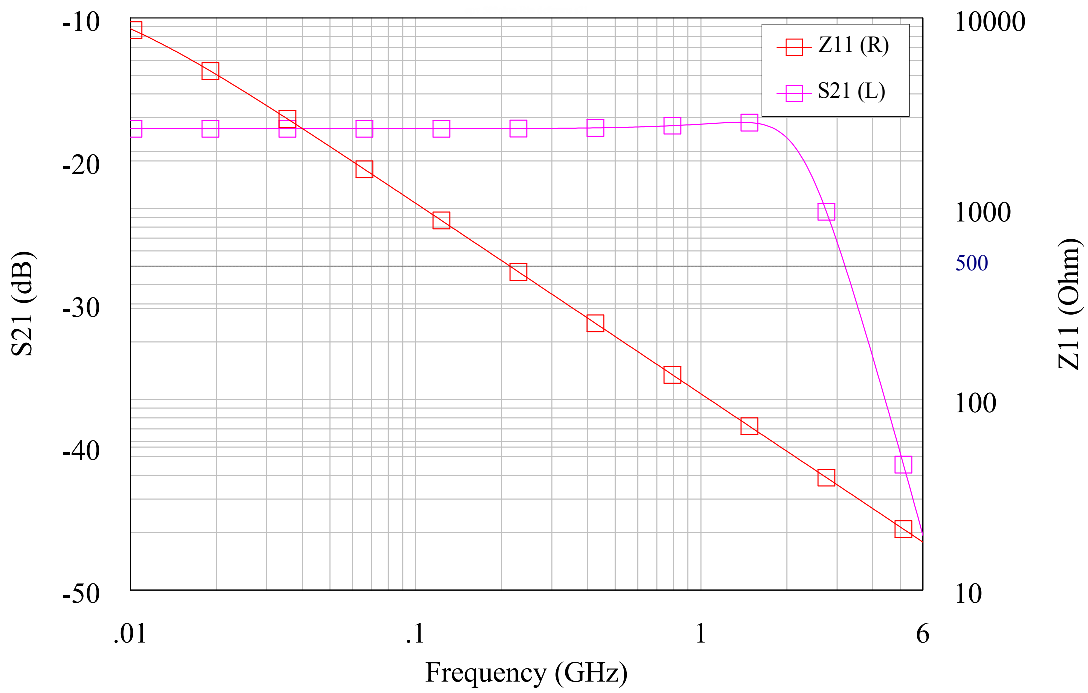

Figure 2.8: performance of the Opvprobe when simulating a $500\,\Omega$ input resistor

2.6 PCB Design

The following paragraphs will explain some design-decisions, which went into creating PCBs from the presented schematics.

For prototyping, a LPKF Protomat S-series milling machine and $512\,\mu\text{m}$ thick Rogers 4003 material with $17\,\mu\text{m}$ copper has been used.

To precisely supply the right voltages, LM317LCDR Voltage regulators have been used, to make both probes useable with a $12 - 30\,\text{V}$ power supply[7]. The case consists of two slightly larger FR4-boards, with a kapton-tape finish (Fig. 2.9). For power indication, the Fetprobe has been equipped with a blue SMD LED and the Opvprobe with a red one.

General

When designing a RF application device, the major concern naturally is the RF path. Most critical is the input path, because in this setup it is a high impedance section of the circuit which is especially drawn to be effected by parasitics, i.e. capacity via the groundplane, the input tip or any adjacent elements in the input path. Hence it has to be kept as short and direct as possible, and interference with adjacent elements has to be minimized via keeping a certain distance (about one trace-width). Since the mounting of the probe tip had significant effect on the performance as well, several tests were conducted: Using superglue to hold down the tip increased the input capacity of the probe, acting as an undesired additional load.
Then, for gaining some distance to the groundplane, the first version's $20\,\text{mm}$ steeltip had been taken

[7] at $12\,\text{V}$, less than $100\,\text{mA}$ are required

Figure 2.9: probe cover

parallel to the board. Its fixture consisted of punctuating a Rohacell ($\varepsilon r \approx 1$) cube ($7 - 10\,\mathrm{mm}$) one the one side and being soldered to the upright installed[8] input capacitor on the other (see Fig. 2.10). That significantly lowered the input capacitance.
However, in the final version, $13\,\mathrm{mm}$ pogo-testpins have been soldered directly onto the board to improve reliability, with no groundplane (and its associated capacity) beneath it. This shifted the main resonance to around 850 MHz, but was required to increase its overall ruggedness. Nevertheless, the Filter in the Fetprobe's output path can counteract this to a certain degree.
As for the parasitic capacitance in the input path, the groundplane was removed underneath the input and the input-side of the active devices (Fig. 2.17 and 2.13).
Of course, the input and output-traces' width have to be chosen to have the chosen to be suitable for wave-propagation, however elsewhere in the circuit a different trace width may be used. When soldering both case-groundplanes of the used FR4-boards to the probe's ground, a resonance at 300 MHz appeared in S21, so that idea was scrapped. For mounting, $15\,\mathrm{mm}$ M3 bolts ($18\,\mathrm{mm}$ total length) and $5\,\mathrm{mm}$ plastic-tube-spacers have been used (see: Fig. 3.3).

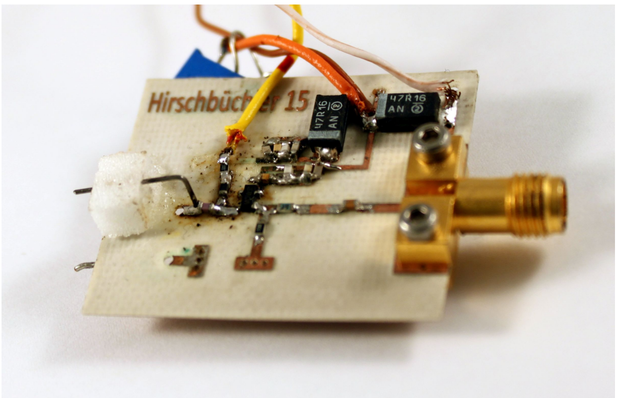

Figure 2.10: first version of Fetprobe

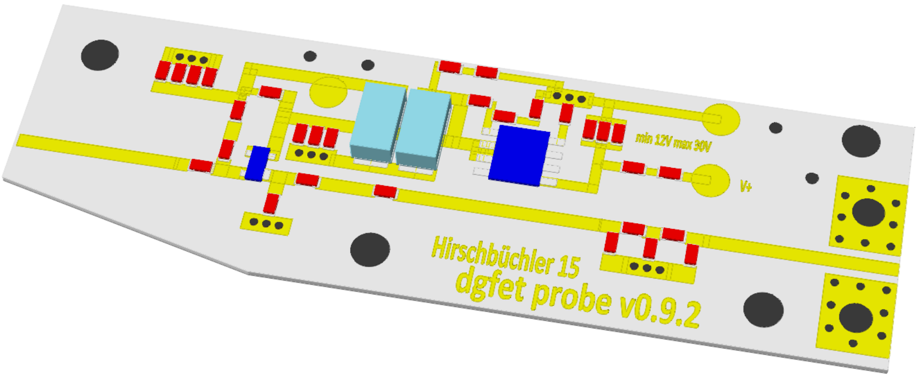

Figure 2.11: 3d-view of Fetprobe

Fetprobe

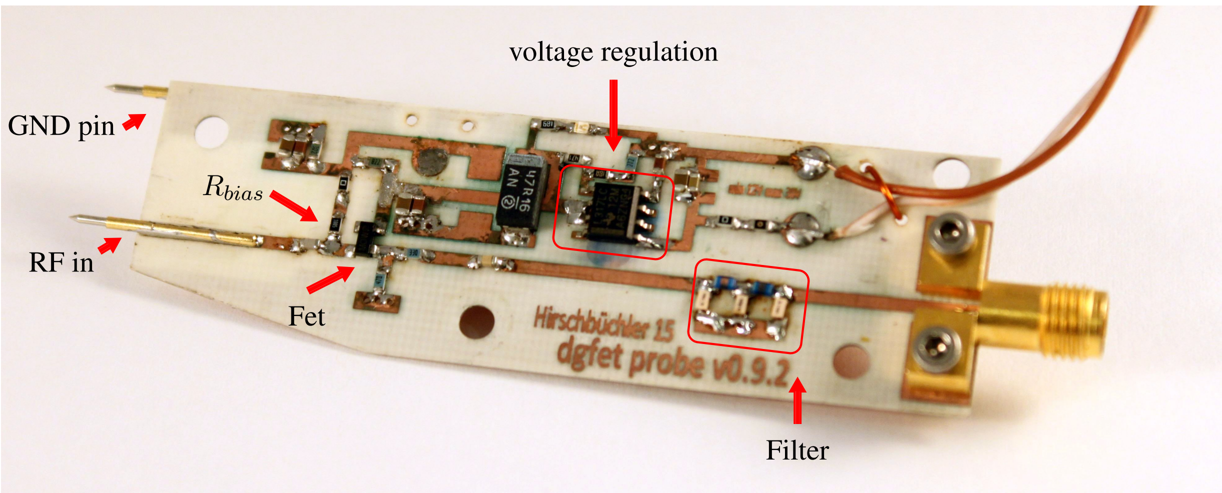

Figure 2.12: Fetprobe

[8] "tombstone" configuration

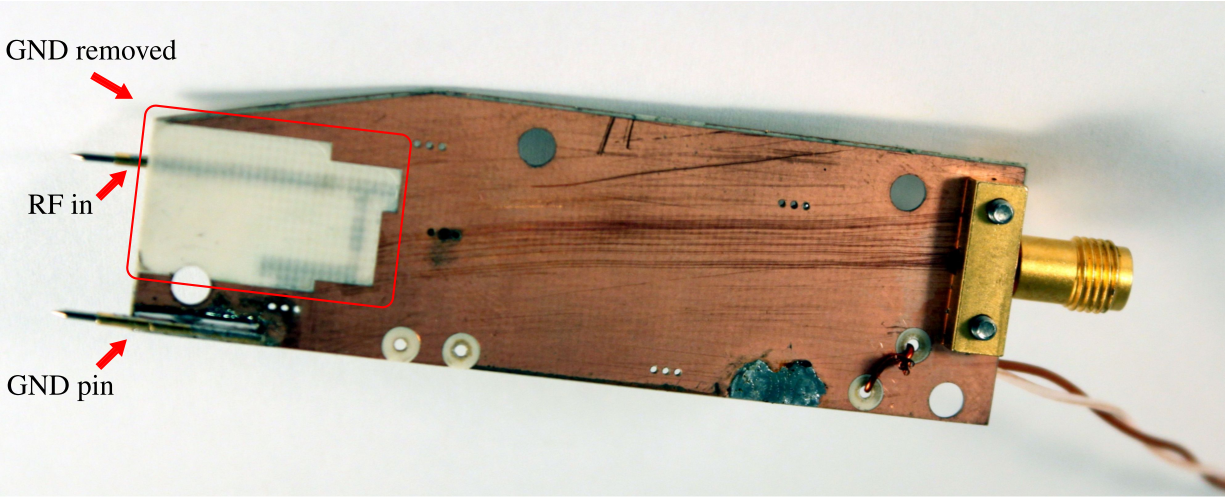

Figure 2.13: Fetprobe back

Opvprobe

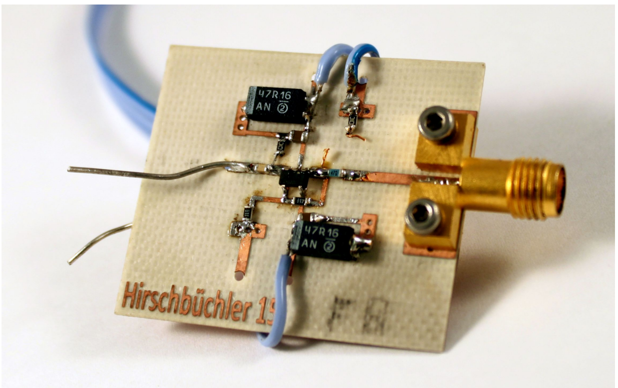

Figure 2.14: first version of Opvprobe

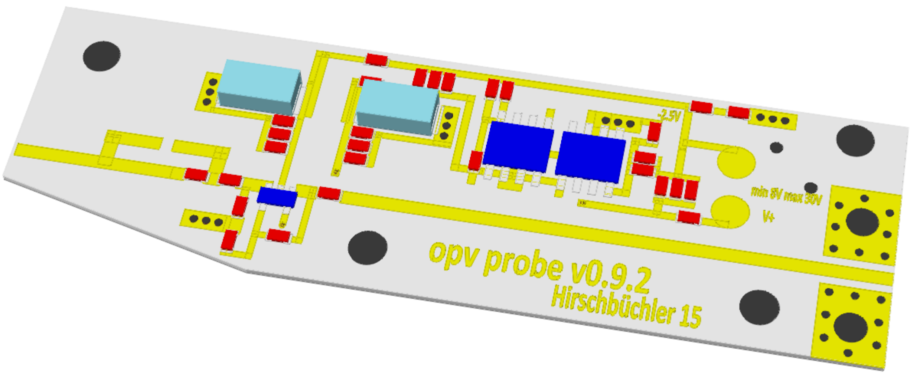

Figure 2.15: 3d-view of Opvprobe

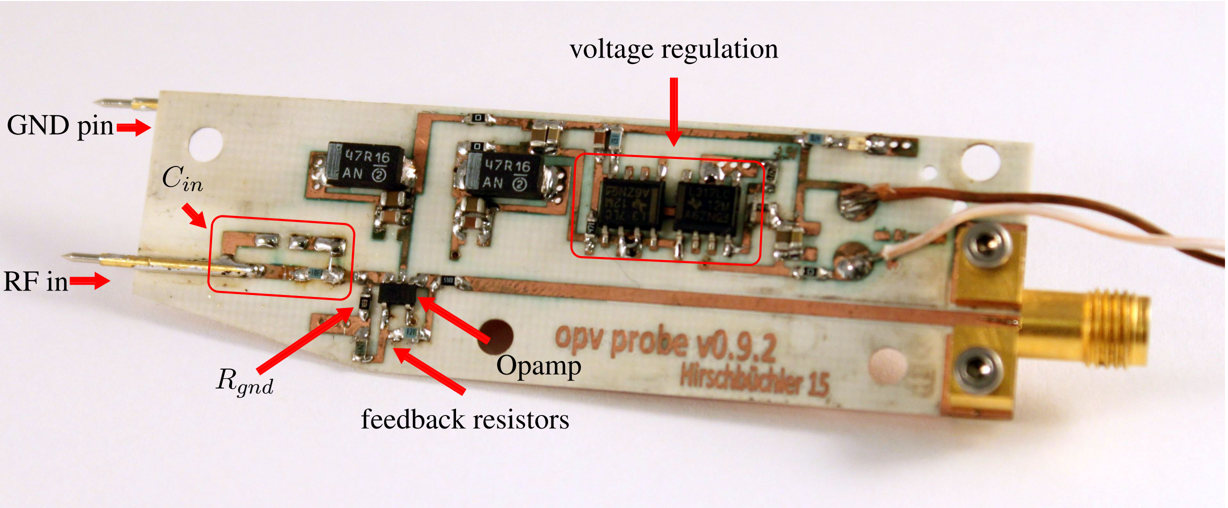

Figure 2.16: Opvprobe

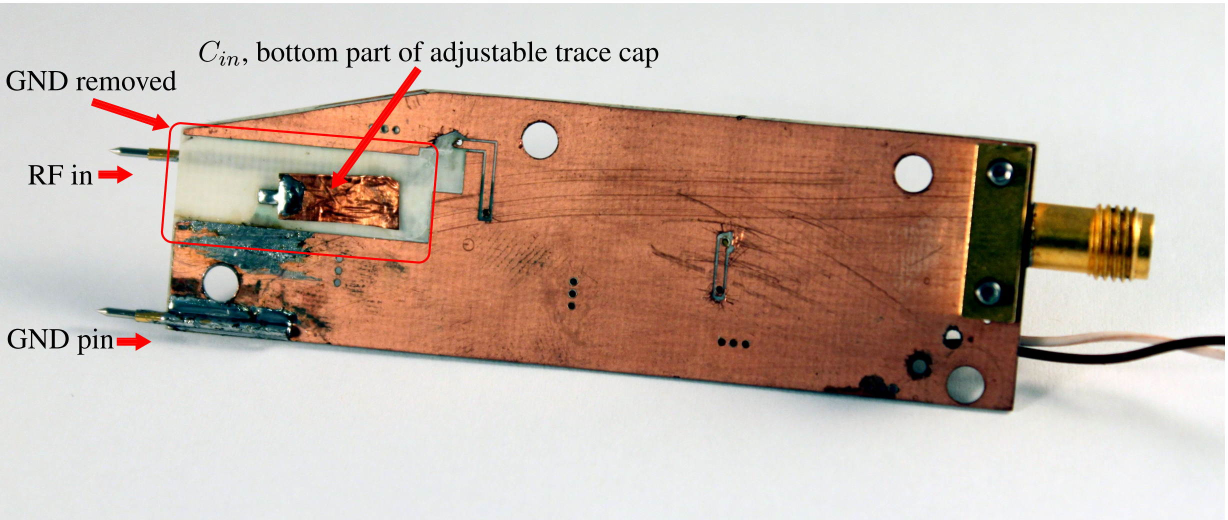

Figure 2.17: Opvprobe back

Sidenotes

It was theorized that maybe ATC-500 Caps in the main input path are required to get a satisfactory transmission function, but it will become obvious lateron that that wasn't necessary.
The attempt to improve the simulation model by means of importing measured port parameters from a separate test fixture for i.e. a $10\,\mathrm{M\Omega}$ resistor, failed, as the spice models didn't correlate with the actual measurements that well in the first place. Even compensating the trace length of the SMD measurement fixture didn't improve the simulation. The fault is expected to lie within the component models, not the simulation environment.
To further improve RF-blocking over the Fetprobe's bias circuitry, a series inductor (RF-bead) was tested before and after R_{bias} , but since neither proved to have significant effect they were removed again.

3 Measurements

Below some measurements to verify the probe design are shown, and a comparison against two commercial probes is made.

3.1 Overview

Beforehand, an introduction to probes and related work in the field of homebrew active probes were given, as well as how to select a suitable impedance converter and how to build an active probe around them. Then, some board design considerations were described, which will be verified in this section. Now, after the completion of the probe-design, measurements will be shown. The test setup that was used to gauge the probes was set up according to Fig. 3.1 and 3.2.

The idea is to probe a test-trace, which is naturally terminated with $50\,\Omega$ system impedance for simulating an ideally terminated signal line. By doing so, the impact of the probe towards the test-trace can be observed. To get the S-parameters, a Vector Network Analyzer is being used (Fig. 3.4). All used instruments and software will be listed in the Addendum (Section 4).

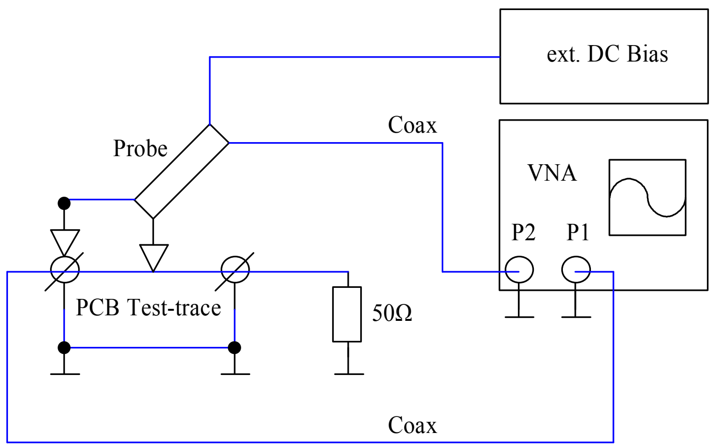

Figure 3.1: schematic of test trace

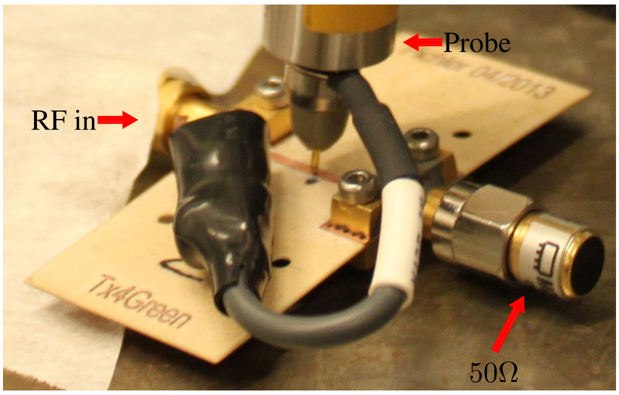

Figure 3.2: test trace

To characterize the impact on the device under test, as well as its transmission capabilities, following measurements have been conducted: S21, S11, pulse response and harmonic distortion.

The transfer function (aka S21) is of interest, because the rang, where it is constant without significant ripple is a good estimate of what the probe's bandwidth may be.

For getting an indication about how the probe may affect the transmitted signal's shape, the pulse-response-test yields some insights.

Also, as the signal goes through the active device, there may be subtle changes in which frequencies form the actual shape of the signal: Here, the THD (Total Harmonic Distortion) and it's raw data (a graph of harmonic integer-multipliers over frequency) show how the output has differently weighted fourier-row frequency components, which is a measure for the nonlinear-behaviour of the probe.

As test-fixture, a small steel table and a 3-axis holder have been used to hold the probe against the test-trace (Fig. 3.3). The impact of the setup on the measurements has been tested for the S21 setup and found to be negligible.

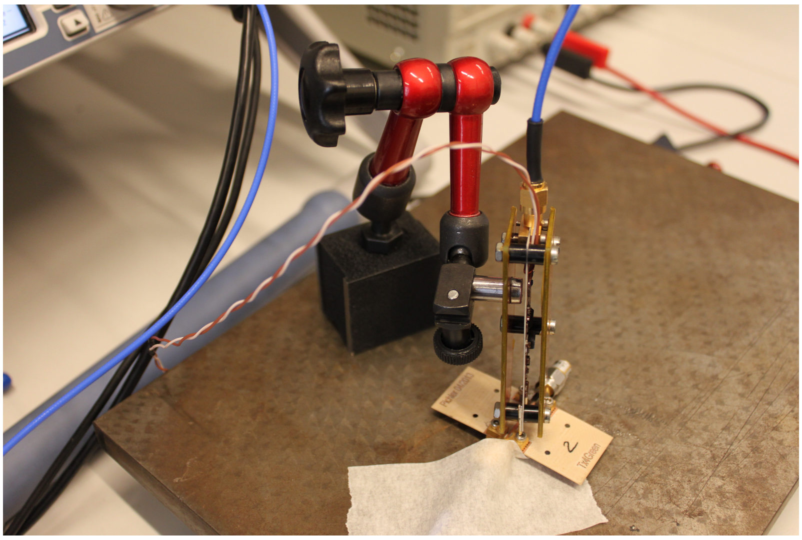

Figure 3.3: test fixture

3.2 S-Parameters

Ideally, the probes influence on the line would be minimal, as stated in the design goals[1]: S11 may vary but has to stay at least one magnitude below signal level. It is expected to drop off around 1 GHz because of the devices limitations. The very first sweeps yielded some unanticipated ripples in the early MHz range, which were removed by improving the grounding concept[2].

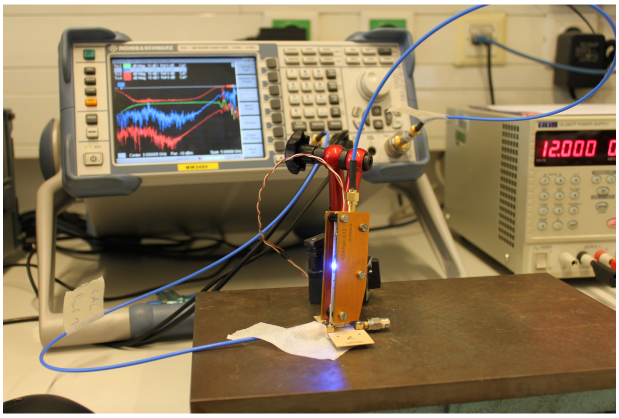

Figure 3.4: measurement setup for S-Parameters

Fig. 3.5 shows the transfer function of both probes, where we see that indeed the Fetprobe performs better, as expected (back in Section 2.4)[3].

As for Z11, direct measurement is not feasible[4], so S11 of the probed and unprobed test line has to be looked at instead. Due to the smaller input capacitor the Fetprobe was anticipated to work better, which was confirmed by Fig. 3.6. Though up to 1 GHz both probes stay below -10 dB return loss, note that the change in comparison to the (unprobed) terminated line is of more significance, as it shows how the probes impact the test-trace.

Since the output reflection coefficient S22 doesn't look that good (Fig. 3.7), it may provide a source of error if the other system components are not well at 50 Ω system impedance. However, this is not directly relevant to the general function, as this measurement is performed into the output of the probes.

[1] see: Section 1.3

[2] it is advised against using RF-probes below 1 MHz, as at some point the AC-coupling may distort lower frequency signals

[3] also, a $-26\,\mathrm{dB}$ (=>1/20) configuration is shown, which would be more sensible for oscilloscope use than the $1/14_{th}$ version. Note that its lower bandwidth is due to a different soldering technique and probably the associated capacity change in the output-Filter

[4] as it would require an unterminated line, which in itself would prevent proper wave propagation

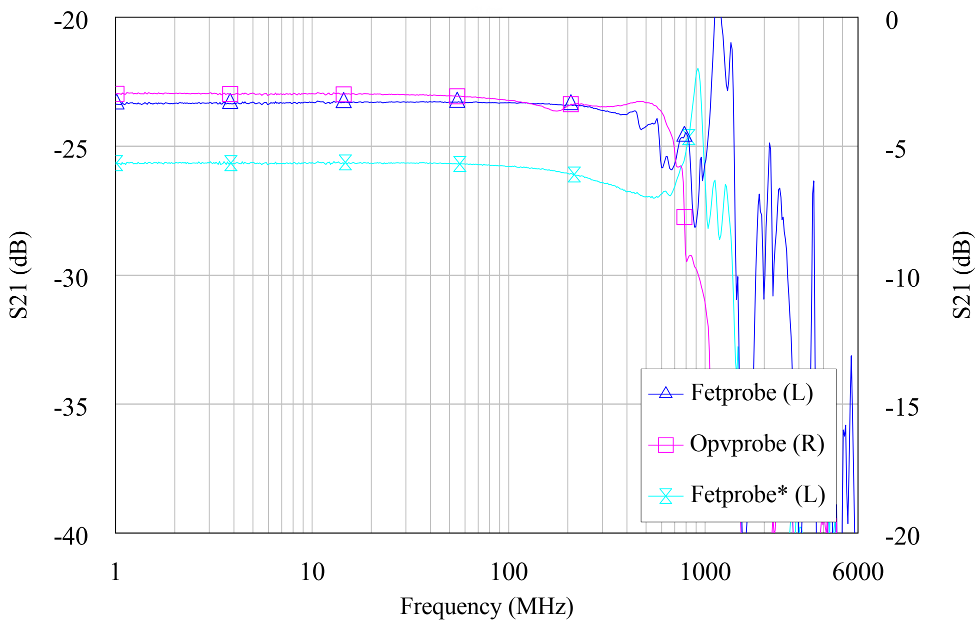

Figure 3.5: Transfer function of both active probes

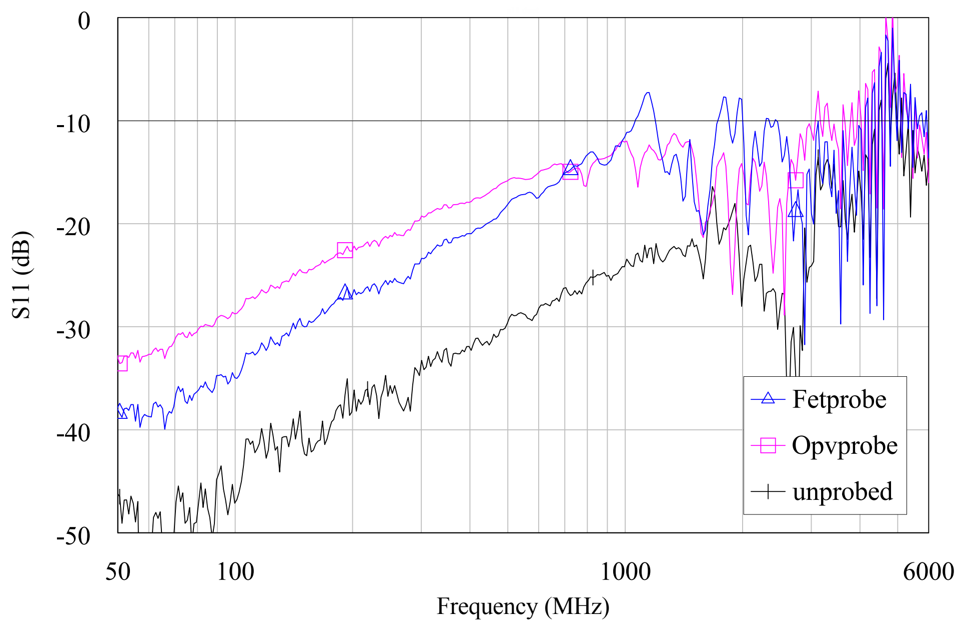

Figure 3.6: Input return loss of both active probes

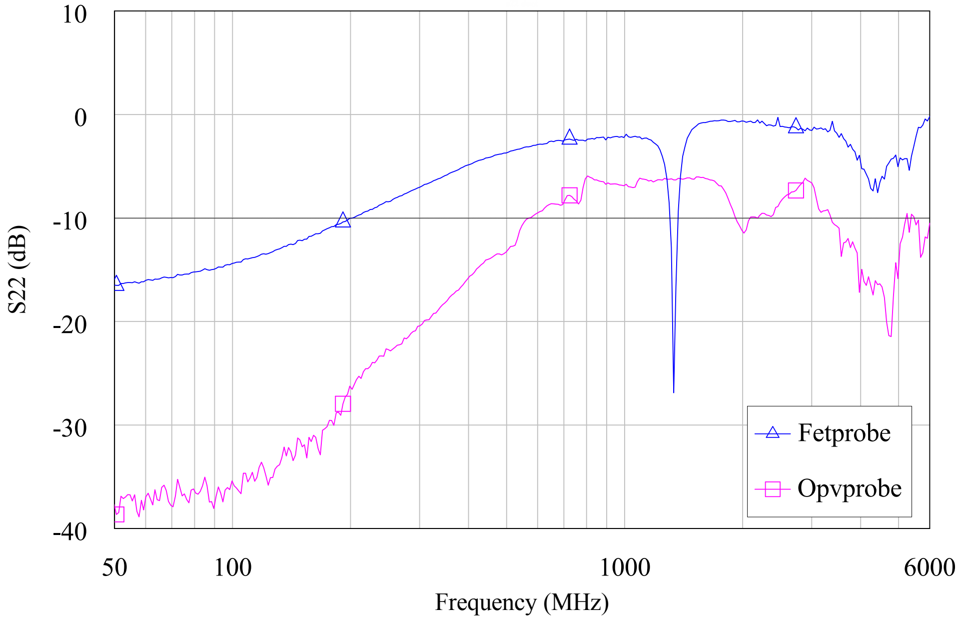

Figure 3.7: Output return loss of both active probes

3.3 Pulse Response

To test how reliable the probes can represent the shape of an waveform, a rectangular pulse is applied. Because the amount of frequency components needed to archive the steep transitions between 0 and V_{amp}, it is suited well for that purpose. A slight modification of the measurement-setup is necessary: The Pulse generator gets connected to the test trace, which in turn goes to the oscilloscope and gets terminated there via an internal resistor (Fig. 3.8).

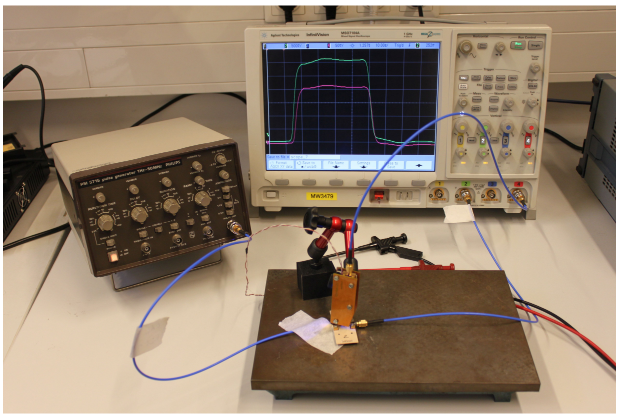

Figure 3.8: pulse response setup

In Fig. 3.9 we see that both probes response pretty well to a 0.5 V pulse, while the Opvprobe has a very small DC offset and the Fetprobe a very small undershoot when returning to zero.

Then, in Fig. 3.10 it can be observed how the Fet performs well for a 5 V pulse too, but the Opamp clips massively, as its input rating of 2 V is exceeded.

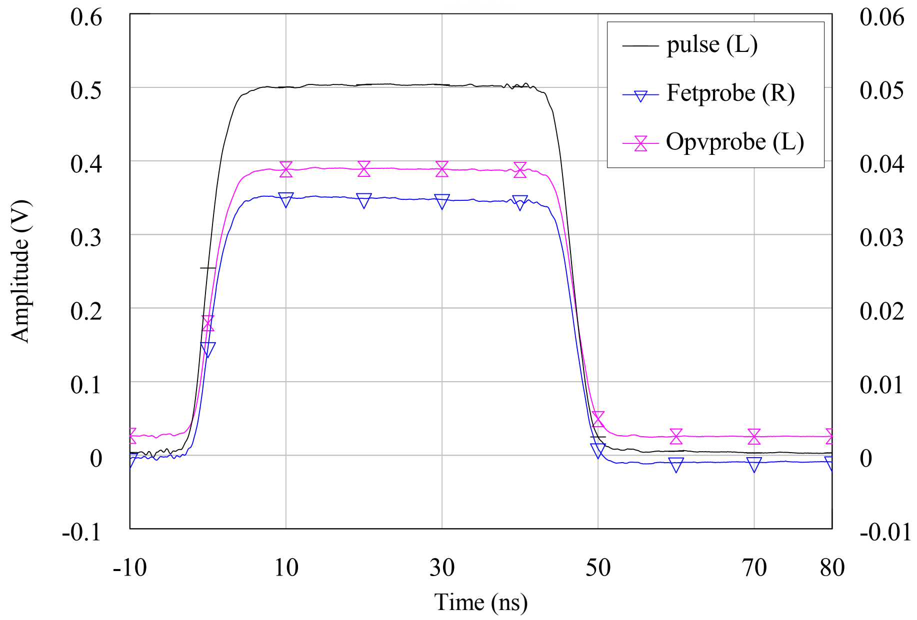

Figure 3.9: responses of both active probes to 500mV 50ns pulse

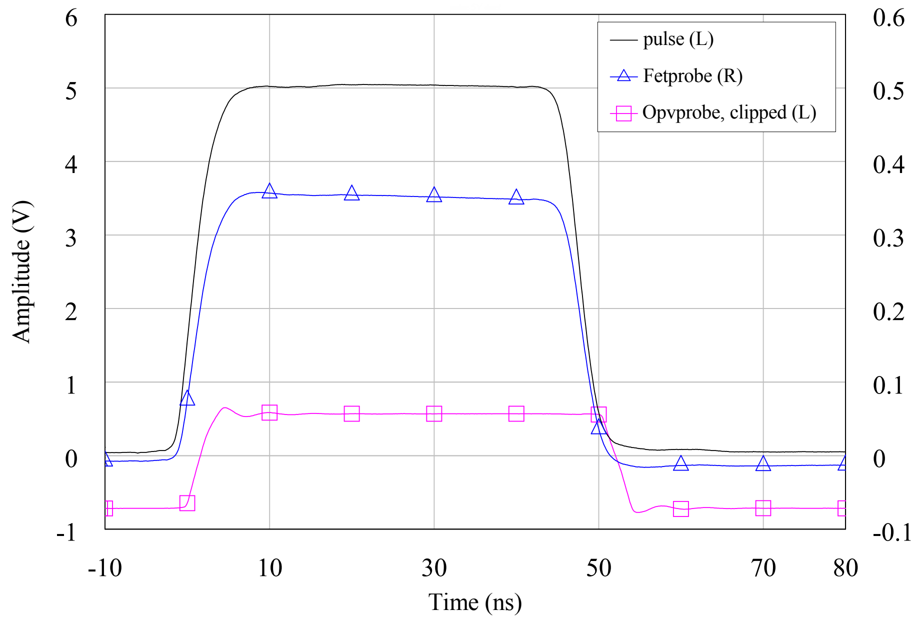

Figure 3.10: responses of both active probes to 5V 50ns pulse

3.4 Harmonic Distortion Effects and THD

In a real measurement setup however, it is important to quantify how much a signal at a given power level may be distorted by the probe in use. These non-linear effects may not be spotted as easily (or at all) on a pulse-response or transfer function (S21) analysis. For visualizing and quantifying this, the Total Harmonic Distortion (THD) analysis can be useful. It is a measure of how the device may produce nonlinear frequency components in respect to the base output frequency.
That works by inputting a signal at a fixed frequency and amplitude, and observing how the carrier frequency and some of its first harmonic multipliers come through. Ideally, the harmonic multipliers would be highly attenuated, resulting in a low THD. It is calculated as shown in Eq. 3.1, whereas V_1 is the signal component at the carrier frequency and n the total number of harmonics which have been captured for calculation. V_x represents the respective signal component at the multiplier x of the carrier frequency.

$$THD = \frac{\sqrt{\sum_{x=2}^{n} V_x^2}}{V_1} \tag{3.1}$$

A small THD means little distortion happens and the device behaves almost linear. But because it is relative to the level of the base frequency, for easy comparison between the probes the graphs mostly have two axes: One for each probe, for an alignment of their base levels. The test-trace is configured the same way as initially for the S21 measurement (Fig. 3.1 and 3.2), the setup is shown in Fig. 3.11.

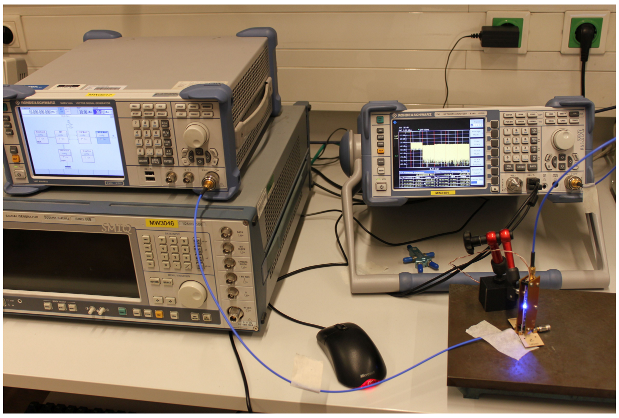

Figure 3.11: harmonic distortion setup

We expect a better performance from the Fetprobe, as it only uses one active component in contrast to the Opvprobe, which has several integrated internally into one package which have been built for a narrower frequency band. Fig. 3.12 to 3.15 confirm this assumption, as the Opvprobe's nonlinear components have a greater magnitude than the Fetprobe ones in almost all cases.
As 20dBm (2.25 V) exceed the Opamp's differential input voltage rating of 2 V, distortions as in Fig. 3.13 and 3.15 were to be expected.

As already addressed in Circuit Design (Section 2.3), setting the Fetprobe's DC-working point to 2.4 V results in the 1^{st} harmonic being suppressed further (Fig. 3.16), as its negative halfwave potentially contributes most to the THD, if biased insufficiently[5]. Also, the THD of the Fetprobe is slightly different to previous graphs, though the same power and frequency are used because the bias is being fed in externally rather than being derived from a voltage divider.

[5] unfortunately, the bias has been proven to be poorly implemented in its spice model

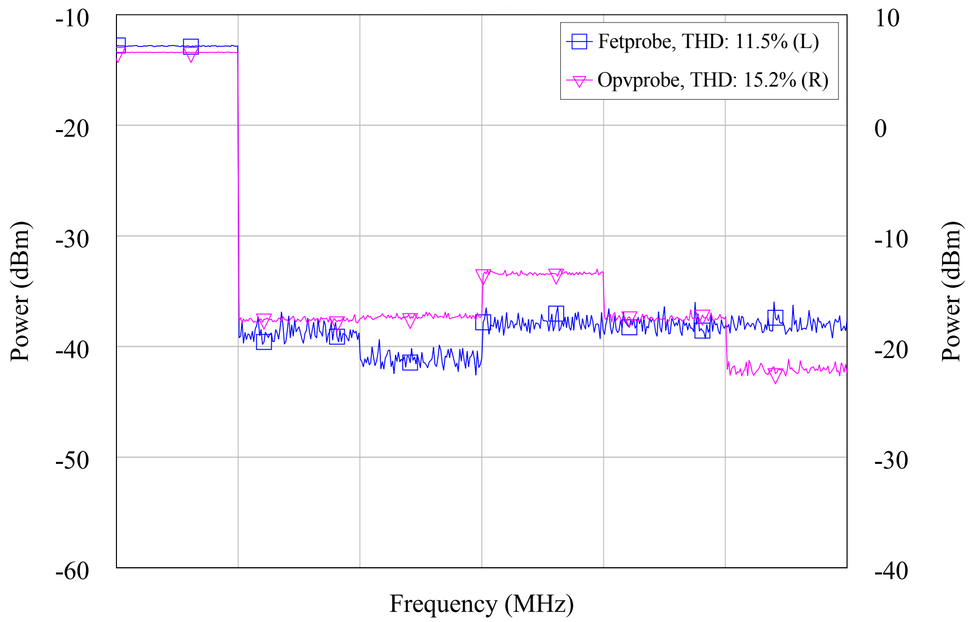

Figure 3.12: THD comparison of both active probes (10 MHz@10 dBm)

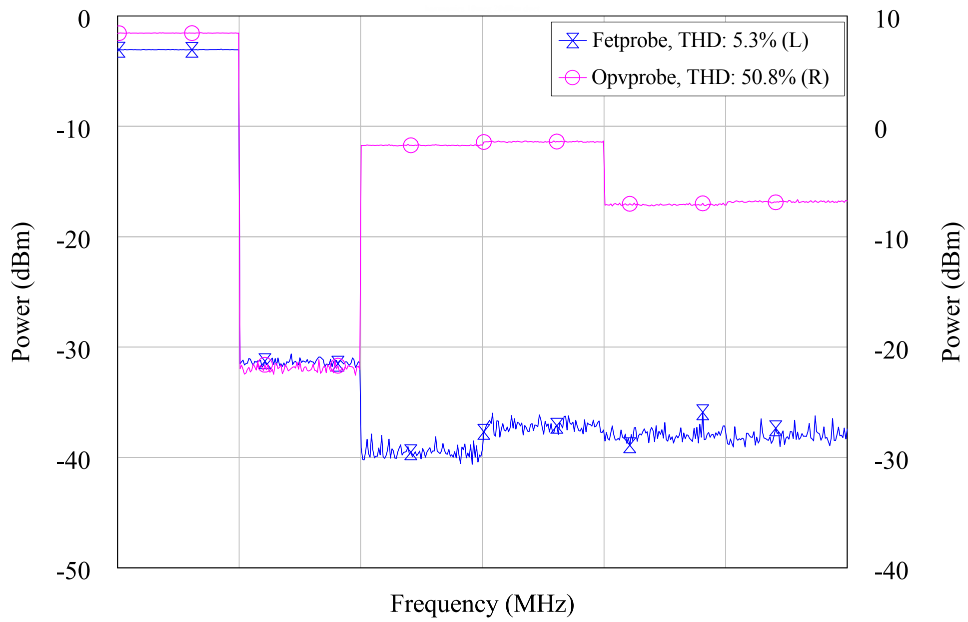

Figure 3.13: THD comparison of both active probes (10 MHz@20 dBm)

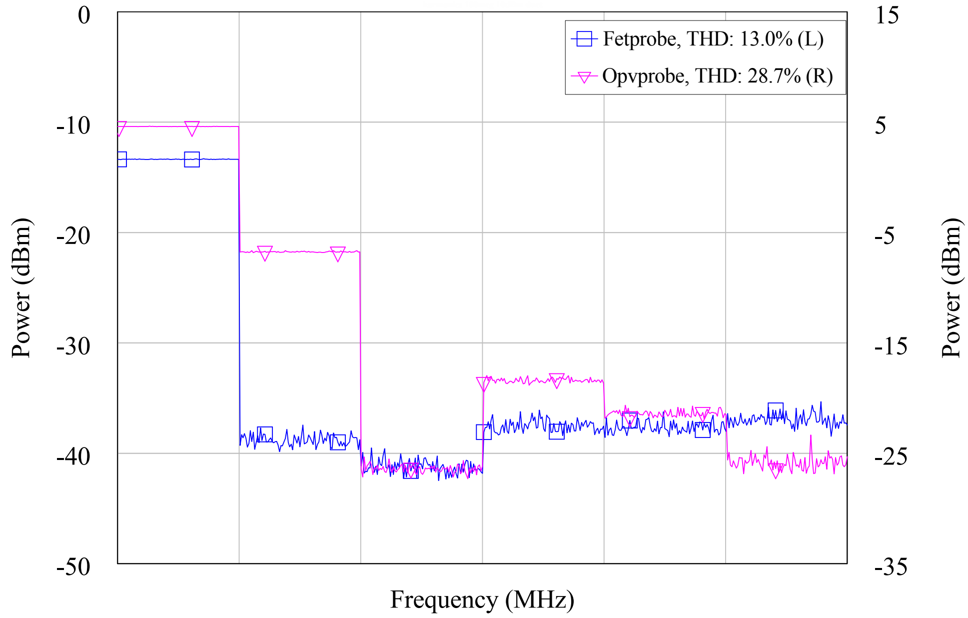

Figure 3.14: THD comparison of both active probes (100 MHz@10 dBm)

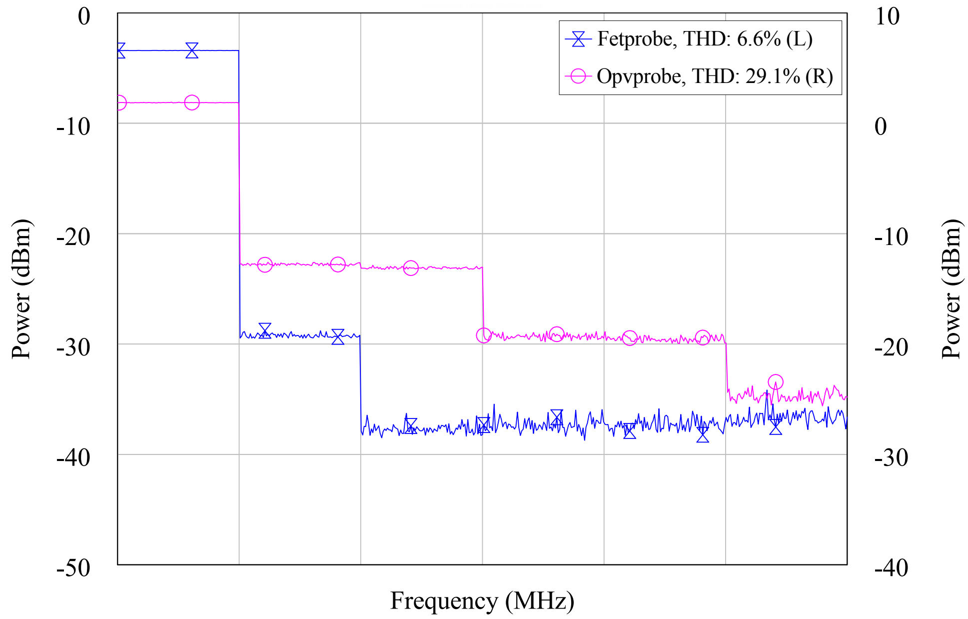

Figure 3.15: THD comparison of both active probes (100 MHz@20 dBm)

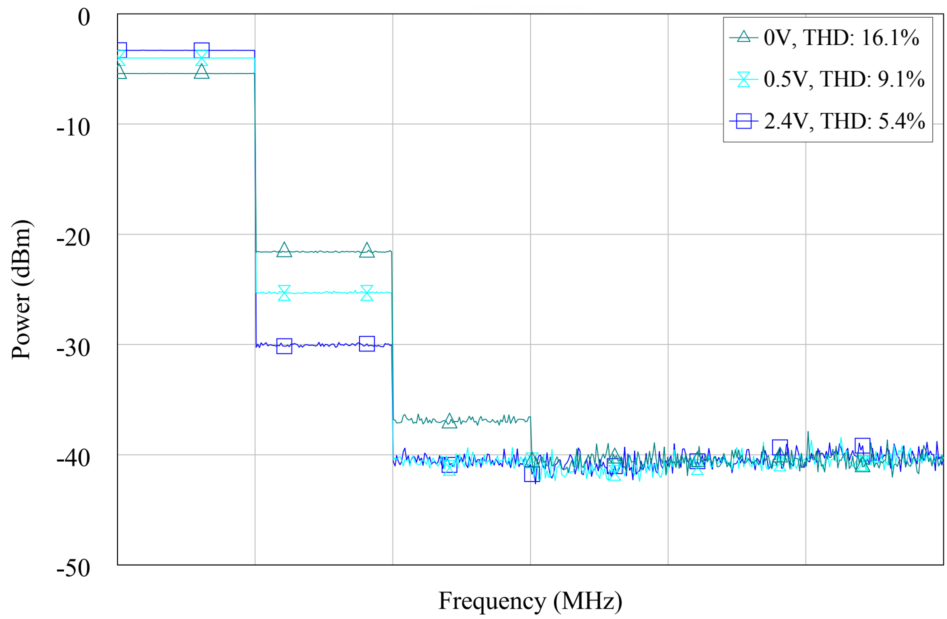

Figure 3.16: Fet bias influence on harmonic distortion (100MHz@20dBm)

3.5 Comparison to commercial Probes

Last but not least, a comparison to commercial probes has to be done. How does the Fetprobe fare against the 3 GHz HP 85024A and 650 MHz Philips PM8943 probes (listed in Addendum: Section 4). Since the Opvprobe is inferior it will be excluded.

As we see in Fig. 3.17, the Fetprobe clearly performs better than the ancient[6] Philips probe, and has a similarly flat response as the HP probe up to 1 GHz. Unfortunately, the -23.3 dB Level means the probe is of type "times 14.3", which is rather inconvenient for oscilloscope use[7], as probe attenuation factors are typically decadic, i.e. times 10 or 20[8]. For use with a Network Analyzer that doesn't matter, as it can be calibrated to the specific probe.

As for the commercial probes, their influence on the circuit under test seems to be smaller than the one of the Fetprobe (Fig. 3.18). Still, up to 1 GHz it is below -10 dB as well.

We note that S22 of the HP probe looks even worse, tough as mentioned before, this isn't really relevant for most applications (Fig. 3.19).

Yet, the pulse responses seems more accurate on the Fetprobe (Fig. 3.20 and 3.21), tough it has some undershoot after returning to zero. As for the HP probe, at first glance it may seem overcompensated[9], but when looking at Fig. 3.17 it becomes clear that this isn't the case: As the drop on the left suggests, the HP probe attenuates lower frequency signals quite significantly. So in case of the pulse the probe fails to stay constant on the "high"-level because the needed frequency components are very low, if not DC.

[6] 1985

[7] that means linear vertical measurements may have to be done manually

[8] as shown in Fig. 3.5

[9] high-pass characteristic

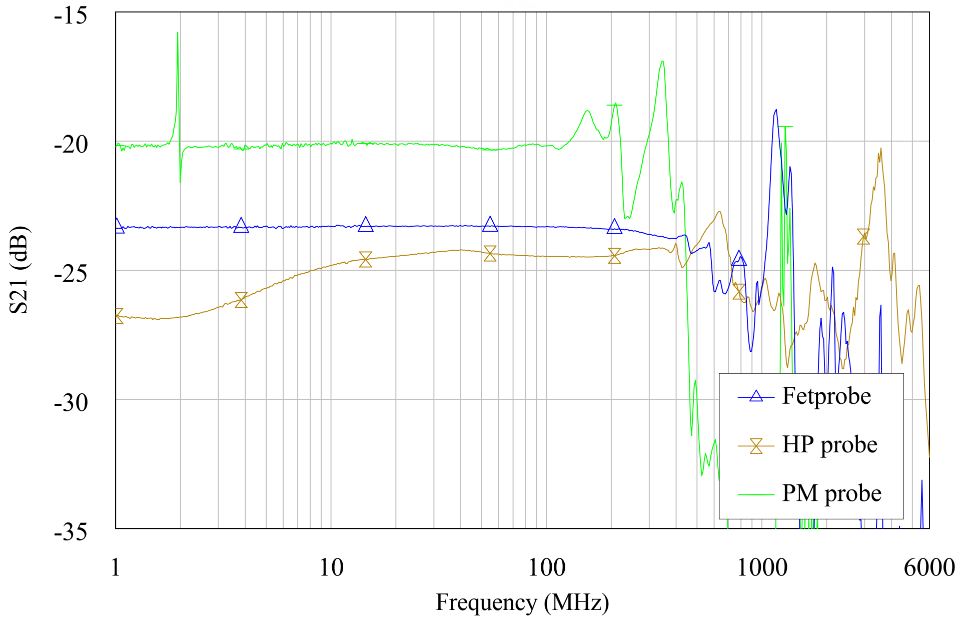

Figure 3.17: S21 of Fetprobe and commercial probes

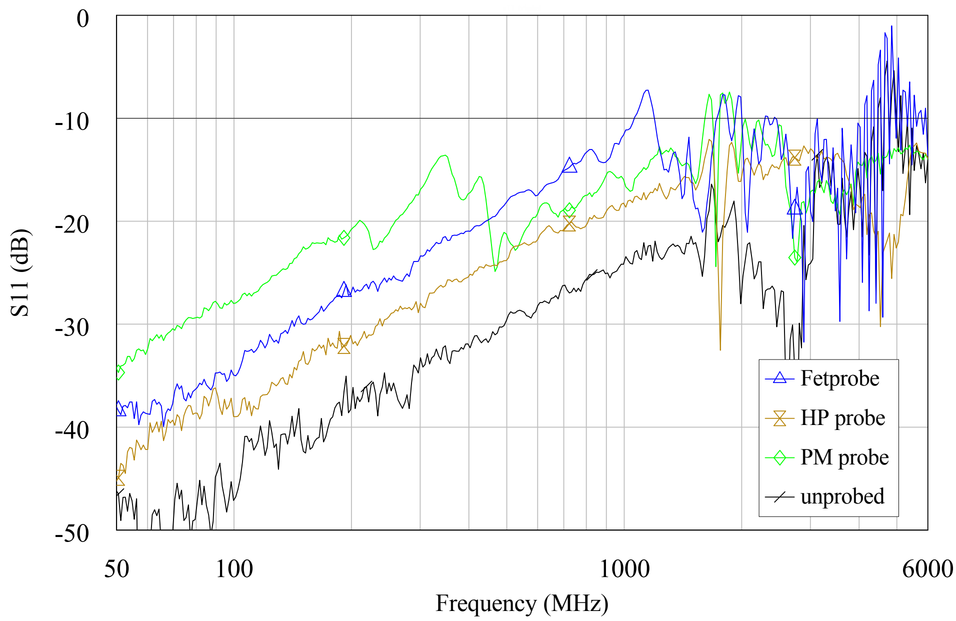

Figure 3.18: S11 of Fetprobe and commercial probes

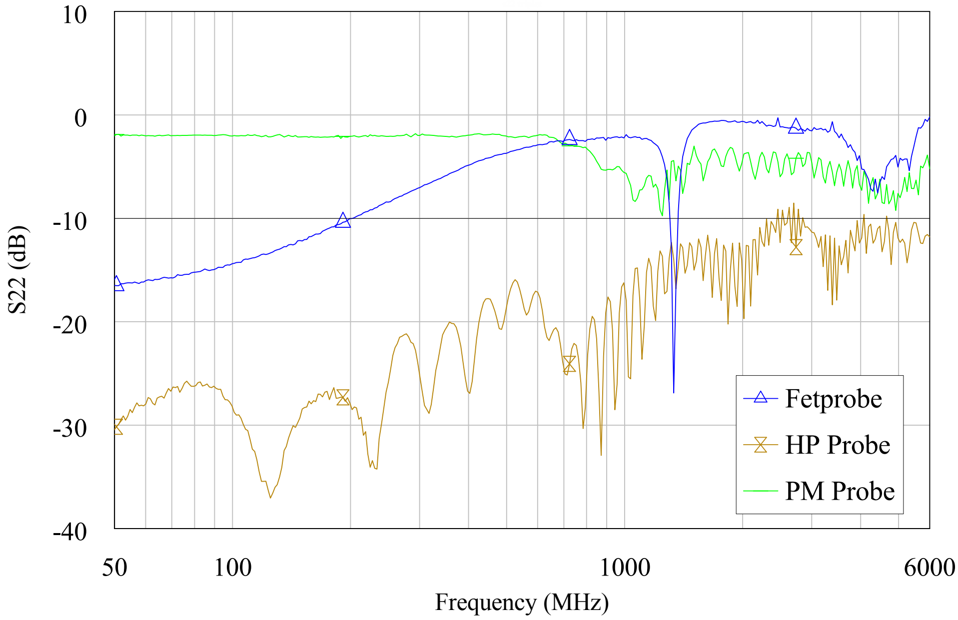

Figure 3.19: S22 of Fetprobe and commercial probes

The PM probe performs not that well either when being subjected to the 0.5 V pulse by having a 0.14 V DC offset. The overall right-shift of the commerical probes' pulse response can be accounted for by their longer cables and the corresponding wave propagation delay.

When looking at the harmonic distortion measurements (Fig. 3.22 to 3.25), it is notable that none of the probes have significant harmonic multipliers, while the Fetprobe clearly lies ahead.

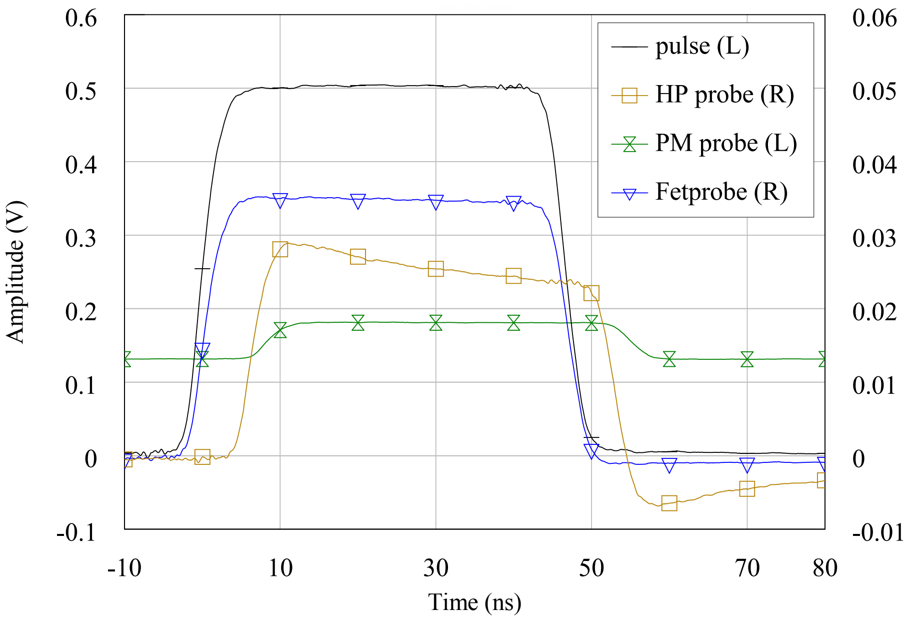

Figure 3.20: responses of both active probes to 500mV 50ns pulse

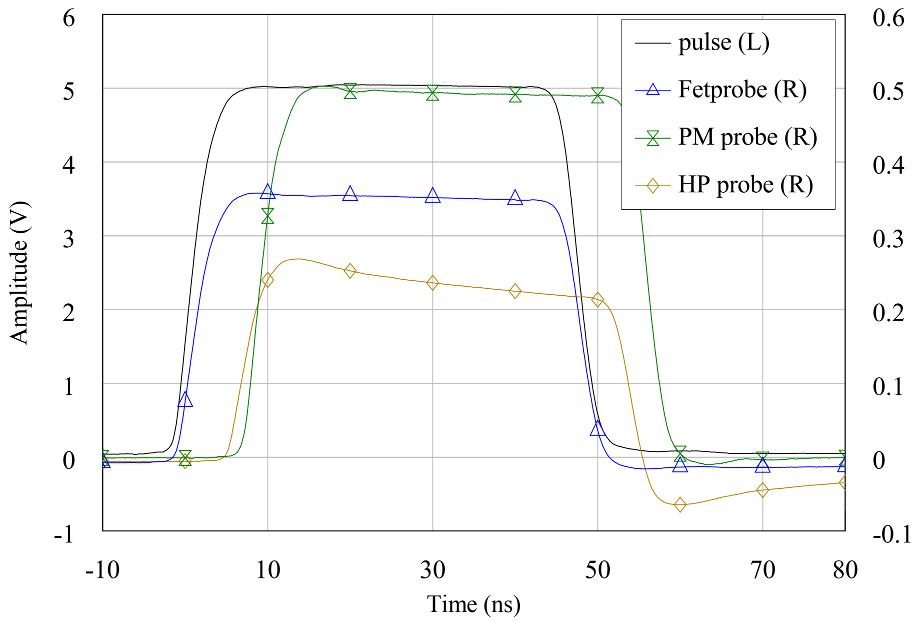

Figure 3.21: responses of both active probes to 5V 50ns pulse

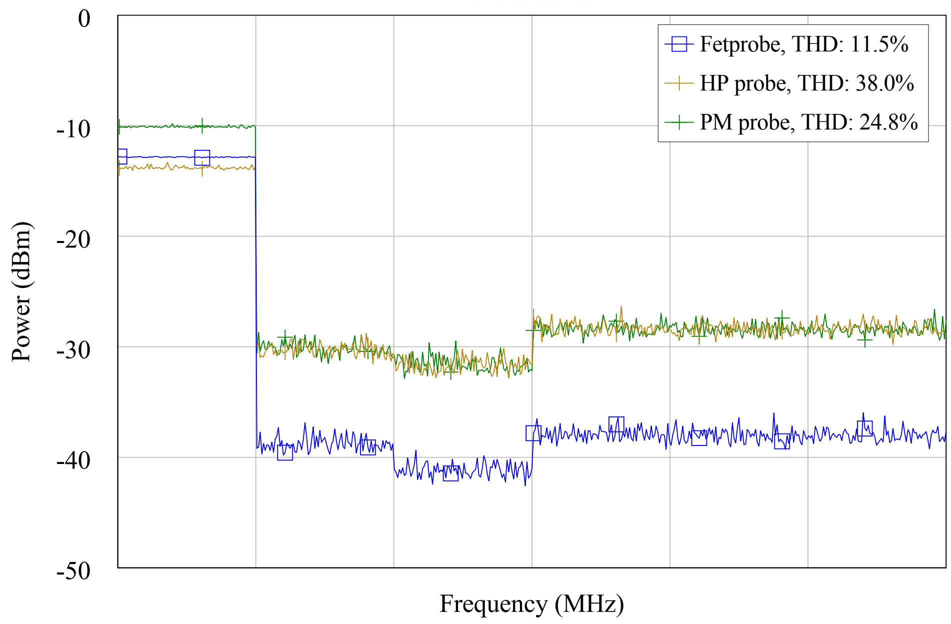

Figure 3.22: THD of Fetprobe and commerical probes (10 MHz@10 dBm)

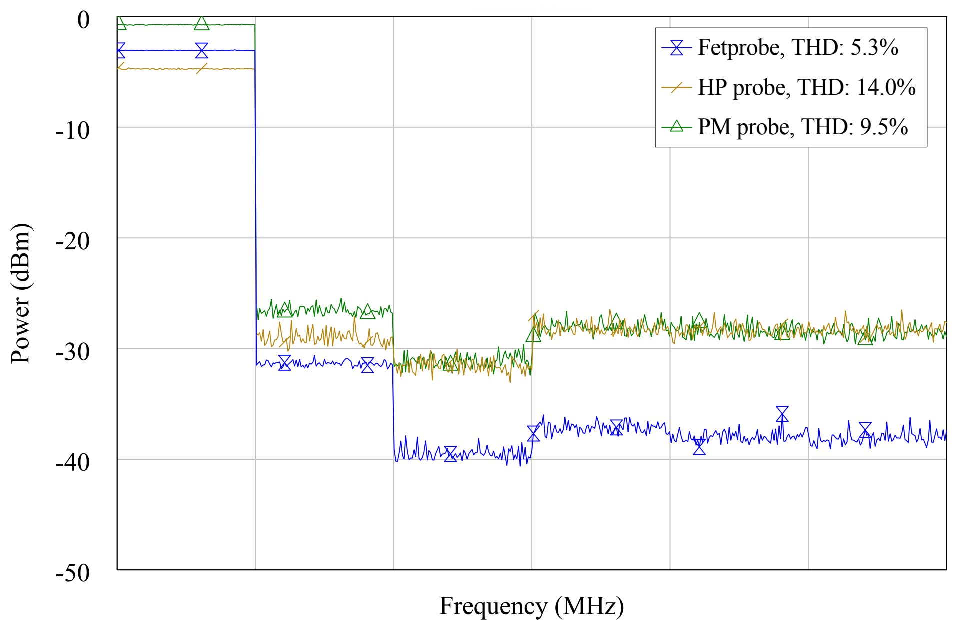

Figure 3.23: THD of Fetprobe and commerical probes (10 MHz@20 dBm)

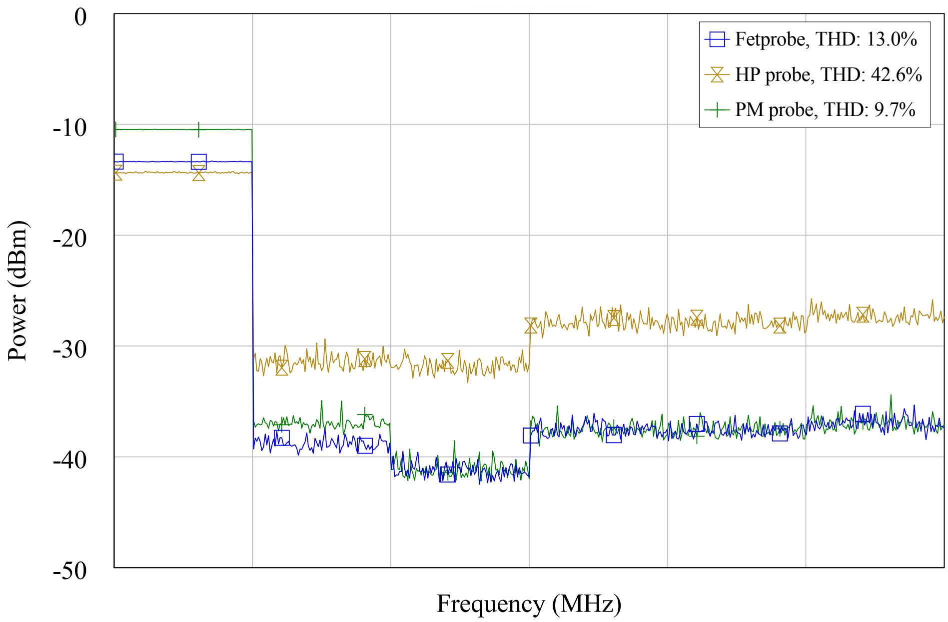

Figure 3.24: THD of Fetprobe and commerical probes (100 MHz@10 dBm)

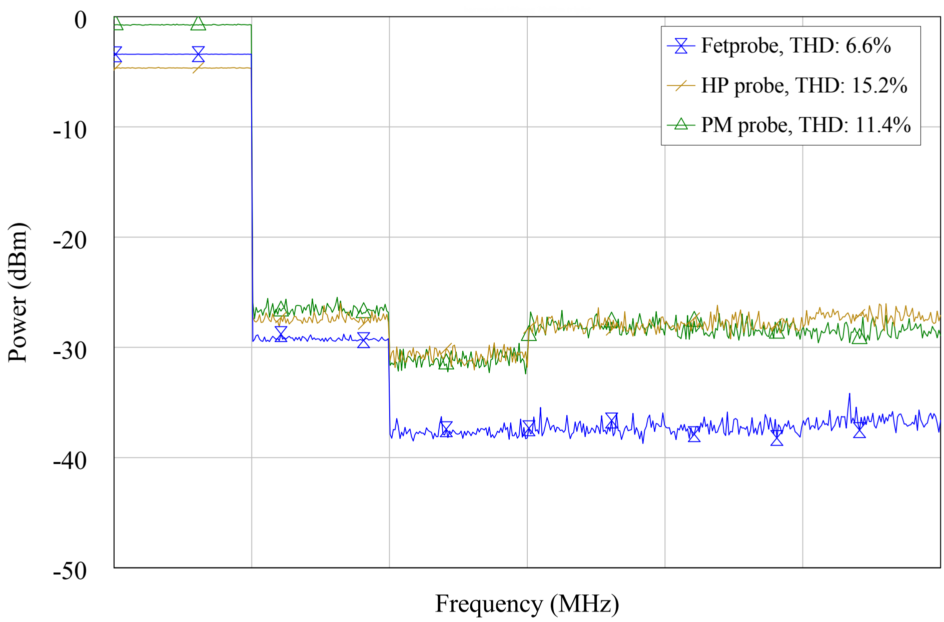

Figure 3.25: THD of Fetprobe and commerical probes (100 MHz@20 dBm)

4 Conclusion and Outlook

To recapitulate, the Fetprobe has quite some potential and even manages to hold up against certain commercial probes, in some ways. The pulse response ripple, over-/undercompensation and nonlinearities (via THD) were lower, the transfer function compareable. Regarding the low price of this project it may be usable for both student and low-level field use, especially with Network Analyzers. What remains to be optimized is the gain (i.e. 20:1 as shown in Fig. 3.5 instead of 14:1), maybe the input path (less capacity via other tips or other substrate in input area) and the output filter.
Nevertheless, it has been proven that even with little money the construction of an active probe up to 1 GHz is feasible.

ADDENDUM

used Hardware and Software

National Instruments AWR Microwave Office: [3] (design & simulation, graphs)
R& S ZVL-K1, 9 kHz-6 GHz, network analyzer mode (S21 & S11 analysis)
Settings: span: 10 kHz-6 GHz, 1001 sweep-points, 10 averages, power level: -10dBm
VNA Calibration Kit: ZV-Z132
R& S SMBV100A (signal generator for THD meas.)
R& S ZVL-K1, spectrum analyzer mode, 10 MHz external from SMBV, 20dB att. (THD meas.)
Philips PM7515 1 Hz-50 MHz (pulse generator), pulse: 500mV/5V x 50ns
MSO7104A 1 GHz 4 GSa/s oscilloscope (pulse response meas., two inputs used (per measurement))
HP 85024A 300 kHz-3 GHz with 10:1 tip (HP probe)
Philips PM8943 0 Hz-650 MHz with 10:1 tip (PM probe)

BOM

Table 4.1: Bill of Materials for Fetprobe

x	Name	Size	add. Info	used for/in
1	NXP BF998	SC-61B 4pin	N-MOSFET	main amp/converter
1	Vishay 10MΩ	0603	CRCW +-0.1% 0.1W	Fet bias: RF block
2	pogopins	13mm		RF in, GND
1	47μF cap	2412	12V or higher	Fet supply
2	atc 1.8pF cap	0603	atc 500s 1r8 npo c	output filter
1	atc 1.0pF cap	0603	atc 500s 1r0 npo c	output filter
2	wuerth 22nH inductor	0603	744 761 122	output filter
1	blue SMD LED	0603	LTST-C191TBKT	LED
1	680Ω	0603		LED
1	Voltage regulator	SOIC 8-pin	TI LM317LCDR	power supply
4	2.3uF cap	0603		V_{in}, Fet, bias, C_{adj} at LM317
3	100nF cap	0603		V_{in}, Fet, bias
1	150nF cap	0603		RF output cap
1	33Ω	0603		Fet output matching
1	47OΩ	0603		Fet gain control
1	0.5pF cap	0603		RF input cap
1	3kΩ	0603		bias voltage divider
1	8.2kΩ	0603		bias voltage divider
1	2.7kΩ	0603		Lm317 circuitry
1	470Ω	0603		Lm317 circuitry
1	150Ω	0603		Lm317 circuitry
1	Sma connector			RF out

Literature

[1] "Poor man's 500mhz active fet probe with opa659," visited 07.09.2015. [Online]. Available: http://www.mikrocontroller.net/topic/188227 4

[2] David Jewsbury, "Poor man's 1ghz active probe: Diy saves a pretty penny," *Elektor*, no. 4, pp. 36–38, 2004. 4

[3] NI, "Ni awr website," visited 10.10.2015. [Online]. Available: http://www.awrcorp.com/products/microwave-office 5, 32

[4] U. Tietze, C. Schenk, and E. Gamm, *Halbleiter-Schaltungstechnik*, 13th ed. Heidelberg: Springer, 2010. 7

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