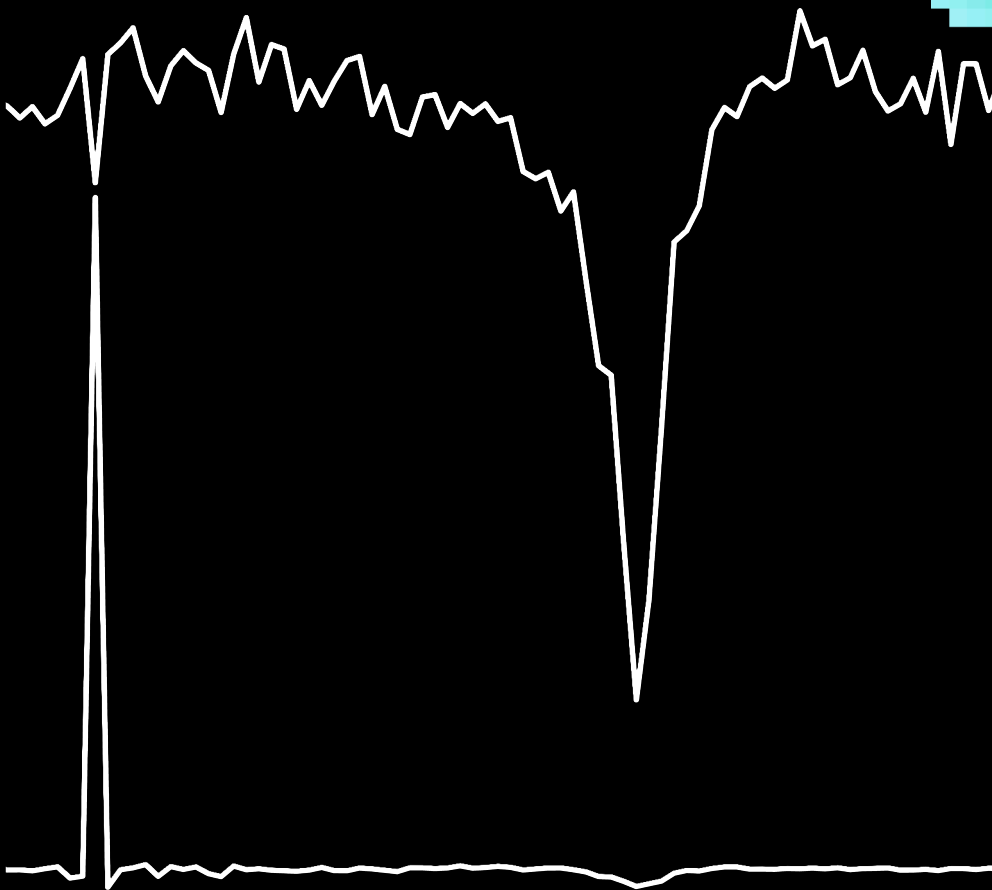
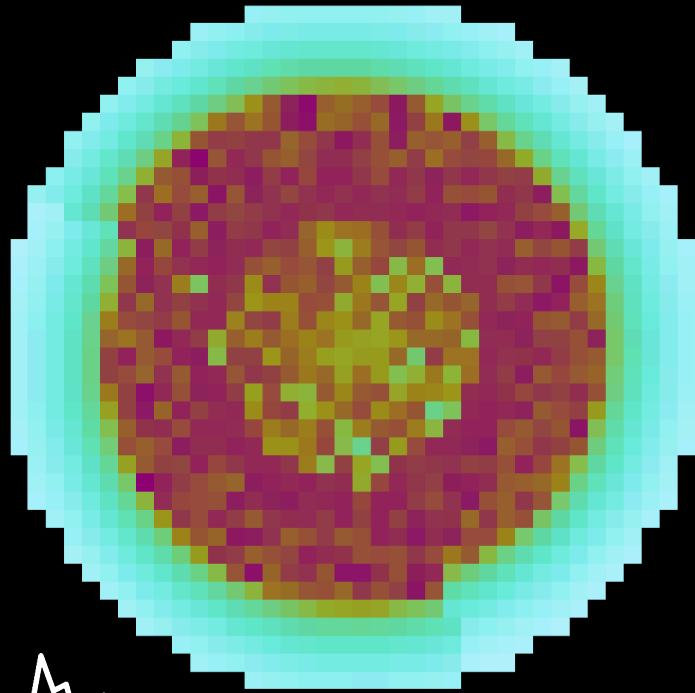


Automated Carrier Cancellation for Quantum Microwave Experiments

Thomas Bosch
Bachelor Thesis



Automated Carrier Cancellation for Quantum Microwave Experiments

by

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Cover:	A before (below) and after (above) cancellation trace of log-scaled amplitude w.r.t. frequency on the bottom left, and a heatmap of the final dB value after cancellation for complex voltage goal values, centered on $0 + 0i$, on the right.
Style:	TU Delft Report Style, with modifications by Daan Zwaneveld and some tweaks by the author

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Abstract

Quantum limited amplification of a weak microwave signal requires that no signals significantly larger in amplitude are present, to avoid saturation of the amplifier. If a large carrier signal is present next to such a small signal, carrier cancellation by way of destructive interference may be utilized to enable amplification. Automation of the process of finding the correct settings of a cancellation device would enable automated measurements at different frequency and power settings of the large signal's source. A general test of the performance both in cancellation depth and convergence speed using the recursive linear interpolation algorithm was performed using both single and double cancellation arms were used to target a complex transmission coefficient using a VNA. The cancellation devices, being controlled digitally, which were used in these experiments were tested before incorporation into the experimental setup and were found to be well-behaved enough to be used in this cancellation experiment. After the general test, the carrier provided by an external pump was successfully cancelled, reducing the carrier amplitude by 69.5 dB. Finally, a test device, a microwave cavity, was used with a carrier close to its resonance in frequency driving it, whilst a VNA was used to probe over a range of frequencies, at a much lower power than the carrier source. Using the recursive linear interpolation algorithm, a cancellation depth of 68 dB was achieved. Further research into the integration of this process with experimental setups may be required to enable incorporation into certain experimental setups, especially focussing on re-establishing an adequate level of cancellation if pump frequency or power drifts are expected to occur.

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1

Introduction

In the SteeleLab, research is being done in order to progress towards bringing a mechanical resonator into a quantum superposition. This mechanical resonator takes the form of a superconductive drum suspended over an indent on a chip, where inside the indent another superconductive plate is present. A diagram of this setup can be seen in figure 1.1.

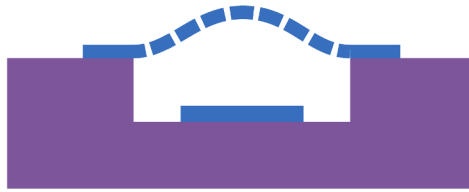


Figure 1.1: A vacuum gap capacitor on a chip. The blue elements are the superconducting drum and plate. Image adapted from [12].

The two conductive plates together form a capacitor. Incorporating this capacitor into an LC circuit can cause the resonance frequency of that circuit to oscillate with the same frequency as the mechanical resonator. A circuit as shown in figure 1.2 will then have a signal, the result of driving an LC circuit with an oscillating capacitance, from the loop on the right coupled back to the left. More information on these types of circuits and their physics can be found in [3].

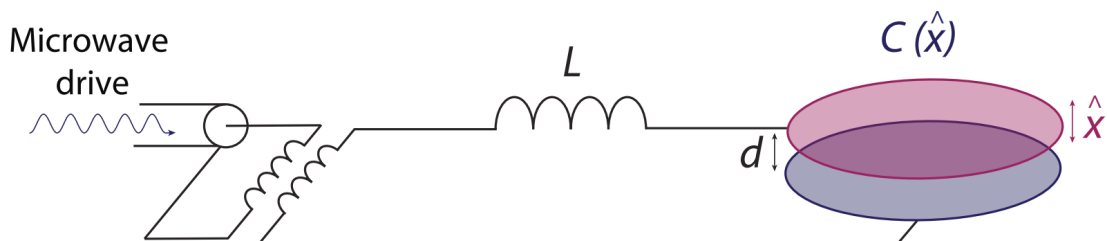


Figure 1.2: An LC circuit with an oscillating capacitance, inductively coupled to a microwave drive. Image taken from [8]

Together, the total signal over the leftmost inductor will be a sum of the microwave drive and the added signal coupled back from the loop on the right. The added signal is usually very small, and thus for the purposes of performing a high-fidelity measurement, it must be amplified to a level where the

signal-to-noise ratio is high. However, amplifiers, such as a SNAIL Parametric Amplifier [4], which introduces very little noise, can get saturated if the signal to be amplified is too strong, at which point the signal coming out will be useless. To avoid saturating the amplifiers then, the removal of the driving signal is needed. This need exists in many more experimental setups, where a system is being driven and produces a weak response. For all these setups where a carrier, i.e. a driving signal, needs to be removed to enable precise measurement, carrier cancellation can be utilized. Carrier cancellation is the principle of having the signal coming out of a device driven by a carrier signal destructively interfere with the original carrier signal. In the example setup in figure 1.2 this carrier signal would be the microwave drive. This technique of carrier cancellation rids the signal of the carrier, leaving only the added signal of interest, which can then be successfully amplified.

Getting the carrier to destructively interfere with itself requires the addition of an extra path for the carrier, which meets the original right before the amplification takes place. This recombination will only result in destructive interference if the two signals are in anti-phase and equal in amplitude. One way to achieve this is by the use of a cancellation device, which attenuates and shifts the phase of the carrier on the added path in the correct manner. Currently in the SteeleLab, in setting up the cancellation line, the correct settings of such a cancellation device are found by turning knobs until the cancellation is successful. For measurements where the driving signal is unchanged through the whole process, this is not that much of a problem. Finding the right settings might take little time, but once found the measurement can be performed. The only problem would then be any drift in attenuation or phase shift due to warming equipment, cables being deformed, etc. This limits measurements to durations shorter than it takes for the cancellation to degrade significantly. However, for measurements where the power of the driving signal being varied, the frequency of the driving signal is being varied, or the response of the driven system is changed by other factors (e.g. the application of a magnetic field), the cancellation device might need readjustment to successfully reestablish carrier cancellation. In such a case, reconfiguring the cancellation device manually every time such a change occurs can dramatically extend the time needed for a measurement, and can occupy a researcher near full time. Therefore, this thesis will explore the possibility of automating this configuration of a cancellation device. The main question to be answered will be whether or not automated cancellation is possible, whilst achieving a cancellation depth of 60 dB or more, a requirement formulated in [6].

First, theory used in this thesis will be covered in chapter 2. Then, a characterization of the cancellation devices used will be given in chapter 3. Then, in chapter 4, four test setups will be used to test the algorithm using only a VNA source, using only an external source, and using both simultaneously. Finally, the results are summarized and a view on future research is presented in chapter 5.

2

Theory

In this chapter, the concept and context of carrier cancellation are sketched as well as the impact of non-idealities within a setup. Furthermore, a description is given of the algorithm that will be used to automate carrier cancellation.

2.1. Mathematical Framework: Rotating Frame and Scattering Matrices

In order to more easily work with the subject of microwave electronics, where complex voltages are omnipresent, this thesis will use phasors to represent voltages instead of (combinations of) trigonometric functions. In addition, a rotating frame of reference (counterclockwise) will be made use of to remove the time dependency of most signals. This means that a signal originally represented as

$$U = U_0 e^{i\omega t + i\phi}$$

comes out as

$$U = U_0 e^{i\phi}$$

Another concept often made use of in this thesis are the S-parameters [7]. In describing components or systems which work at microwave (GHz) frequencies, these complex ratios are often used to characterize the relationships between inputs and outputs of the system. This characterization is given by the scattering matrix S , which relates inputs a_i and outputs b_i of a systems with N ports as

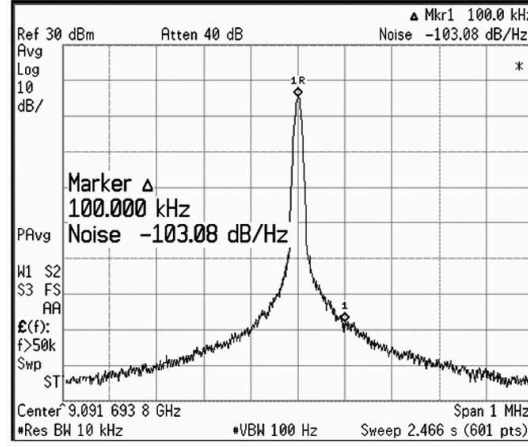
$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1N} \\ S_{21} & S_{22} & \dots & S_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & \dots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix}. \quad (2.1)$$

Measuring these S-parameters is often done using a Vector Network Analyser (VNA). A VNA will compare the signals it measures as a complex voltage at either port to the signals it sends out at either port (in practice, the VNA used in this thesis will only produce an output at a single port). The ratios of these complex numbers are the S-parameters.

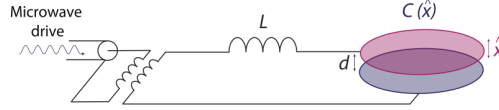
2.2. Necessity, Working Principle and Limitations of Carrier Cancellation

To see why performing carrier cancellation is preferred to using a band-gap filter, consider again the setup shown in figure 1.2. The usage of a band-gap filter to remove the driving signal is made infeasible by the fact that the pump frequency is often close enough to the added frequency that usage of a filter will also suppress that frequency, as well as the fact the pump suffers from phase noise. This phase noise results in a power spectrum where not only the driving frequency is present, but frequencies

close to the driving frequency are also present, as shown in figure 2.1a, this means these frequencies can overlap with the returned frequency. Thus, band-gap filtering also removes pertinent information, and so another method ought to be utilized. This thesis considers the method of the signal coming from the pump being partly funnelled into an attenuator (A_1) and phase shifter (ϕ_1) in order to perform carrier cancellation.



(a)



(b)

Figure 2.1: (a) Frequency spectrum of a pump, showing not only the expected peak but also the unwanted output at other frequencies, taken from [9]. (b) An LC circuit with an oscillating capacitance, inductively coupled to a microwave drive. Image taken from [8].

These components are meant to attenuate the amplitude and shift the phase of the pump signal in such a way that at the measuring input, or in the case of an amplifier being used, at the input of the amplifier, destructive interference of this modified signal with the signal coming from the device will cause only the added response to remain.

The attenuator and phase shifter are, unfortunately, limited in their capabilities. They have a finite accuracy, and this has consequences for the cancellation of the pump signal. Namely, a limited cancellation depth. The cancellation depth is the ratio, expressed in dB, between the original amplitude of the carrier signal (provided by the pump), and the amplitude of that same frequency after adjusting the attenuator and phase shifter to their optimal settings. A simplified visualization of this principle is shown in figure 2.2, where complex voltages are represented as vectors in the complex plane. Here, the blue arrow represents the large pump peak coming from the device, and by the rules of vector addition, the green vector should be added to achieve complete destructive interference. The black arrow represents the closest the system with a single cancellation arm can come. This finite cancellation depth is a consequence of both the finite step size of the attenuator and of the phase shifter. The finite attenuation step size means the length of the black vector will almost certainly be smaller or greater than the green vector. The finite phase shift step size results in the rotational difference between the black and green vectors.

A way of mitigating this problem is to add a second arm containing another phase shifter and attenuator in parallel to the existing arm. This additional arm could then provide an additional vector, bridging (part of) the gap, as shown in figure 2.2. This should, in principle, reduce the residual signal by the same factor as the single arm reduced the original, since the arms are identical. All in all, this two-arm setup can in theory provide double the guaranteed cancellation depth [12], which can be computed using:

$$20 \log \left(\frac{U_{\text{after}}}{U_{\text{before}}} \right) = 10 \log \left(\Delta\phi^2 + \left(\frac{\ln(10)}{20} \Delta(\text{Att.})_{dB} \right) \right), \quad (2.2)$$

where U is a signal amplitude, $\Delta\phi$ is the phase accuracy in radians and $\Delta(\text{Att.})_{dB}$ is the attenuation accuracy in dB.

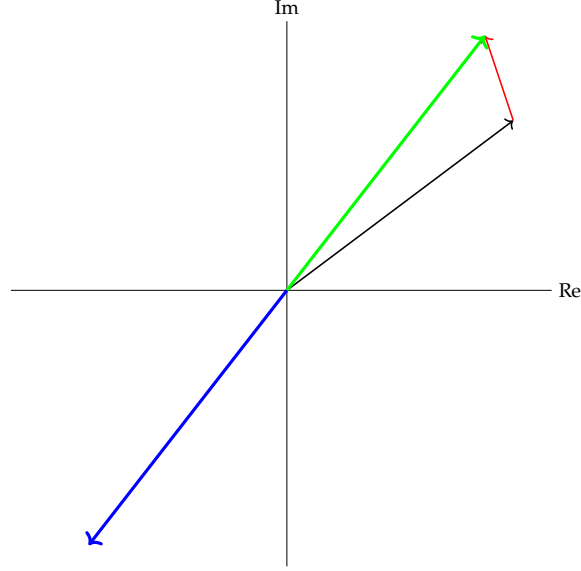


Figure 2.2: A plot of the carrier cancellation principle and limitations in vector form. The blue vector is the one to be cancelled, the green vector is needed to achieve that. The black vector is the result of a single cancellation arm, whilst the red vector is the result of the second arm.

2.3. Algorithmic Automation of Device Adjustments

One way of automating the adjustment a cancellation device would be, using digitally adjustable equipment, to loop through all the settings until the best one is found. However, the knowledge of which set of settings (for phase shifter(s) and attenuator(s)) is best will strictly only be known when all settings have been tried. The digital attenuators and phase shifters in use have 600 and 360 settings each respectively. With the dual-arm setup this would result in $600^2 \cdot 360^2 = 4.67 \cdot 10^{10}$ settings having to be set, measured and stored. Aside from the time it would take (about a year of continuous measurement, assuming each measurement takes a millisecond), it would also take up a considerable amount of storage space if all data was stored. In addition, the best setting found on one setup is likely different on another. Thus, unless a single unchanging setup is to be used for an extended period of time, this seems unworkable.

A better way could be an algorithm, which seeks the minimum signal amplitude at the frequency of the carrier. This algorithm should *require* no previous data, but may benefit from it. Working from the assumption that the output of an arm is locally linear with respect to the settings, both being a complex number, the method of recursive linear interpolation can be used. This method, for a function $y = y(x)$, consists of taking the difference between the x and y values of two points, and interpolate between those points. Then, using that linearization, the expected zero point is calculated. This expected zero point is then used to calculate the next difference, again interpolating and getting the updated expected zero point. Mathematically, it can be stated as:

$$x_{n+1} = x_n - \alpha \frac{x_n - x_n e^{i\theta}}{y_n - y_{n,\theta}} y_n. \quad (2.3)$$

Here, y is a complex number representing the S_{21} parameter measured by the VNA, and $x = 10^{-|A|/20} e^{i\phi}$ is a complex number of which the absolute value is the attenuation setting A converted to a linear scale, and normalized so that a setting of 0 dB results in a magnitude of 1. The phase setting ϕ is retrieved

by calculating the argument of x . The parameter θ is some angle the second point is removed from the first, and α is a dampening factor to prevent oscillatory behaviour. The last step of the method is of a more practical nature, namely converting the newly calculated value of x into an attenuation setting and a phase setting, whilst snapping to the closest discrete value in doing so.

3

Characterization of the Vaunix Devices

Before using any equipment in an experiment, it is generally wise to check its performance. This is done for the same reason parachute manufacturers check the performance of their products: it would be preferable to find any insufficiencies in a controlled environment, and not after reaching terminal velocity towards the earth's surface. In the case of carrier cancellation, the consequences of neglecting the testing of the equipment might not be as severe, but could still have a major impact on the project. Discovering a malfunctioning piece of equipment after two weeks of troubleshooting is much less pleasant than discovering it at the start and taking steps toward mitigation at that time. Furthermore, an analysis of the performance data might reveal any deficiencies not apparent from reading the datasheet, which might impact the performance of the final setup. For this thesis, the attenuator used was the Vaunix LDA-802 [10], and the phase shifter used was the Vaunix LPS-802 [11].

3.1. Measurement Method

The measurement methodology for the attenuator and phase shifter was nearly identical, so they are presented as one, with any differences pointed out. The measurement setup shown in figure 3.1 was used for both devices. The devices were connected with two impedance matched (50Ω) SMA Flex cables, which almost all wires used in setups in this thesis will be. Exceptions will be clearly stated.

The attenuator was set to 0 dB of attenuation, after which a frequency sweep was performed. The frequency sweep consisted of 40 equally spaced frequencies between 4 and 8 GHz for the attenuator. After the frequency sweep, the attenuator was set to the next setting. The next setting for the attenuator was the previous minus one, with the last setting being -60 dB. The phase shifter looped through settings between 0 and 360 degrees, not including 360, with steps of 1° for 11 equally spaced frequencies in the same range of 4–8 GHz. For the purpose of controlling the Vaunix devices as well as controlling the VNA and saving the measurement data, use was made of the `stlab` Python library [1]. The measurement data was saved in a HDF5 [5] formatted file.

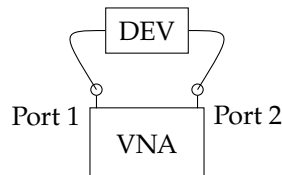


Figure 3.1: Measurement setup for the performance test of Vaunix devices: VNA output port (VNA P1) is connected to the device (DEV), the device output is connected to the VNA input port (VNA P2)

3.2. Results and Discussion

Using the Python programming language in combination with the Data Explorer [2] package as well as the pandas, numpy and matplotlib packages, the data was imported, visualized and analysed.

3.2.1. Attenuator

The measurement results were obtained for the attenuator using the setup described in section 3.1 and pictured in figure 3.2a. Starting with figure 3.2b, the phase of the received signal with respect to the output signal (the argument of S_{21}) is shown. For every frequency, the data is vertically translated so that the plotted points corresponding to a setting of 0 dB end up at a phase shift of 0° . This is done to make the comparison across frequencies and progression with attenuation setting easier to visualize and compare. The result is shown for 5 frequencies, since plotting all 40 traces would render them hard to differentiate. Also shown in figure 3.2b is the "Ideal Device", which represents an attenuator which introduces no phase shift and whose $|S_{21}|$ corresponds perfectly to its setting. A general trend can be discerned where $\angle S_{21}$ tends to increase as the attenuation setting becomes more negative. After an attenuation setting of -45 dB, the trend seems to (partially) reverse for certain frequencies, either going back down until the -60 dB setting or at some point reversing again to an increasing phase.

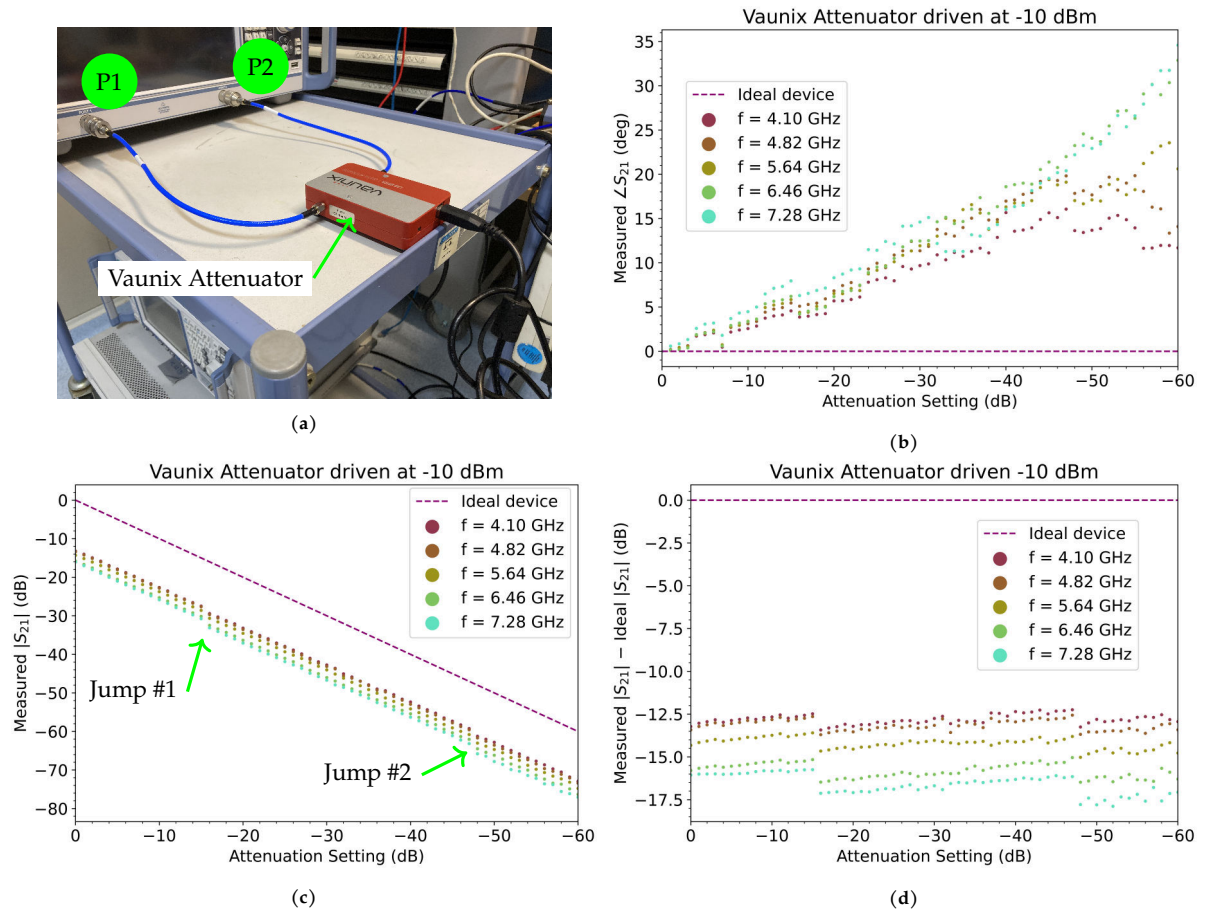


Figure 3.2: (a) A picture of the setup used to characterize the Vaunix attenuator. Both VNA ports and the device itself are identified. (b) The phase of S_{21} with the attenuation setting in dB on the x-axis. Data has been vertically shifted so that the y-value is zero at 0 attenuation setting for every frequency in order to facilitate easy comparison. (c) The $|S_{21}|$ measured by the VNA on the y-axis, and the attenuation setting on the x-axis. Both shown in dB. Two jumps are visible and identified visually. (d) The $|S_{21}|$ measured by the VNA minus the $|S_{21}|$ expected of an ideal attenuator. Two jumps are again visible.

The general trend of increasing phase as the magnitude of the attenuation setting increases in and of itself should not be a large problem for the algorithm, as long as it is close to linear. A larger problem might be the shift towards a downwards slope around -45 dB. Since that is nowhere near linear, the algorithm, assuming (local) linearity, will likely have issues there. Adding a second arm could help remedy this, as it would likely use very heavy attenuation settings if the first arm was already at or

around -45 dB. The fact that the slope will then be flipped should make no difference to the algorithm. The attenuator's $|S_{21}|$ with its attenuation setting is shown in figure 3.2c. Clearly visible is the offset from the "Ideal Device" line. This offset is nearly constant throughout the attenuation settings, as is also visible in figure 3.2d, which shows the difference between the measured $|S_{21}|$ and the ideal $|S_{21}|$ in dB. Next to the offset, two more features are discernible. Most obvious are the two sudden drops, a few dB in size, marked in figure 3.2c. Next is the slow creep towards the ideal device line, making the local slope slightly less than the slope of the ideal device line. The aforementioned sudden drops cause the average (absolute) distance from the datapoints to the ideal line to increase rather than, as might be expected from the difference in slope, decrease.

The offset, roughly equal to the insertion loss given by the datasheet [10], should have no impact on the performance of the algorithm, since it does not require the settings to map closely to the actual attenuation values. As long as the slope does not vary much with attenuation setting, the algorithm should have no issues with it varying, since with (2.3) the slope is recalculated at every step. Therefore, neither the convergence speed nor final cancellation depth will likely be affected. The last because signals needing carrier cancellation are often highly attenuated travelling into and out of the fridge, and therefore the bottleneck for cancellation depth is more likely the limit on the accuracy of the attenuator, rather than the power requirement.

More concerning are the sudden drops, which were not a feature present in the datasheet. They leave a small range of attenuation with no corresponding setting, and therefore, if that attenuation is required for cancellation, the algorithm could be unable to achieve adequate cancellation at least with a single arm. Adding in a second arm may allow the algorithm to compensate the inadequate cancellation so the final result is adequate, but naturally the second arm will run into the same problem if it needs to provide an attenuation unavailable to it.

Overall, S_{21} is likely sufficiently linear with attenuation setting to not form a hindrance to its general performance. The exception being the drops, which make some $|S_{21}|$ values of the attenuator unavailable. Though these do not limit their impact to any algorithm, but rather to the best cancellation possible using the device.

3.2.2. Phase Shifter

The measurement results were obtained for the phase shifter using the setup described in section 3.1 and pictured in figure 3.3a. Starting with figure 3.3b, $|S_{21}|$ is shown with the phase shift setting on the x-axis. The ideal device in this case should introduce no attenuation at any setting, and its $\angle S_{21}$ should perfectly match its setting. The value of $|S_{21}|$ has an offset from the ideal device and increases or decreases at most a few dB over the range of settings, predominantly at the frequencies at the edges of its rating (4–8 GHz), and there exists a difference between the response at 0° and at 390° of a few dB at most. This difference can be seen as a sudden jump at the transition from 359° to 0° , since 360° is equivalent to 0° .

Continuing with $\angle S_{21}$, shown in figure 3.3c with the phase setting on the x-axis, a largely linear response can be observed. The measured phase shift stays close to the ideal response, deviating by less than 6° , as shown in figure 3.3d, where the difference in $\angle S_{21}$ is plotted against the phase setting. The trace at 7.20 GHz deviates the most, by almost 6° . The rest of the deviations don't tend to exceed 2° by much, which, whilst twice as large as the datasheet [11] predicts, is only a small fraction of the total 360° domain. Next to these deviations, all frequencies have, at some phase shift setting, a similarly sized sudden drop of 1° to 2° in $\angle S_{21}$. These have been marked in figure 3.3d. Also for all frequencies, the offset value of $\angle S_{21}$ from the ideal device is different for 0° and 359° . Therefore, the transition from 359° to 0° can as before also be seen as a sudden jump in phase.

The small degree of deviation from the ideal device should prove no significant inhibiting factor to the performance of the algorithm in terms of convergence speed or found minimum, for the same reasons as given in the case of the attenuator. Other than the sudden drop in the case of the attenuator, the drop present in the $\angle S_{21}$ response of the phase shifter causes no $\angle S_{21}$ values to become unavailable. This is because it is a jump downwards, whilst the graph continues to go up afterwards. Thus, the best possible cancellation is not affected by this jump.

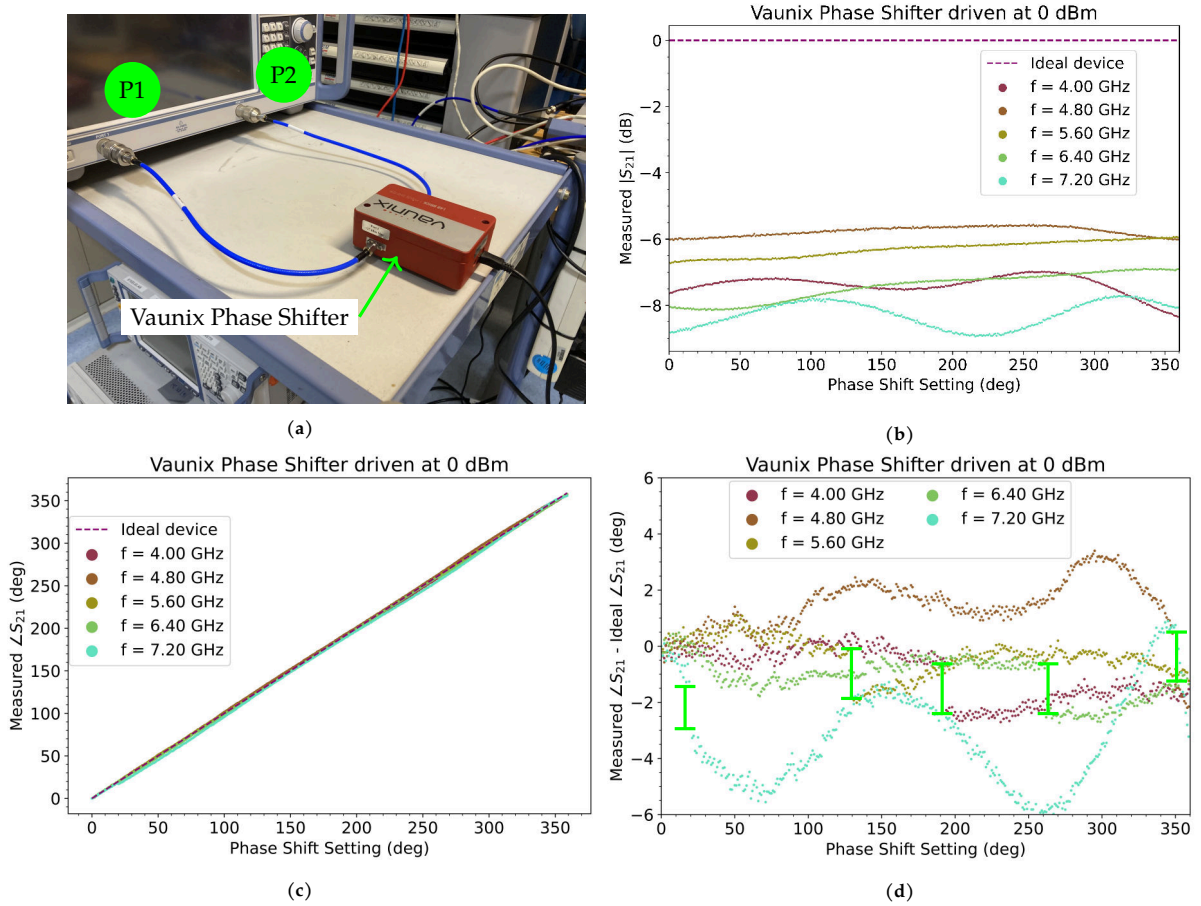


Figure 3.3: (a) A picture of the setup used to characterize the Vaunix Phase Shifter. Both VNA ports and the device itself are identified. (b): The amplitude of S_{21} on the y-axis with the phase shift setting on the x-axis. Also present is a line indicating the ideal device response. (c) The $\angle S_{21}$ value measured by the VNA on the y-axis with the phase setting on the x-axis. Here too, the ideal device line is present. (d) The difference between the measured and ideal $\angle S_{21}$ on the y-axis, with the phase shift setting on the x-axis. Also present are five markers to indicate drop points in the graph.

4

Implementation and Testing of the Recursive Linear Interpolation Algorithm

Since the characterization of the Vaunix devices in chapter 3 revealed no apparent insurmountable obstacles preventing the satisfactory performance of the algorithm, a first step towards use of the algorithm in a measurement setup will be taken. This first step is intended to be the simplest test of the algorithm's performance, and will consist of testing how close the algorithm can get, within 10 steps per arm, to a specific S_{21} value. The usual process of carrier cancellation is in principle exactly this, except the S_{21} value to be reached is the S_{21} value of the carrier, rotated 180° . The performance of the algorithm for a grid of such targets can then be used to determine the maximum S_{21} value the devices and algorithm will be able to cancel, as well as identifying any grid points within those bounds with worse performance compared to their neighbouring grid points. Then, another test is performed where the objective is to cancel the signal from an external source. Finally, the room-temperature setup as described in figure 3.1 is used to see if these devices in combination with this algorithm can be used to cancel carrier signals close in frequency to the resonance frequency of a device, whilst preserving the device's response to the probe signal from the VNA.

4.1. Complex Target Seeking Performance

To start with, a setup using a single cancellation (or, in this case, targeting) arm is used. If this setup reaches an adequate cancellation depth it may also be able to deliver sufficient cancellation incorporated into an experimental setup, thus (partly) eliminating the need for a second arm, thus reducing the time needed by the algorithm to achieve cancellation. Then, another test will be performed with a double arm setup. This test might provide insight into the accuracy of the statement from section 2.2 that two arms can double the cancellation depth.

4.1.1. Single Cancellation Arm Performance

The performance test of a single arm was performed with the setup shown in figure 4.1, where both a diagram and photo are shown. This setup consists of a VNA, the output (Port 1) of which was connected to the attenuator, which was in turn connected to the phase shifter, which was again connected to the VNA measurement port (Port 2). A version of the algorithm was then executed which, instead of targeting zero, targeted the set goal for each gridpoint. It used an initial guess of 0 dB and 0° for the attenuator and phase shifter respectively. The essential parts of the Python code for this algorithm can be found in section A.1 of the appendix.

From the VNA, values for S_{21} are received, and saved for later analysis. This is, however, not the main quantity of interest. That interest lies with the distance from the target vector divided by the length of the target vector, i.e. the cancellation depth, since ultimately it is all about the reduction of the original

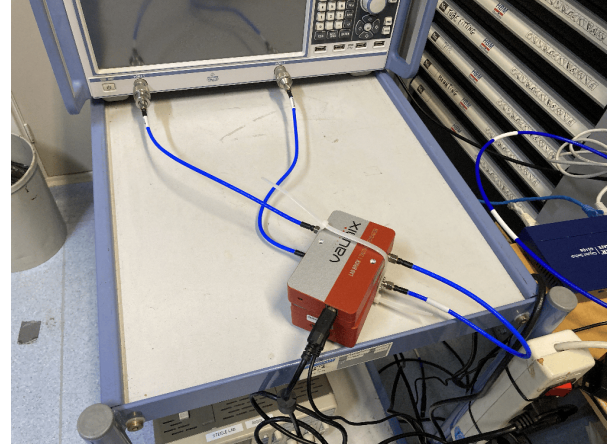
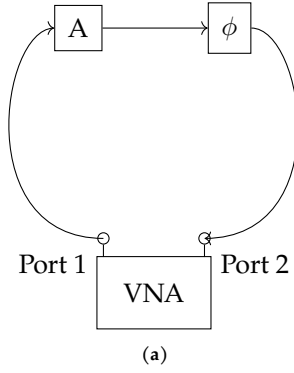


Figure 4.1: A diagram (a) and a picture (b) of the setup used. The signal is passed from port 1 of the VNA, through the attenuator and the phase shifter, and finally arrives at port 2 of the VNA.

signal, which in this case is the target vector. After completion of the algorithm, for every grid point, this quantity of interest was computed and a heatmap was generated, shown in figure 4.2a where the colour of represents the cancellation depth. Additionally, the mean cancellation depth as a function of $|S_{21}|_{\text{goal}}$ is shown in figure 4.2b.

The generated heatmap has several features worth mentioning:

1. There is a clear division between cancellation results at a radius of approximately 0.25, which corresponds to the attenuator's setting of 0 dB.
2. Inside the radius, cancellation depths lower than -30 dB are consistently reached, whilst outside of this radius results do not go below -20 dB.
3. Within the outer radius there exists a ring segment at $|S_{21}|_{\text{goal}} = 0.08$ covering angles 0 to $\frac{3\pi}{2}$ radians, where cancellation values are noticeably worse than the surrounding values. This ring segment corresponds to attenuation settings ranging from -5 dB to -6 dB and phase shift settings ranging from 50° to 300° .
4. The outer radius is not constant, but varies gradually, until suddenly dropping at -0.52 radians, which corresponds to a setting change from 359° to 0° , after which it again starts varying gradually.

Figure 4.2b clearly shows one other feature: within the band on the x-axis where the deepest cancellation is achieved (0.1–0.22) the results have a spread of 10 dB.

The outer radius showing a sharp cut between cancellation depths is probably a result of the decibel scale. Since one would expect the distance from the measured vector to the goal vector to increase linearly as radius increased, whilst the goal vector length also increases in the same manner, this would result in the decibel value being taken of $\frac{x-a}{x} = 1 - \frac{a}{x}$ where x is the vector length and a is the distance at the shift. Taking a logarithm of this expression results in a graph which shows an almost instantaneous increase, after which it remains almost constant.

The consistent achievement of a cancellation depth of -30 dB or better is in agreement with equation 2.2, which gives, for the typical accuracy of the devices as per the datasheets [10, 11], -29 dB of cancellation. The ring segment where cancellation is worse than at neighbouring points does not correspond with the drops shown in figure 3.2. It might be worth investigating whether the accuracy of the phase shifter is worse for the aforementioned frequency range at the input power corresponding to the attenuator being set between -5 dB and -6 dB, or if either device sees an increase in amplitude noise. The drop in outer radius corresponding to the change from setting 359° to 0° is explained by the difference in input attenuation of the phase shifter between those settings, and the attenuator already being set to 0 dB. The linear generation in this case resulted in the highest needed attenuation setting being -12 dB, so

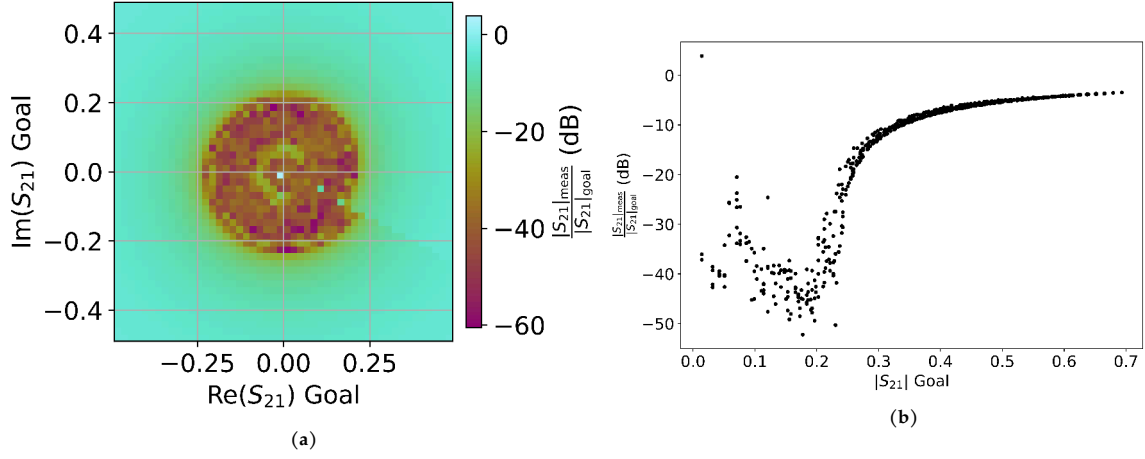


Figure 4.2: (a) A heatmap showing the performance of the one-arm cancellation setup. On the x-axis is the real part, and on the y-axis is the imaginary part, of the complex S_{21} goals. (b) Shows a circular average of the cancellation depth on the y-axis for every radius, shown on the x-axis.

the full range of the attenuator was not explored. If a future measurement of this kind is to be done, consideration might be given to, instead of a grid of uniformly spaced points, the grid being generated by using the logarithm of a uniformly distributed range of radii, and linking each point of it to a number of arguments scaling with its magnitude.

4.1.2. Double Cancellation Arm Performance

To see if the carrier cancellation performance improves upon adding a second arm, one was added to the setup. The second arm was added in parallel to the first, with two power splitters facilitating the splitting and recombining of the arms. The rest of the setup is identical to the single arm version. As with the single-arm version, a version of the algorithm was executed where the single-arm version was executed twice, one time for each arm, for every grid point. During the execution of the algorithm on the first arm, the attenuator of the second arm was set to maximum attenuation. This essential parts of this version of the algorithm can also be found in the appendix, in section A.2.

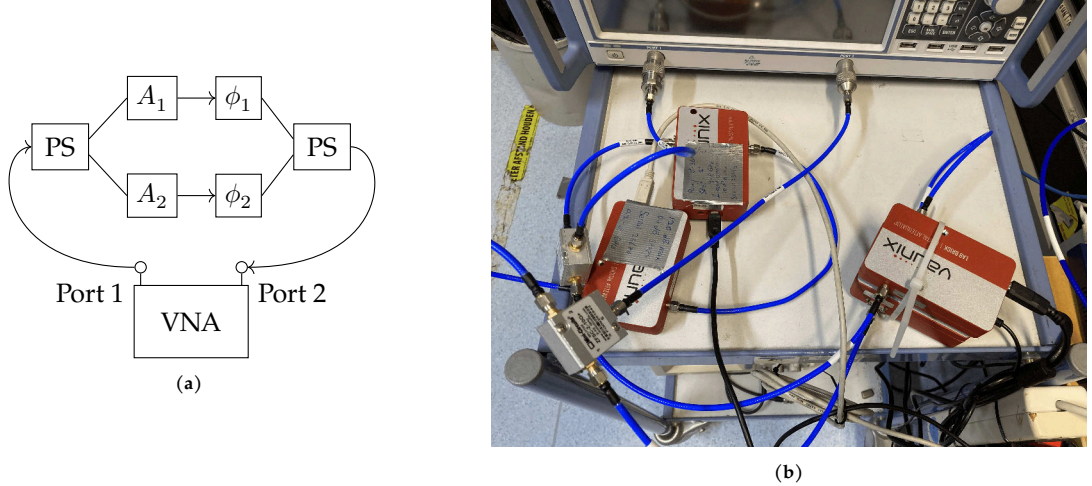


Figure 4.3: A diagram (a) and a picture (b) of the setup used. The output from port 1 of the VNA gets split in two, after which it passes through either arm, both containing an attenuator and a phase shifter. The signals are subsequently recombined in the second power splitter and passed to port 2 of the VNA.

This measurement consisted of a 40×40 grid, but unlike the single-arm grid some values were skipped. This was done to save time, and the radius beyond which no carrier cancellation was attempted was determined by the output of the circuit when both attenuators were set to 0 dB. The maximum number

of steps for each arm was 10, the same as for the single-arm setup. The results of this measurement are displayed in figure 4.4, in the form of a heatmap of cancellation depth for all grid points and a plot of the mean cancellation depth with the amplitude of the goal.

The results show both commonalities and one striking difference compared to the single-arm results. Starting with the commonalities:

1. An outer radius is present, at $|S_{21}| = 0.18$, outside of which the cancellation depth is clearly much shallower (-10 dB to -20 dB) than inside (deeper than -30 dB).
2. A drop in outer radius is present at -1.22 radians, corresponding to the phase setting of 0° of the first arm.

With the difference being that whilst an inner radius of 0.09 can be discerned, it is not, as with the single arm, a ring. Instead, it is a circle, within which cancellation values are consistently worse (between -30 dB and -50 dB) than between the inner and outer radius, where cancellation is consistently at or better than -50 dB.

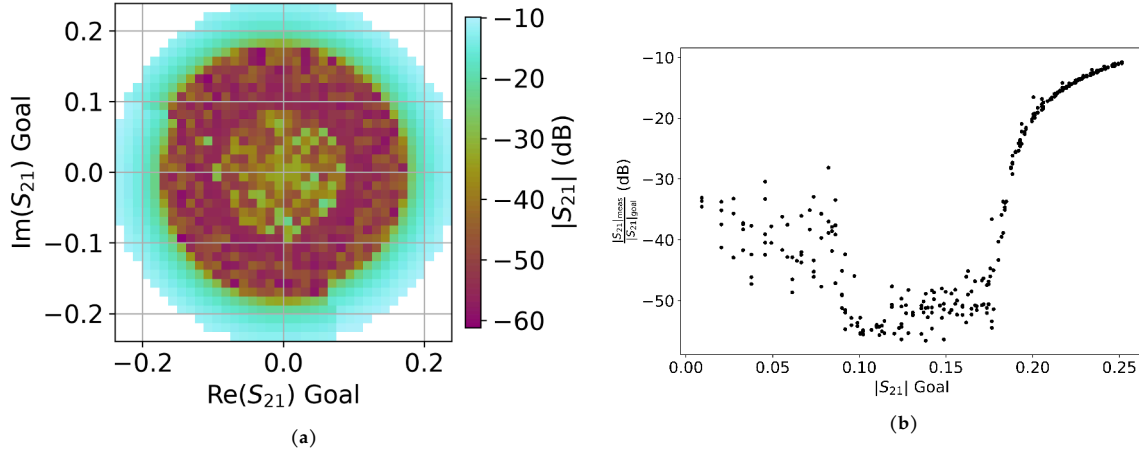


Figure 4.4: (a) A heatmap showing the performance of the two-arm cancellation setup. On the x-axis is the real part, and on the y-axis is the imaginary part, of the complex S_{21} goals. (b) Shows a circular average of the cancellation depth on the y-axis for every radius, shown on the x-axis.

The outer radius being smaller is likely due to the additional attenuation from the power splitters and extra cables. The inner circle where the attenuation is worse than in the outer ring could be due to some device or algorithm limitation, but a more likely explanation might be that, since the VNA was set up to perform quick measurements, the noise in the data is larger there with respect to the goal magnitudes, and thus even if successful cancellation would be achieved, the measured cancellation depth is limited. To resolve this question a repeat measurement could be performed where all VNA measurements are increased in their precision. Then, if the radius of the inner circle shrinks, that would provide support for the latter explanation being correct. Inside the ring between the inner and outer radius, cancellation depths are consistently 10 dB lower than those achieved by the single-arm setup. This is not the doubling of the cancellation depth theorized by [12], but this too might be due to the limited precision of the VNA. Finally, the results overall do not necessarily represent the best possible result one will be able to achieve using the algorithm, because the number of allowed iterations was limited to 10 and the precision of the VNA was limited in favour of faster measurements.

4.2. Cancelling an External Pump Signal

Since in most practical measurement setups an external signal generator, also called a pump, will be used to provide the driving signal, an attempt will be made to cancel such a signal. A diagram and a picture of the setup used to measure the cancellation performance of the algorithm with an external source are shown in figure 4.5. Here, a pump's signal is transferred through a power splitter, a wire, and a second power splitter, to a power spectrum analyser. That first power splitter also sends the signal though the double cancellation arm, and the last power splitter recombines the signal coming

through the wire and cancellation arms. The pump was set at a frequency of 6 GHz and a power of 0 dBm. An initial frequency sweep, with a center frequency of 6 GHz and a span of 3 kHz, was performed where both cancellation arms were set to maximum attenuation, in order to, as much as possible, only measure the signal coming through the wire. The algorithm was run on the first cancellation arm, and after that on the second cancellation arm. The essential code used can be found in section A.3. After running the algorithm for both arms, another frequency sweep, identical to the first, was performed.

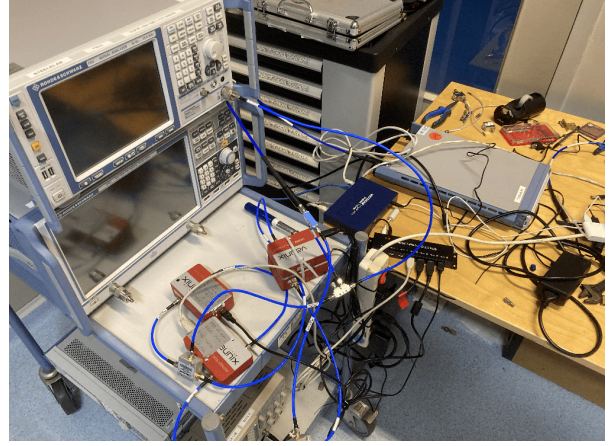
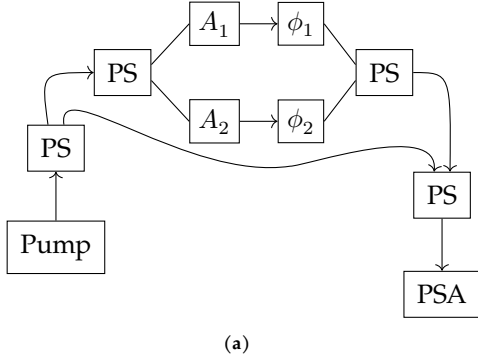


Figure 4.5: A diagram (a) and a picture (b) of the measurement setup used. The pump outputs a signal at 6 GHz which is split between a wire and the two cancellation arms, recombining inside another power splitter. The power spectrum analyser and the pump are synchronized via an extra cable on which a 10 MHz signal is provided by the pump.

Using python, all recorded amplitudes in the sweeps were divided by the maximum value of the initial sweep, thus establishing that peak as 0 dB. Then, both the sweep before and the sweep after running the algorithm were plotted, as shown in figure 4.6. Here, next to the peak, the phase noise of the pump is clearly visible in the before picture around the main peak, decreasing in amplitude with further removal from the peak frequency. The after picture shows a decrease in peak amplitude of -69.5 dB, whilst the phase noise fully disappears. The performance of the algorithm in this experiment was

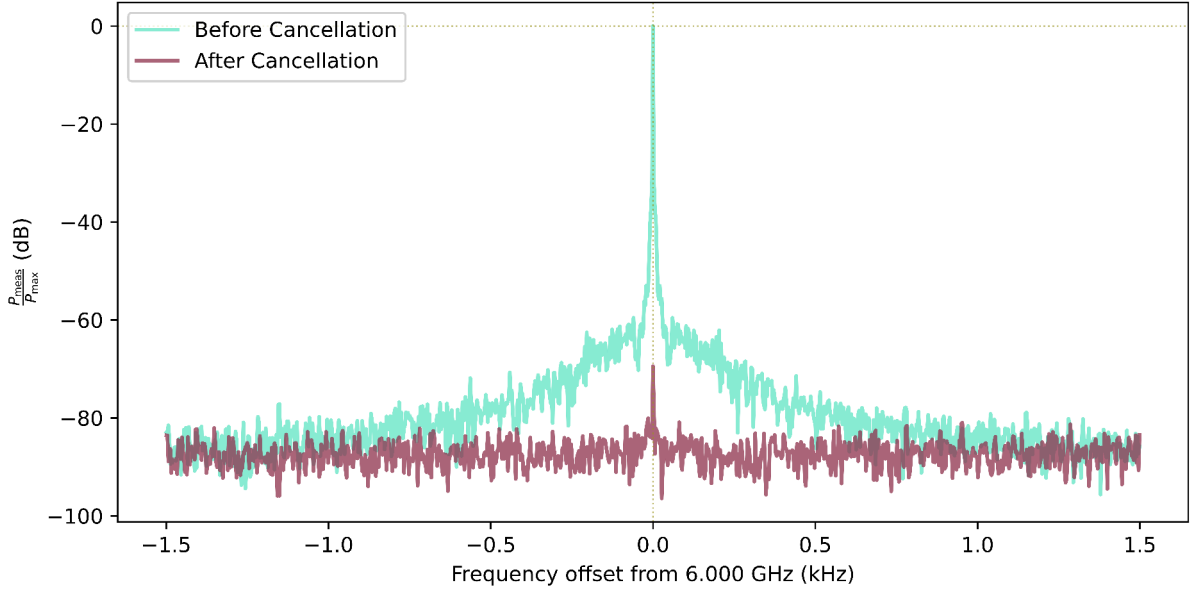


Figure 4.6: The frequency sweep before and after the cancellation algorithm ran. The y-axis shows the fraction of the measured signal compared to the peak height of the first sweep, in order to ease comparison and provide a view of the cancellation depth.

better than one would expect from the results of section 4.1. This could be due to the fact that the

power spectrum analyser measured more precisely than the VNA, since only one run of the algorithm was required, and thus time for a single measurement could be increased. The cancellation of the pump noise provides cause for optimism regarding the applicability of (an adapted version of) this setup in other experiments. An experiment that might be interesting is using this setup to create a map of the performance at different frequencies and powers of the external source. Especially interesting for practical applications might be providing the settings found by the previous run as initial guesses for the next run of the algorithm, and seeing what impact it has on the number of steps required for the convergence of the settings of both cancellation arms. In addition, one might try to establish a minimum for the measurement settings needed to achieve sufficient cancellation, since lower precision corresponds to quicker measurements.

4.3. Driving With a Pump Whilst Probing With a VNA

To see what the effect is of a driving signal, a pump, detuned from the resonance frequency of a device, being cancelled is, a setup using both a VNA to measure and probe and a pump to drive will be used. This setup is shown in figure 4.7, and the algorithm's essential code can be found in section A.4. The setup consists two paths: the first is a pump signal being routed by a directional coupler into a power splitter, through two cancellation arms, through another directional coupler, where it recombines with the signal from the device, into port 2 of a VNA. The second path has two sources: port 1 of the VNA and the other output of the first mentioned directional coupler. These signals combine inside a second directional coupler, whereafter they pass through a device, whose S_{21} as a function of frequency contains a dip at its resonance, thus imitating the behaviour of a setup like shown in figure 1.2 if both plates were fixed. After the device, the signal recombines with the cancellation signal inside the third directional coupler, after which it arrives at port 2 of the VNA. This experiment could provide some insight into the performance of the devices in combination with the algorithm when incorporated into another setup, especially setups where next to a pump used to drive, a VNA is used to probe a device, though actual incorporation would be the only way to be fully sure whether or not the performance is adequate.

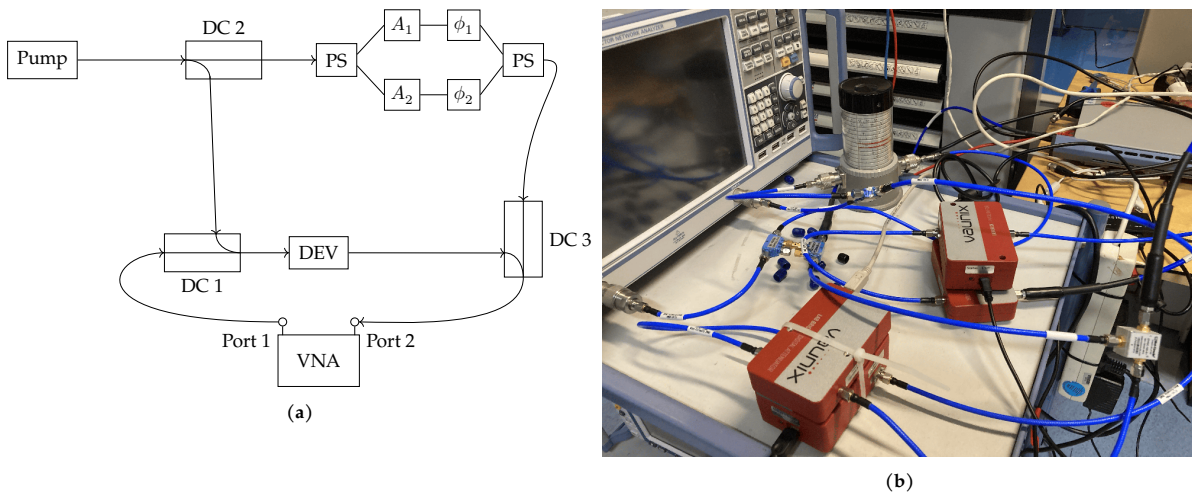


Figure 4.7: A diagram (a) and a picture (b) of the setup used in the experiment. The pump supplies a single frequency, high power signal to the device and the cancellation arm, whilst the VNA sweeps across frequencies, supplying very little power to the device only. Both the cancellation arm and device arm recombine inside the third directional coupler, before reaching port 2 of the VNA.

The procedure with regard to the algorithm is identical to the procedure of section 4.2. The pump power was set to 25 dBm at 6 GHz, and the VNA probe power was set to -30 dBm. A frequency sweep centered on 6 GHz with a span of 700 MHz was performed before and after running the algorithm on both cancellation arms. Comparing the two sweeps, shown in figure 4.8, a cancellation depth of the peak of 68 dB can be observed, whilst no change to the device response is apparent, apart from it appearing to be larger figure 4.8b because of the scaling of the y-axis.

The observed cancellation depth should be sufficient for experiments [6]. Whether the phase noise of

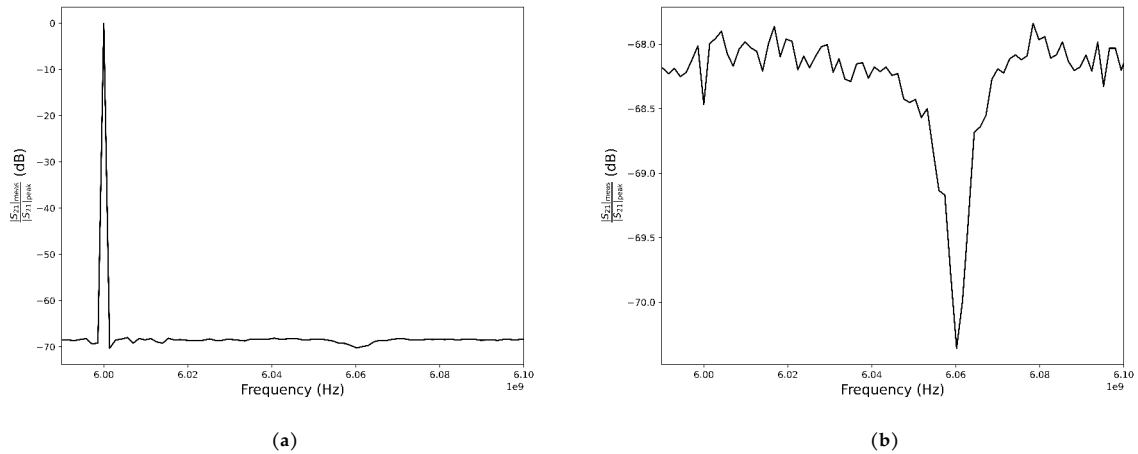


Figure 4.8: (a) Part of the frequency sweep done before running the algorithm. The peak at the pump frequency can be clearly seen, and the device response can be identified at 6.06 GHz. (b) The same part of the frequency sweep, this time after the algorithm had run. The peak at the pump frequency has disappeared, even dipping 0.5 dB below the probe level of -68 dB. The device response can be clearly seen at 6.06 GHz.

the pump was cancelled cannot be observed, since the points are spaced too far apart in this measurement to distinguish it. A future experiment that might be worth doing could be, as in section 4.2, to perform the same test for multiple pump powers and frequencies. This was not done for this thesis because of time constraints. Future experiments will have to determine how well these results translate to the experiments performed both in the SteeleLab and elsewhere, should others find this approach suits their needs. In addition to this, attention should be paid to what happens after the algorithm has finished running. If the phase shift or attenuation level produced by either the device or the cancellation equipment drifts over time, mitigation could be required to keep adequate levels of carrier cancellation. Possible methods to mitigate drift could be the rerunning of the algorithm using the found settings as a starting point, or using another algorithm which is designed to perform well close to a minimum.

5

Summary and Outlook

In this thesis, to enable the high-fidelity amplification of signals next to a respectively large signal close (or overlapping) in frequency, an attempt has been made to automate the process of cancelling a carrier signal by use of digital attenuators and digital phase shifters, whilst achieving a cancellation depth of 60 dB or more. To this end, the S_{21} parameter of the equipment, namely the Vaunix LPS-802 Digital Phase Shifter and the Vaunix LDA-802EH Digital Attenuator, was measured with varying settings of phase shift and attenuation respectively. The result of this measurement revealed no features that would render the automation of carrier cancellation using this equipment an insurmountable challenge. It did reveal several small jumps in the attenuation and phase of S_{21} with the setting of the attenuator and phase shifter respectively. Then, the regressive linear interpolation algorithm was used to target a grid of S_{21} values. This showed that carrier cancellation using two cancellation arms achieved better results than a setup using a single arm, though the limited steps the algorithm was allowed in combination with the limited time allotted to each measurement meant the achieved cancellation values were not necessarily the best achievable.

Subsequently, an experiment was performed where instead of a VNA supplying and measuring the complex voltages, the input was supplied by an external power supply and all measurements were performed using a power spectrum analyser. This experiment used more precise measurements, and was able to achieve a cancellation depth of 69.5 dB whilst also cancelling the phase noise of the pump. Lastly, an experiment was done where an external pump was used to supply a voltage at a frequency close to the resonance frequency of a device to that device, which was then probed by a VNA. Here, the two cancellation arms managed to achieve a cancellation depth of 68 dB, whilst the VNA was still able to measure the response of the device.

Future research could focus on answering questions about the performance of the algorithm at different pump frequencies or powers than those used in the last two experiments, as well as the integration of the algorithm into an experiment in a cryogenic environment. Another line of research could be on strategies to, once sufficient cancellation has been achieved, keep the cancellation from getting worse due to drifting of attenuation or phase shift in any equipment or devices.

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Algorithm Pseudocode

A.1. Single Arm Target Seeking

```
1 import numpy as np
2
3 def complex_to_settings(complex_setting: complex):
4     '''Returns a tuple of attenuator and phase shifter settings from a complex settings
5     phasor'''
6     return 20 * np.log10(np.abs(complex_setting)), np.rad2deg(np.angle(setting))
7
8 def measure_s21(complex_setting: complex):
9     '''Returns the s21 value as if a signal to be cancelled (goal) was present'''
10    attenuator_setting, phase_setting = complex_to_settings(complex_setting)
11
12    attenuator.set_attenuation(attenuator_setting)
13    phase_shifter.set_phase_shift(phase_setting)
14
15    measured_s21 = vna.measure_s21()
16    return measured_s21 - goal # If it were to return the actual S21 value all of the grid
17                               # would be the attenuator going to -60 dB, which would be useless
18
19 def find_next_setting(previous_complex_setting: complex, previous_s21: complex, alpha: float
20                       = 0.8, theta: float = 90):
21     '''Uses the previous setting and s21 resulting from it to find the next setting'''
22     rotated_test_setting = previous_complex_setting * np.exp(1j * theta)
23     rotated_test_s21 = measure_s21(rotated_test_setting)
24     new_settings = previous_complex_setting - alpha * previous_s21 * (
25         previous_complex_setting - rotated_test_setting) / (previous_s21 - rotated_test_s21)
26     return new_settings
27
28 attenuator_stepsize_decibel = 0.1
29 phase_shift_stepsize_degree = 1
30 max_iterations = 10
31
32 grid_size = 0.5
33 grid_points_number_per_axis = 50
34 gridpoints_1D = np.linspace(-grid_size/2, grid_size/2, grid_points_number_per_axis)
35 real, imag = np.meshgrid(gridpoints_1D, gridpoints_1D)
36
37 for re in real:
38     for im in imag:
39         goal = re + 1j * im
40         current_complex_setting = 0 + 0j # Initial guess
41         current_s21 = measure_s21(current_complex_setting)
42
43         for _ in range(max_iterations):
44             next_complex_setting = find_next_setting(current_complex_setting, current_s21)
45             next_s21 = measure_s21(next_complex_setting)
```

```

42
43     next_attenuator_setting_decibel, next_phase_setting_degree = complex_to_settings(
44         next_complex_setting)
45     current_attenuator_setting_decibel, current_phase_setting_degree =
46         complex_to_settings(current_complex_setting)
47
48     # If the step the algorithm wants to take is less than the stepsize for both the
49     # attenuator and phase shifter, save the result and stop.
50     if (np.abs(next_attenuator_setting_decibel - current_attenuator_setting_decibel)
51         < attenuator_stepsize_decibel
52         or np.abs(next_phase_setting_degree - current_phase_setting_degree) <
53             phase_shift_stepsize_degree):
54         save_data(goal, current_complex_setting, current_s21)
55         break
56
57     current_complex_setting = next_complex_setting
58     current_s21 = next_s21

```

A.2. Double Arm Target Seeking

```

1 import numpy as np
2
3 def complex_to_settings(complex_setting: complex):
4     '''Returns a tuple of attenuator and phase shifter settings from a complex settings
5     phasor'''
6     return 20 * np.log10(np.abs(complex_setting)), np.rad2deg(np.angle(setting))
7
8 def measure_s21(complex_setting: complex, arm: int = 0):
9     '''Returns the s21 value as if a signal to be cancelled (goal) was present'''
10    attenuator_setting, phase_setting = complex_to_settings(complex_setting)
11    if not arm:
12        attenuator_0.set_attenuation(attenuator_setting)
13        phase_shifter_0.set_phase_shift(phase_setting)
14    else:
15        attenuator_1.set_attenuation(attenuator_setting)
16        phase_shifter_1.set_phase_shift(phase_setting)
17    measured_s21 = vna.measure_s21()
18    return measured_s21 - goal # If it were to return the actual S21 value all of the grid
19    would be the attenuator going to -60 dB, which would be useless
20
21 def find_next_setting(previous_complex_setting: complex, previous_s21: complex, alpha: float
22    = 0.8, theta: float = 90):
23    '''Uses the previous setting and s21 resulting from it to find the next setting'''
24    rotated_test_setting = previous_complex_setting * np.exp(1j * theta)
25    rotated_test_s21 = measure_s21(rotated_test_setting)
26    new_settings = previous_complex_setting - alpha * previous_s21 * (
27        previous_complex_setting - rotated_test_setting) / (previous_s21 - rotated_test_s21)
28    return new_settings
29
30 attenuator_stepsize_decibel = 0.1
31 phase_shift_stepsize_degree = 1
32 max_iterations = 10
33
34 grid_size = 0.5
35 grid_points_number_per_axis = 50
36 gridpoints_1D = np.linspace(-grid_size/2, grid_size/2, grid_points_number_per_axis)
37 real, imag = np.meshgrid(gridpoints_1D, gridpoints_1D)
38
39 for re in real:
40     for im in imag:
41         goal = re + 1j * im
42         current_complex_setting = 0 + 0j # Initial guess
43         current_s21 = measure_s21(current_complex_setting)
44         for arm in range(2):
45             for _ in range(max_iterations):
46                 next_complex_setting = find_next_setting(current_complex_setting, current_s21

```

```

    )
    next_s21 = measure_s21(next_complex_setting, arm)
    next_attenuator_setting_decibel, next_phase_setting_degree =
        complex_to_settings(next_complex_setting)
    current_attenuator_setting_decibel, current_phase_setting_degree =
        complex_to_settings(current_complex_setting)

    # If the step the algorithm wants to take is less than the stepsize for both
    # the attenuator and phase shifter, save the result and stop.
    if (np.abs(next_attenuator_setting_decibel -
        current_attenuator_setting_decibel) < attenuator_stepsize_decibel
        or np.abs(next_phase_setting_degree - current_phase_setting_degree) <
        phase_shift_stepsize_degree):
        save_data(goal, current_complex_setting, current_s21)
        break

    current_complex_setting = next_complex_setting
    current_s21 = next_s21

```

A.3. External Pump Cancellation

```

1 import numpy as np
2
3 def complex_to_settings(complex_setting: complex):
4     '''Returns a tuple of attenuator and phase shifter settings from a complex settings
5     phasor'''
6     return 20 * np.log10(np.abs(complex_setting)), np.rad2deg(np.angle(setting))
7
8 def measure_complex_voltage(complex_setting: complex, arm: int = 0):
9     '''Returns the complex voltage value as if a signal to be cancelled (goal) was present'''
10    attenuator_setting, phase_setting = complex_to_settings(complex_setting)
11    if not arm:
12        attenuator_0.set_attenuation(attenuator_setting)
13        phase_shifter_0.set_phase_shift(phase_setting)
14    else:
15        attenuator_1.set_attenuation(attenuator_setting)
16        phase_shifter_1.set_phase_shift(phase_setting)
17    measured_complex_voltage = psa.measure_complex_voltage()
18    return measured_complex_voltage
19
20 def find_next_setting(previous_complex_setting: complex, previous_complex_voltage: complex,
21     alpha: float = 0.8, theta: float = 90):
22     '''Uses the previous setting and complex voltage resulting from it to find the next
23     setting'''
24     rotated_test_setting = previous_complex_setting * np.exp(1j * theta)
25     rotated_test_complex_voltage = measure_complex_voltage(rotated_test_setting)
26     new_settings = previous_complex_setting - alpha * previous_complex_voltage * (
27         previous_complex_setting - rotated_test_setting) / (previous_complex_voltage -
28         rotated_test_complex_voltage)
29     return new_settings
30
31 attenuator_stepsize_decibel = 0.1
32 phase_shift_stepsize_degree = 1
33 max_iterations = 100
34
35 current_complex_setting = 0 + 0j # Initial guess
36 current_complex_voltage = measure_complex_voltage(current_complex_setting)
37 for arm in range(2):
38     for _ in range(max_iterations):
39         next_complex_setting = find_next_setting(current_complex_setting,
40             current_complex_voltage)
41         next_complex_voltage = measure_complex_voltage(next_complex_setting, arm)
42
43         next_attenuator_setting_decibel, next_phase_setting_degree = complex_to_settings(
44             next_complex_setting)

```

```

38     current_attenuator_setting_decibel, current_phase_setting_degree =
        complex_to_settings(current_complex_setting)
39
40     # If the step the algorithm wants to take is less than the stepsize for both the
        attenuator and phase shifter, save the result and stop.
41     if (np.abs(next_attenuator_setting_decibel - current_attenuator_setting_decibel) <
        attenuator_stepsize_decibel
42         or np.abs(next_phase_setting_degree - current_phase_setting_degree) <
        phase_shift_stepsize_degree):
43         save_data(goal, current_complex_setting, current_complex_voltage)
44         break
45
46     current_complex_setting = next_complex_setting
47     current_complex_voltage = next_complex_voltage

```

A.4. Pump Drive VNA Probe

```

1  import numpy as np
2
3  def complex_to_settings(complex_setting: complex):
4      '''Returns a tuple of attenuator and phase shifter settings from a complex settings
        phasor'''
5      return 20 * np.log10(np.abs(complex_setting)), np.rad2deg(np.angle(setting))
6
7  def measure_s21(complex_setting: complex, arm: int = 0):
8      '''Returns the s21 value as if a signal to be cancelled (goal) was present'''
9      attenuator_setting, phase_setting = complex_to_settings(complex_setting)
10     if not arm:
11         attenuator_0.set_attenuation(attenuator_setting)
12         phase_shifter_0.set_phase_shift(phase_setting)
13     else:
14         attenuator_1.set_attenuation(attenuator_setting)
15         phase_shifter_1.set_phase_shift(phase_setting)
16     measured_s21 = vna.measure_s21()
17     return measured_s21 - goal # If it were to return the actual S21 value all of the grid
        would be the attenuator going to -60 dB, which would be useless
18
19 def find_next_setting(previous_complex_setting: complex, previous_s21: complex, alpha: float
    = 0.8, theta: float = 90):
20     '''Uses the previous setting and s21 resulting from it to find the next setting'''
21     rotated_test_setting = previous_complex_setting * np.exp(1j * theta)
22     rotated_test_s21 = measure_s21(rotated_test_setting)
23     new_settings = previous_complex_setting - alpha * previous_s21 * (
        previous_complex_setting - rotated_test_setting) / (previous_s21 - rotated_test_s21)
24     return new_settings
25
26 attenuator_stepsize_decibel = 0.1
27 phase_shift_stepsize_degree = 1
28 max_iterations = 100
29
30 current_complex_setting = 0 + 0j # Initial guess
31 current_s21 = measure_s21(current_complex_setting)
32 for arm in range(2):
33     for _ in range(max_iterations):
34         next_complex_setting = find_next_setting(current_complex_setting, current_s21)
35         next_s21 = measure_s21(next_complex_setting, arm)
36
37         next_attenuator_setting_decibel, next_phase_setting_degree = complex_to_settings(
            next_complex_setting)
38         current_attenuator_setting_decibel, current_phase_setting_degree =
            complex_to_settings(current_complex_setting)
39
40         # If the step the algorithm wants to take is less than the stepsize for both the
            attenuator and phase shifter, save the result and stop.
41         if (np.abs(next_attenuator_setting_decibel - current_attenuator_setting_decibel) <
            attenuator_stepsize_decibel

```

```
42         or np.abs(next_phase_setting_degree - current_phase_setting_degree) <
           phase_shift_stepsize_degree):
43         save_data(goal, current_complex_setting, current_s21)
44         break
45
46     current_complex_setting = next_complex_setting
47     current_s21 = next_s21
```