Further developments on the Conversion Box

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Abstract

The goal of this thesis was to improve the down-conversion board by implementing filters to decrease the noise level and filter out additional frequencies resulting from the setup. In addition to this I implemented an automatisation of the switch in the mixer calibration circuit.

Contents

1 Introduction and motivation

In this semester project the up- and down- conversion process of microwave signals are studied in detail and the existing hardware implemented is improved. In the Quantum Device Lab at ETH Zürich, microwave signals are used to manipulate the state of superconducting transmon qubits [1] or to readout the qubit state by driving a resonator which is coupled to it. In the setup conversion boards are used to convert the signal frequency. Those boards are called up- and down-conversion board and besides those the setup contains a warm amplifier board which amplifies the signal before it gets down-converted and digitized by the FPGA (Field Programmable Gateway Array) and a switch board which is used when the mixer on the conversion board needs to be calibrated.

The existing down-conversion board was designed to use the full bandwidth of the FPGA which is 500 MHz. In the new board the bandwidth is reduced to a minimum to ensure less disturbing frequencies in the measurement.

The resonator signal consists of several photons which need to be amplified first to become detectable. Therefore we use a Josephson Parametric Amplifier that is driven by a strong tone close to the resonator frequency, called "pump tone"[2]. In a new setup the pump tone is approximately 300 MHz separated from the signal which makes it fall in the detection bandwidth. The new idea is to create a bandpass board which limits the detection bandwidth and only passes the signal tone and filters out low frequency noise and other tones that appear due to the close pump tone.

In a further experiment I tested filters for the up-conversion process. The goal was to filter out higher frequencies which drive higher transmon levels.

2 Theory of the mixer

The transmon qubits use microwave signals to coherently drive from one state to another. It is difficult to create a precise signal at GHz frequency which is needed to drive the qubit. For that reason the desired signal is generated at MHz frequency and a mixer is used to convert it to the GHz regime. A mixer is a device that can convert a frequency by multiplying two signals. It has three ports: a radio frequency port (RF), a local oscillator port (LO), and an intermediate frequency port (IF). The LO is used to apply a constant strong microwave signal at a frequency of f_{LO}. In the up-

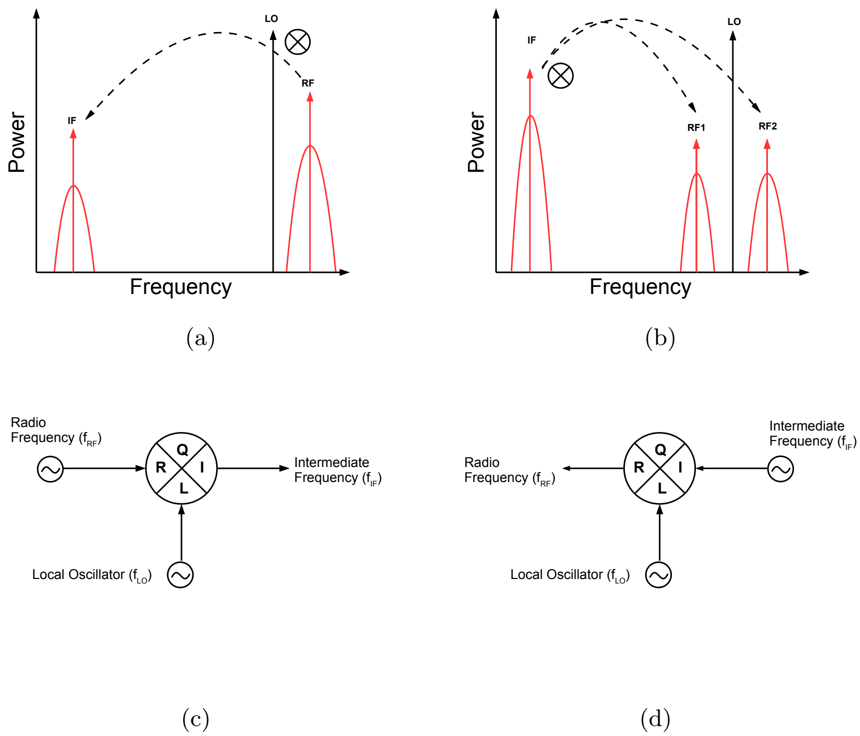


Figure 1: a) RF signal gets down-converted by multiplying with the LO. b) IF signal gets up-converted by multiplying with the LO. c) Mixer configuration during down-conversion. d) Mixer configuration during up-conversion

conversion a signal tone f_{IF} is sent to the IF port where it mixes with f_{LO} which results in an output frequency at RF of

$$f_{\text{RF}} = |f_{\text{IF}} \pm f_{\text{LO}}| \tag{1}$$

as it is shown in Figure 1(b).

The down- conversion process is similar. An incoming signal f_{RF} mixes with f_{LO} which produces an outgoing signal at the IF port

$$f_{\text{IF}} = |f_{\text{RF}} \pm f_{\text{LO}}| \tag{2}$$

as shown in Figure 1(a) [3].

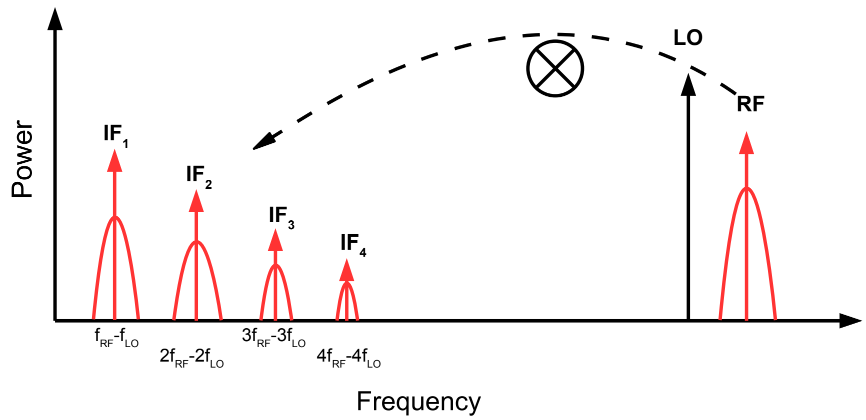


Figure 2: Harmonic modes of the down-converted signal.

2.1 Two tone intermodulation

The mixing processes described above are ideal cases where the signals only mix once. In a real mixer more intermodulation frequencies occur which consists of different combinations of the incoming signals [4]. The function to calculate those is a generalization of Equation 2:

$$f_{\mathrm{IF}} = |\mathrm{m} f_{\mathrm{RF}} + \mathrm{n} f_{\mathrm{LO}}| \tag{3}$$

with $\mathrm{m}, \mathrm{n} = 0, \pm 1, \pm 2, \pm 3, ...$ and $|\mathrm{m}| + |\mathrm{n}|$ is the order of down-conversion. The same holds for the up-conversion process where f_{RF} and f_{IF} are exchanged [3].

3 Measurement device

3.1 FPGA

The measurement device that is usually used to analyze the data is an FPGA. It is programmed to measure the power of an incoming digital signal and Fourier transform it to get the power spectrum. The FPGA has an effective bandwidth of 500 MHz. Every higher frequency gets folded back into the detection bandwidth and are therefore filtered out.

The data processing on the FPGA contains a digital DC which converts a signal at 250 MHz down to 0 MHz. Because of this conversion we see negative frequencies in the measurements.

4 Down-conversion bandpass board

In the down-conversion board the GHz signal from the resonator gets down-converted to 250 MHz where it gets read by the ADC (Analogue Digital Converter). For single photon measurements we use a JPA (Josephson Parametric Amplifier) inside the cryostat for first amplification. This amplifier has a gain up to 30 dB and adds noise near the limits of quantum fluctuations from the electromagnetic vacuum [2]. The JPA gain is centered around a pump frequency which has to be set close to the signal tone for maximal amplification. This makes the pump tone appear in the detection bandwidth of the FPGA. The new down-conversion bandpass board is designed to cancel out this frequency and other intermodulations that occur.

4.1 Basic design

The basic design of the down-conversion bandpass board is shown in Figure 3. Its main components are a mixer (Marki IQ-4509MPX) that operates at 4.5-9.6 GHz, an amplifier (ZFL-500LN+) which has a gain of 35 dB, and filters to create the bandpass. Since the mixer is not well impedance matched attenuators are needed to be place at all ports to avoid standing waves.

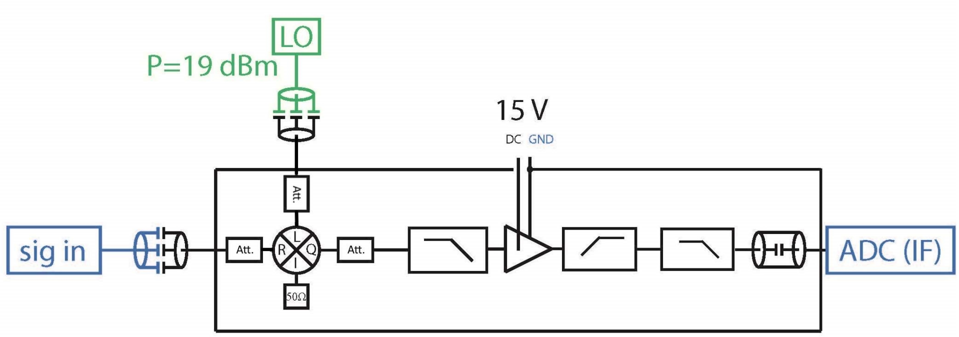


Figure 3: Schematic of the down-conversion bandpass board.

Filters		cut-off freq.	Type
ZX75LP-320-S+	(LP-320)	345 MHz	LP
SLP-550-S+	(LP-550)	570 MHz	LP
SLP-250	(LP-250)	250 MHz	LP
SHP-175+	(HP-175)	140 MHz	HP
SHP-200+	(HP-200)	164 MHz	HP

Table 1: Low- and high pass filters(LP\HP) from Mini-Circuits.

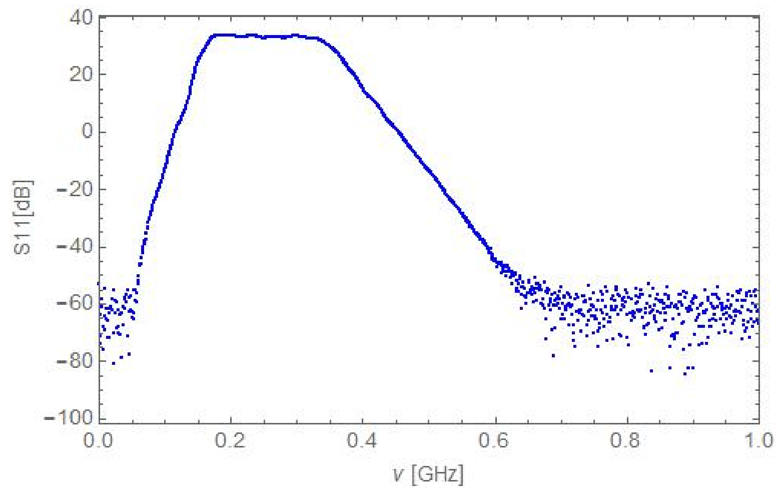


Figure 4: Measurement of the transmission amplitude of the first bandpass setup which consists of three filters SHP-200+, SLP-550+, and ZX75LP-320-S+ and the amplifier.

In this new down-conversion bandpass board the filters are used to create a symmetrical bandpass around the 250 MHz signal, with a bandwidth between $100 - 200$ MHz to avoid cutting off a signal tone which has a typical bandwidth of 30 MHz. Table 1 shows filters that fulfill the requirements for such a board based on their specifications provided by Mini-Circuits and are therefore chosen to make further tests.

As the basic setup to test which filters should be implemented in the new bandpass board (see Figure 3), three filters and one amplifier were chosen. In the first setup one low- and one high-pass filter are placed in front of the amplifier to shield it from noise. Since low-pass filters do not have such a steep suppression line as high pass filters an other low-pass filter is placed at the end of the board to reduce further noise generated by the amplifier. Figure 4 shows the measurement of this setup using a VNA. The graph shows a drop of 80 dB in power over 0.2 GHz at the higher frequency side of the bandpass and 80 dB over 0.1 GHz for the low frequency side. The HP-175 filter would have been equally suitable for the setup but by taking the HP-200 filter the bandwidth of the bandpass is 190 MHz instead of 210 MHz which further limits the space for disturbing frequencies in our measurements.

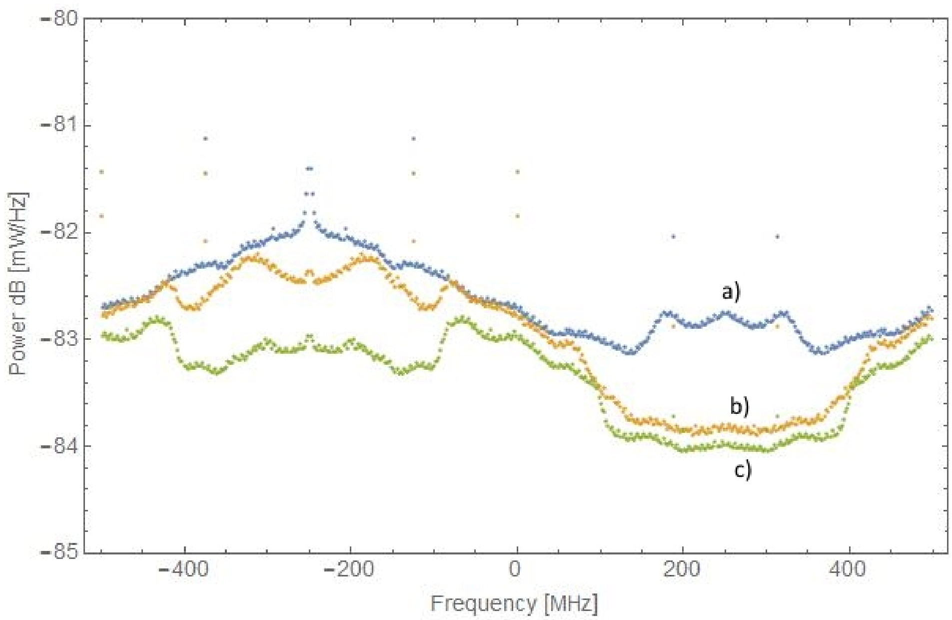


Figure 5: FPGA measurement of the noise level on different setups of the down-conversion bandpass board. Setup a) is with the existing virtex 6 full bandwidth board which consists of a SLP-550+ and a ZFLP-450+ low-pass filter, b) is after exchanging ZFLP-450+ with a ZX75LP-320-S+ filter and adding a SHP-200+ high-pass before the amplifier. c) is the final setup where also a high-pass filter is placed after the amplifier.

4.2 Low frequency noise

The next step is to test the setup from Figure 4 with the virtex 6 FPGA and study how it effects the noise level. Especially, the low frequency noise used to be a source of problems while measuring with the full bandwidth down-conversion board since it only had two low pass filters that cut off around 500 MHz and no high pass filters.

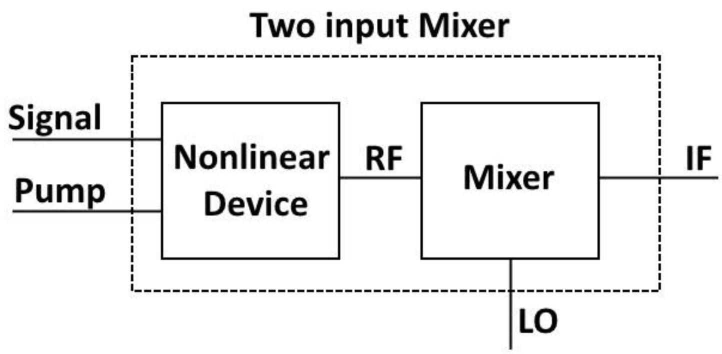


Figure 6: Mixer with two input frequencies separated into an non-linear device which mixes the incoming signals and normal mixer which has an LO and one RF signal.

The results are shown in Figure 5 with the different setups. The noise in the measurement is a combination of digital noise that results from the computation on the FPGA and analogue noise from the setup.

Setup c) improves the noise cancelling for high and low frequencies as one can see by comparing it to setup a) where no noise gets cancelled or setup b) where only high frequency noise gets cancelled. By placing both a high-pass and a low-pass filter after the amplifier its noise gets cancelled out. By adding more filters the noise level does not drop further which means the remaining noise is a digital artefact on the FPGA.

4.3 Multi-tone intermodulation

Intermodulations are frequencies that are created by the mixer if two or more frequencies get sent into it. The mixer is a non-linear device which means every incoming signal and all its harmonics mix. In our setup we have a signal tone, the pump tone and a local oscillator which gives us a three-tone intermodulation [5] and can be described by two separate processes like it is shown in Figure 6.

In the measurement of Figure 7 one can see such intermodulation products. At -10 MHz there is a frequency peak which cannot be explained using the basic mixer formula where signals only get down-converted with the LO. Therefore, we introduce a down-conversion of the signal tone with the pump tone which describes the first step in Figure 6.

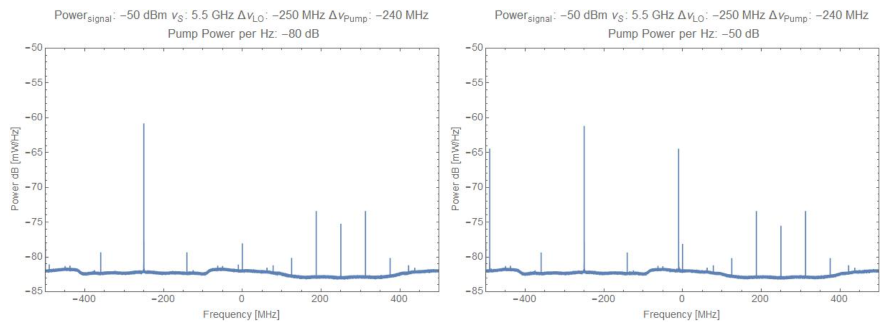


Figure 7: Frequency peak measurement on the down-conversion bandpass board as in the last setup of Figure 5. Pump frequency is on the left side of the bandpass which results in a intermodulation frequency at -10 MHz. Left is a frequency spectrum for a low pump power of -80 dB, on the right the pump power is -50 dB.

To calculate the intermodulation frequencies in our setup one can apply a similar formula as the equation 2. First, mixing at the RF port occurs where the signal and the pump tone mix.

$$f_{\mathrm{RF_{kl}}} = |\mathrm{k} f_{\mathrm{signal}} + \mathrm{l} f_{\mathrm{pump}}| \tag{4}$$

with $\mathrm{k}, \mathrm{l} = 0, \pm1, \pm2, \pm3, ...$ and $|\mathrm{k}| + |\mathrm{l}|$ is the order of intermodulation. Like the higher order of down-conversion those intermodulation frequencies tend to get lower in power with increasing order. The resulting frequencies $f_{\mathrm{RF_{kl}}}$ mix with the LO just like they would in a normal down-conversion process (See equation 3).

In Figure 7 we identify the frequency peak next to the signal as $f_{\mathrm{signal}} - f_{\mathrm{pump}}$. All measurements with a pump frequency between the LO at 5.25 GHz and the signal at 5.5 GHz show intermodulation frequencies near the bandpass therefore I suggest to place the pump tone above 5.75 GHz to avoid intermodulation tones close to the signal tone.

A measurement on a down-conversion board with a bandwidth of 1 GHz and a strong pump and signal tone with 10 dB shows possible intermodulation frequencies that occur by using a mixer. This measurement is shown in Figure 8. The two frequency peaks with the largest power correspond to the down-converted signal and pump tone, all other peaks are intermodulations of these two and the LO.

We found two important results from this measurement. First, those intermodulation frequencies appear clearly in the regime of our signal which

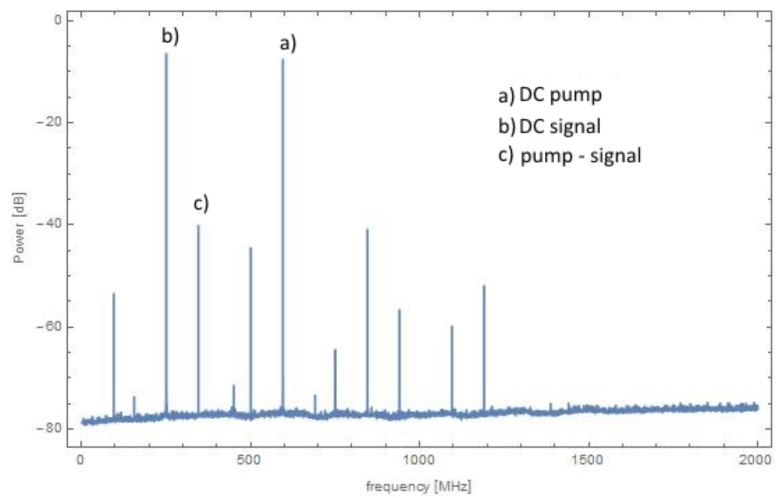


Figure 8: 3 tone intermodulation measurement on a spectrum analyser. The Pump tone is set at 5.845 GHz, the signal tone at 5.5 GHz and the LO at 5.25 GHz. The power of the signal and pump are at 10 dB.

means they can disturb the measurement. Therefore they need to be filtered out using a bandpass filter.

The other problem appears if the pump frequency is chosen to be approximately as fare away from the signal as the LO. In this case the intermodulation frequency cannot be filtered out since it overlaps with the signal tone and the measurement will show an increase in power at the signal frequency if the pump power is increased.

In our setup the frequencies of the signal and LO are fixed. Therefore, we have to select the pump tone in such a way that strong intermodulation frequencies do not lie inside the bandpass.

$$f_{\text{pump}} - f_{\text{signal}} \quad \text{m = 1, n = 0, k = 1, l = -1}$$

This frequency is most likely to disturb our measurement due to its strong power and close appearance to the signal tone as already seen in Figure 7 and Figure 8.

It can be filtered out using filters with a cut-off closer to the signal tone or by placing the pump tone further away from the signal such that this intermodulation frequency gets cancelled out by the bandpass filter.

4.4 Power dependence of the intermodulation tones

Intermodulation frequencies have a lower power for a small input but they increase non-linearly which is why they appear in measurements with a strong input power as disturbing frequencies and have to be filtered out. Breaking down the output voltage v_0 in its Taylor series gives us

$$v_0 = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + ... \tag{5}$$

with v_i as the input voltage. The coefficients are defined as

$$a_0 = v_0(0) \tag{6}$$

$$a_1 = \frac{dv_0}{dv_i} \tag{7}$$

$$a_2 = \frac{d^2 v_0}{dv_i^2} \tag{8}$$

In a non linear device not all a_i for i>1 are 0. Thus mixing of frequencies can occur. For two incoming frequencies this gives us

$$\begin{aligned}
v_i &= V_0(\cos\omega_1 t + \cos\omega_2 t) \\
v_0 &= a_0 + a_1 V_0(\cos\omega_1 t + \cos\omega_2 t) + a_2 V_0^2(\cos\omega_1 t + \cos\omega_2 t)^2 + ... \\
&= a_0 + a_1 V_0 \cos\omega_1 t + a_1 V_0 \cos\omega_2 t + \frac{1}{2} a_2 V_0^2 (1 + \cos 2\omega_1 t) \\
&+ \frac{1}{2} a_2 V_0^2 (1 + \cos 2\omega_2 t) + a_2 V_0^2 \cos(\omega_1 - \omega_2)t + a_2 V_0^2 \cos(\omega_1 + \omega_2)t \\
&+ a_3 V_0^3 \left(\frac{3}{4}\cos\omega_1 t + \frac{1}{4}\cos 3\omega_1 t\right) + a_3 V_0^3 \left(\frac{3}{4}\cos\omega_2 t + \frac{1}{4}\cos 3\omega_2 t\right) \\
&+ a_3 V_0^3 \left(\frac{3}{2}\cos\omega_2 t + \frac{3}{4}\cos(2\omega_1 - \omega_2)t + \frac{3}{4}\cos(2\omega_1 + \omega_2)t\right) + ...
\end{aligned} \tag{9}$$

From equation 9 follows the frequencies of the second order depend on V_0^2. This means for a small input power those intermodulation product will be small but increase quickly as the input power increases. Furthermore in second order, the intermodulation products $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$ have an amplitude twice of the harmonics $2\omega_1$ and $2\omega_2$. Thus the power of the harmonics are 6 dB lower than the once of the intermodulation products[4]. This can be applied to all higher order intermodulations.

A measurement shown in Figure 4.4 shows this behaviour of intermodulation frequencies for 3 tones. Higher order frequencies like $f_{pump} - f_{sig}$ are lower in power but increase more rapidly than first order frequencies like

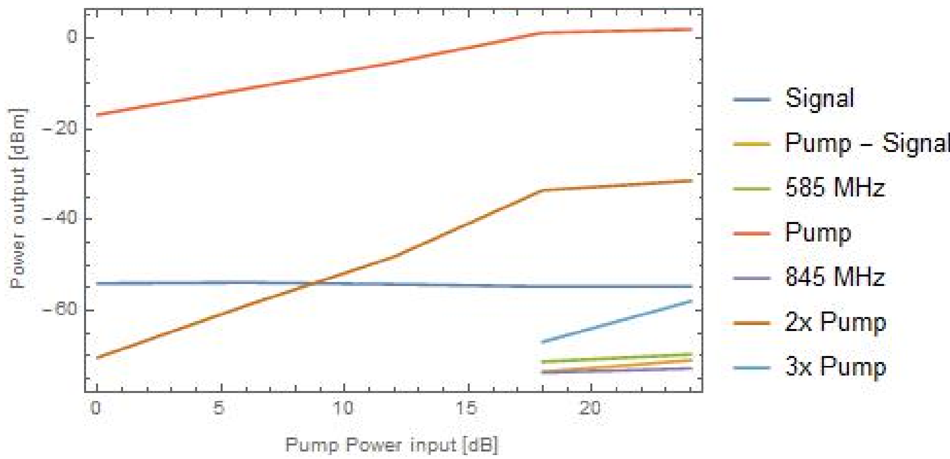


Figure 9: Measurement of the power dependence of the frequency peaks in an asymmetric case where the signal power stays constant and the pump power is increased.

f_{pump}. In this measurement only the pump power was increased to make sure it does not effect the signal power. At a pump power of 18 dB the saturation of the amplifier is reached.

4.5 Final setup

The final setup is shown in Figure 10. The SLP-250 low-pass filter is to cancel out the close $f_{\text{pump}} - f_{\text{signal}}$ tone. This filter, which has a cutoff frequency at the signal frequency suppresses higher intermodulation tones close to the signal tone. This setup measured with the FPGA gives a frequency spectrum shown in Figure 11.

As can be seen in Figure 12 while the intermodulation frequency at 345 MHz is visible in a) it gets cancelled out after replacing one low-pass filter with the SLP-250 filter.

These plots are made using a subtraction method. Because it is difficult to distinguish frequency peaks of the actual measurement from the FPGA internal clock frequencies I subtracted a measurement, where the pump power is still low from later measurements while sweeping over the pump power. FPGA noise will be cancelled out or appear as random signals which do not correlate with the increasing power.

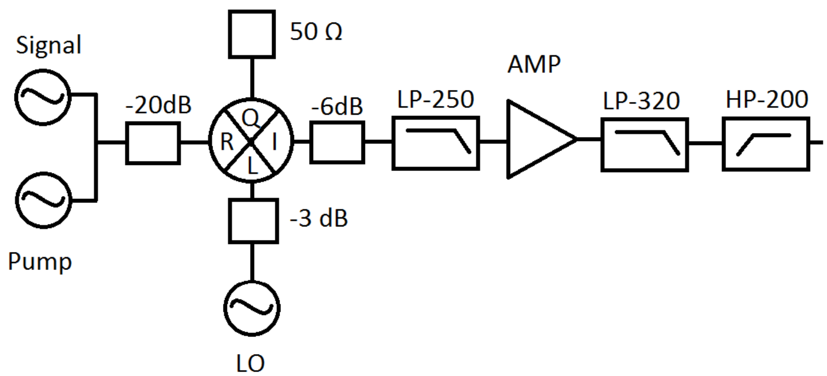


Figure 10: Down-conversion bandpass board setup for filtering close intermodulation frequencies.

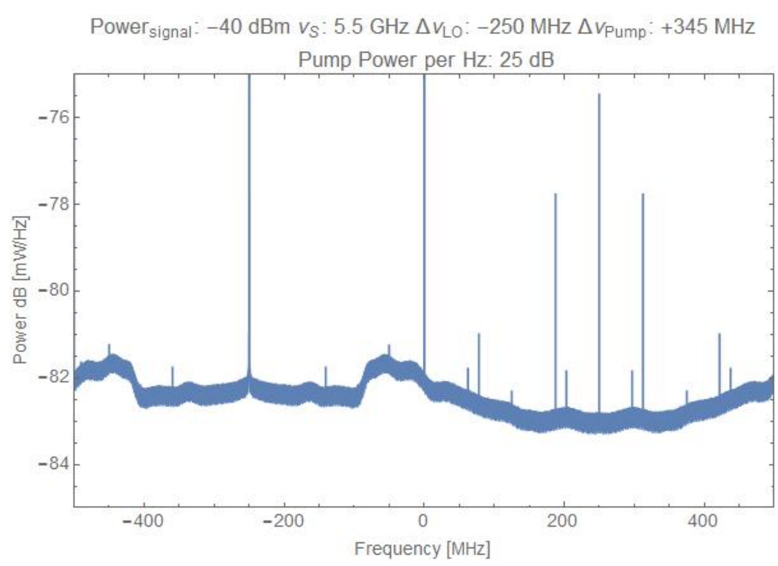


Figure 11: Power spectrum measurement with the FPGA on the final down-conversion bandpass board.

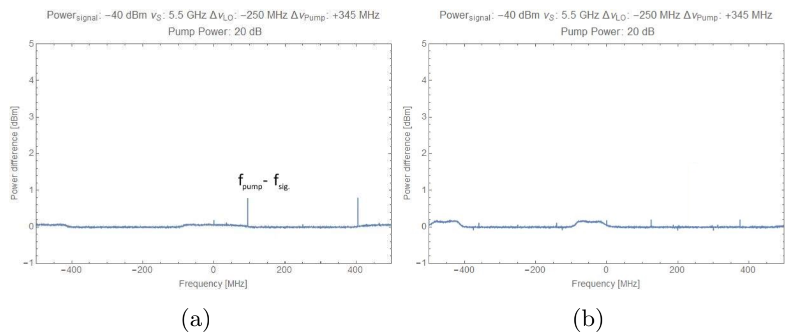


Figure 12: Power spectrum measurement with the FPGA on the setup of Figure 10 with a LP-320 filter in a) and a LP-250 filter in b). $f_{\text{pump}} - f_{\text{signal}}$ is visible at 95 MHz in a)

Still not all intermodulations get cancelled out. If the pump tone is chosen to be $\sim$ 250 MHz away from the signal it still appears in the measurement. This is shown in Figure 13 where a pump tone is at 5.745 GHz and therefore, an intermodulation frequency appears at -5 MHz.

One disadvantage of this filter is the steep suppression of the area around the signal. The filter has an insertion loss of 5 dB at 250 MHz. Therefore, a 6 dB attenuator after the mixer is used instead of a 10 dB as it is in the full bandwidth down-conversion board. In addition, the bandpass is not symmetric around the signal. In Figure 14 a measurement is shown where the signal is amplified by a warm amplifier which generates more noise and the action of the low pass filter is clearly visible. This asymmetry results in a drop of power of 8 dB over the bandwidth of a 20 MHz wide signal and for a 2 MHz bandwidth a drop of 1 dB.

5 Up-conversion board

While the down-conversion process is used mainly to read signals which come from the resonator, the up-conversion process is used to send signals to the qubit to manipulate the state of it.

The signal tone which is created by a arbitrary wave generator (AWG) at MHz frequency and up converted by the mixer to GHz is able to excite a qubit. This transition frequency ν_{ge} of the first state depends on the qubit design and usually lies between 4-9 GHz. The next excited state ν_{gf} of the qubit is at

$$\nu_{\text{gf}} = 2\nu_{\text{ge}} - \alpha \tag{10}$$

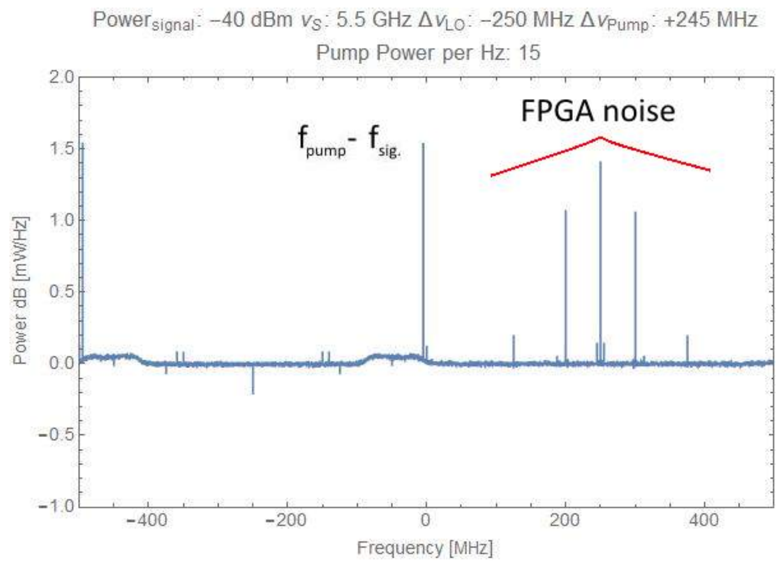


Figure 13: Power spectrum of the down-conversion bandpass board with a pump tone at 5.745 GHz. Besides FPGA noise there is also an intermodulation frequency visible at -5 MHz.

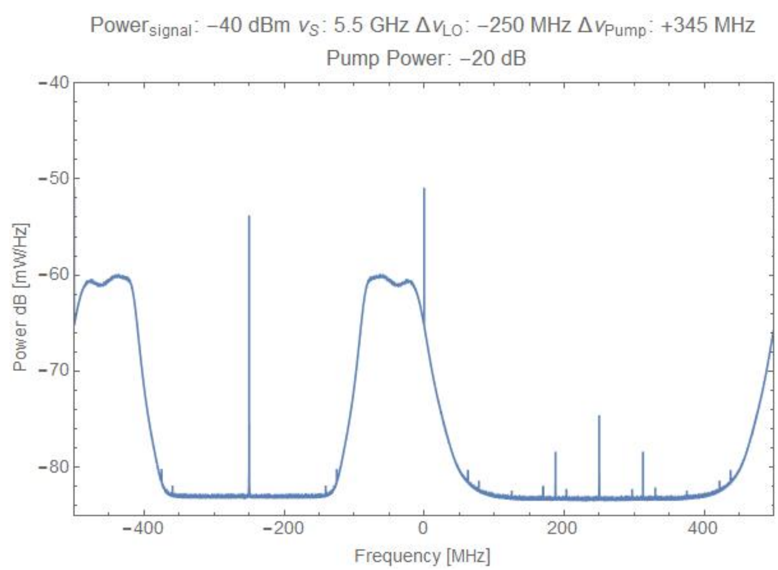


Figure 14: Measurement of a resonator inside the cryostat. The high noise level results from the warm amplifier board inside the conversion box.

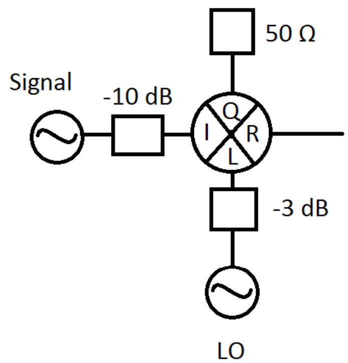


Figure 15: Setup of the up-conversion Board

Where α is called the anharmonicity of the transmon qubit and is usually around 300 MHz. This brings ν_{gf} to 8-18 GHz. Since the space should be a two level system, driving the ν_{gf} frequency has to be avoided.

In the up-conversion process a mixer creates two microwave signals

$$f_{\text{LO}} + f_{\text{sig}} \tag{11}$$

$$f_{\text{LO}} - f_{\text{sig}} \tag{12}$$

to the 1^{st} order which can both be used to drive the qubit. In higher order up-conversion multiples of these frequencies appear which are lower in power but still visible in measurements, e.g.

$$2 \cdot f_{\text{LO}} + 2 \cdot f_{\text{sig}} \tag{13}$$

$$2 \cdot f_{\text{LO}} - 2 \cdot f_{\text{sig}} \tag{14}$$

have still a very large power according to the measurement in Figure 16 (a) which is measured on the existing up-conversion board (Figure 15) using a spectrum analyser. The high power of these frequencies is going to be a problem because ν_{gf} gets driven by higher orders which results in excitation out of the qubit subspace.

To avoid this overlaps one can use the $f_{\text{LO}} - f_{\text{sig}}$ frequency to drive the qubit which leaves a bandwidth of $\Delta\nu = \alpha$ between ν_{gf} and the second harmonic mode. This works only for signal with a narrow bandwidth. A new approach is to use a filter which suppresses higher harmonics of the signal. Measurements with low-pass filters show, without any loss at the main frequencies the harmonic modes can be filtered out as shown in Figure 16 b).

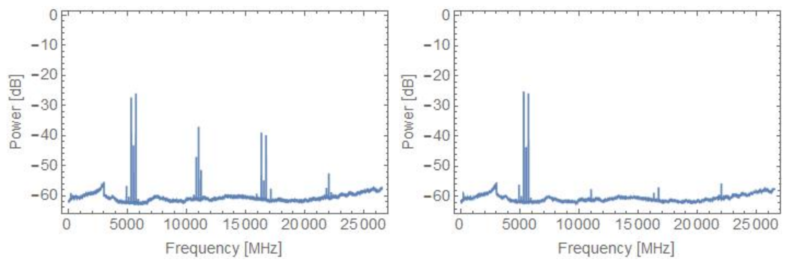


Figure 16: Measurement with a spectrum analyser of a up-conversion board with no filters in a) and a 6.7 GHz low pass filter in b).

6 Switch board

For accurate measurements with a mixer one has to perform a mixer calibration first.

For the conversion board the mixer calibration program is already implemented, where one had to select the channels for the automatic mixer calibration but switch the ports on the switch board manually first. To operate the switch board the program shown in Figure 17 is used. Before starting the mixer calibration the switch board had to be adjusted manually by selecting the port which is connected to the conversion board and the wave generator had to be set to continuous drive. After the calibration all the adjustments had to be reversed to be able to preform measurements on the qubit.

6.1 Automatisation of the switching

To automatise the switching I have assigned the switch ports to a specific channel. For the calibration you now have to choose the channel which is assigned to the port onto which your board is attached. If one would like to change the configuration you can do this by going to *config File* > *RFLineSwitchMixerCalibPaths* > *VALUE* (see Figure 18) where the numbers correspond to the ports and the position to the channel pairs. The default case where the signal is send to the cryostat is in the first place and should always be connected to port 1. The second position stands for the channels 1 & 2, the third for channel 3 & 4 and so on.

In the automatic mixer calibration the ports are chosen corresponding to the selected channel pairs and switch configuration is set to *Continuous Drive/ Mixer Calibration*. After the mixer calibration the settings get set

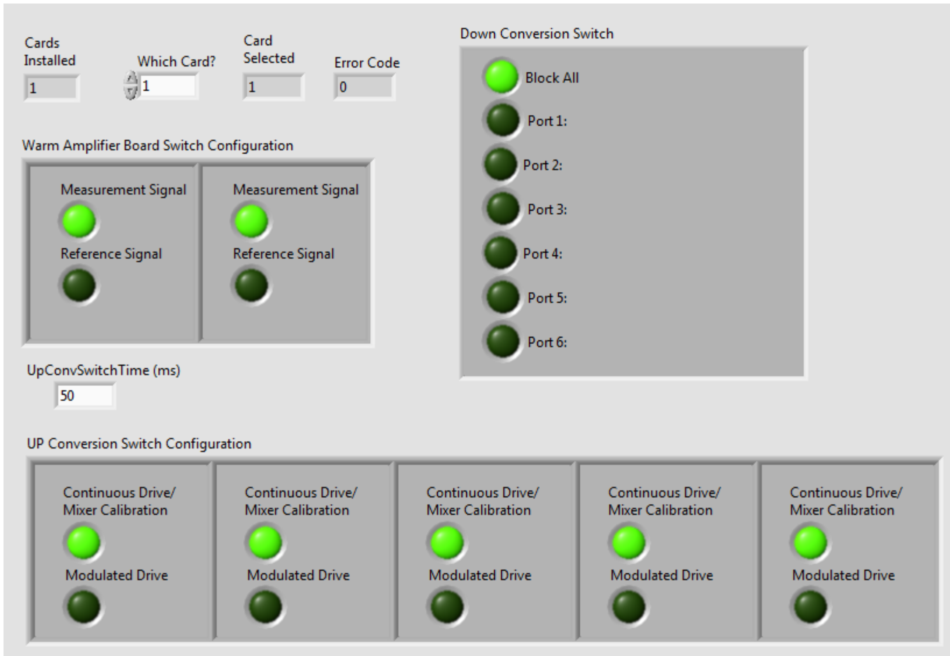
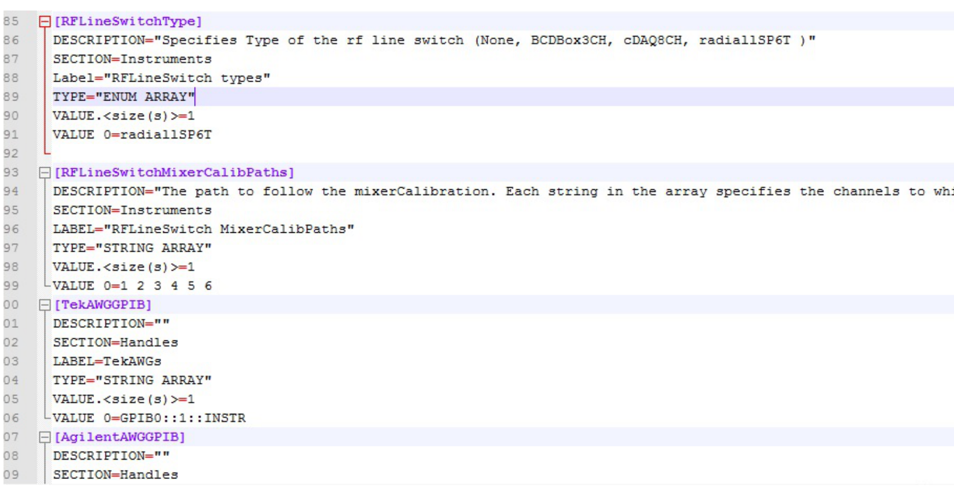


Figure 17: Program of the switch board for changing the port and setting up the mixer calibration.



```
[RFLineSwitchType]
DESCRIPTION="Specifies Type of the rf line switch (None, BCDBox3CH, cDAQ8CH, radiallSP6T )"
SECTION=Instruments
Label="RFLineSwitch types"
TYPE="ENUM ARRAY"
VALUE.<size(s)>=1
VALUE 0=radiallSP6T

[RFLineSwitchMixerCalibPaths]
DESCRIPTION="The path to follow the mixerCalibration. Each string in the array specifies the channels to whi
SECTION=Instruments
LABEL="RFLineSwitch MixerCalibPaths"
TYPE="STRING ARRAY"
VALUE.<size(s)>=1
VALUE 0=1 2 3 4 5 6
[TekAWGGPIB]
DESCRIPTION=""
SECTION=Handles
LABEL=TekAWGs
TYPE="STRING ARRAY"
VALUE.<size(s)>=1
VALUE 0=GPIB0::1::INSTR
[AgilentAWGGPIB]
DESCRIPTION=""
SECTION=Handles
```

Figure 18: Config file with the new switch board implemented.

back to the default state, which is port 1 that is connected to the cryostat and *Modulated Drive* as the switch position.

7 Conclusion

In summary this work on the down-conversion board showed that one has to be aware of higher order effects while working with non-linear devices like mixers. I would recommend a quick calculation of the possible intermodulation frequencies that occur in the detection bandwidth before choosing a pump frequency to see if the bandpass board is sufficient to cancel them out. In the case of the down-conversion the calculation can be done using

$$f_{\mathrm{IF}} = |\mathrm{k} f_{\mathrm{sig}} + \mathrm{l} f_{\mathrm{pump}} + \mathrm{n} f_{\mathrm{LO}}| \tag{15}$$

where k,l,n $= \pm 0, \pm 1, \pm 2, \ldots$. Since the power of the intermodulation frequencies decreases with increasing order one can limit the search to k,l,n < 4. Furthermore, frequencies which are more than 1 GHz away from the signal can easily be filtered out and therefore do not have to be considered. This means $k + l + n = 0$ must hold. For the remaining frequencies with high power one has to ensure that they do not overlap with the signal tone and are far enough away so they can also be filtered out.

The setup I chose in Figure 10 works for a pump tone $>$ 300 MHz from the signal which brings the critical frequency ($f_{\mathrm{pump}} - f_{\mathrm{sig}}$) above 300 MHz where it gets cut of by the LP-250 filter. For pump tones closer to the signal further tests have to be made to make sure the intermodulation frequency is weak enough to be cancelled out by the filter. Also this setup is only optimal for a resonator frequency with a small bandwidth since the filter would suppress the signal asymmetrical. If the signal has a bandwidth of more than 10 MHz one can replace the LP-250 filter with a LP-320 filter which would make the bandpass symmetric around 250 MHz but for the $f_{\mathrm{pump}} - f_{\mathrm{sig}}$ intermodulation to be suppressed f_{pump} has to be at least 375 MHz away from the signal.

For the up-conversion board a low-pass filter is of good use. Since the second harmonics are more than 1 GHz away filters can be added without cutting the signal tone if we want to suppress higher modes. As already shown in Figure 16 b) a 6.7 GHz low pass filter works fine for this task and can easily be installed in the existing up-conversion boards.

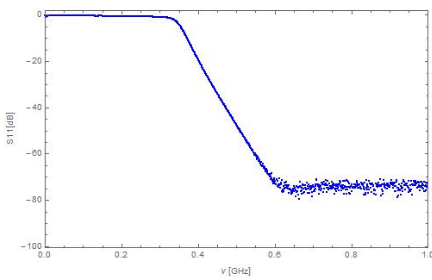
8 Outlook

Since most of the undesired frequencies in the down-conversion process result from the strong pump signal it would be a good approach to filter the pump tone out before it reaches the mixer. The pump tone has to be adjustable since it is used to find the gain of the JPD at the resonator frequency. Furthermore it is close to the signal tone. Therefore, only a well placed filter is able to filter the pump tone while allowing the signal to pass. For this task a tunable bandpass filter would be a good choice. First, one would locate the resonator frequency while the filter is turned off and then once the pump tone is fix the filter can be used to create a bandpass at the exact location of the signal.

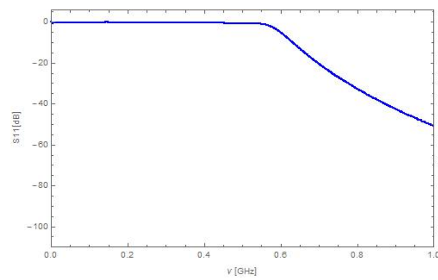
Appendix

A Components

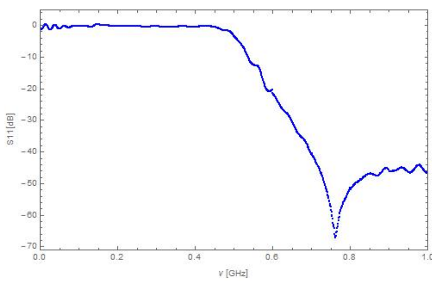
Component	function	manufacturer	Figure
ZX75LP-320-S+	Low pass filter	Minicircuits	19(a)
SLP-550-S+	Low pass filter	Minicircuits	19(b)
ZFLP-450-S+	Low pass filter	Minicircuits	19(c)
SLP-250	Low pass filter	Minicircuits	
SHP-175+	High pass filter	Minicircuits	19(d)
SHP-200+	High pass filter	Minicircuits	19(e)
ZFL-500LN+	Amplifier	Minicircuits	19(f)
Marki IQ-4509MPX	Mixer	Minicircuits	



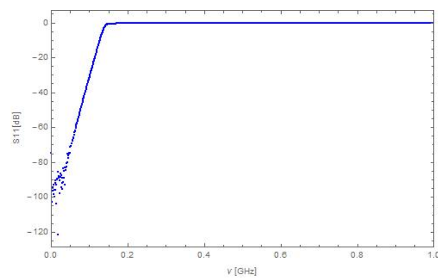
(a) Low-pass filter: ZX75LP-320-S+



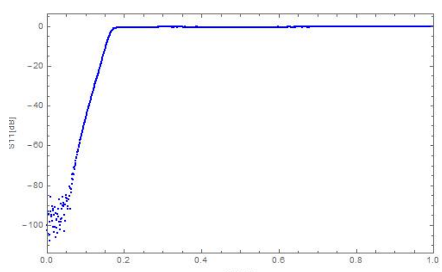
(b) SLP-550-S+



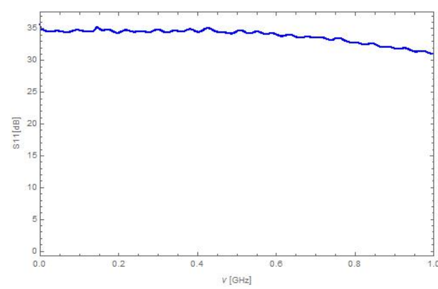
(c) ZFLP-450-S+



(d) High-pass filter: SHP-175+



(e) SHP-200+



(f) Amplifier: ZFL-500LN+

Figure 19: Transmission measurement of the down-conversion board components on a VNA.

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