User's Manual QuTech Duplexer

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Contents

Introduction

Currently, each microwave qubit requires dedicated and expensive peripheral equipment (e.g., microwave source, arbitrary waveform generators, I/Q-mixers, etc.). In the near future, as the number of qubits in quantum processors continues to increase, this will translate into a linear increase in cost, physical space, power consumption and calibration time. In the longer term, as scaling the number of qubits to hundreds or thousands, it may even become impossible to use a dedicated peripheral setup for each qubit.

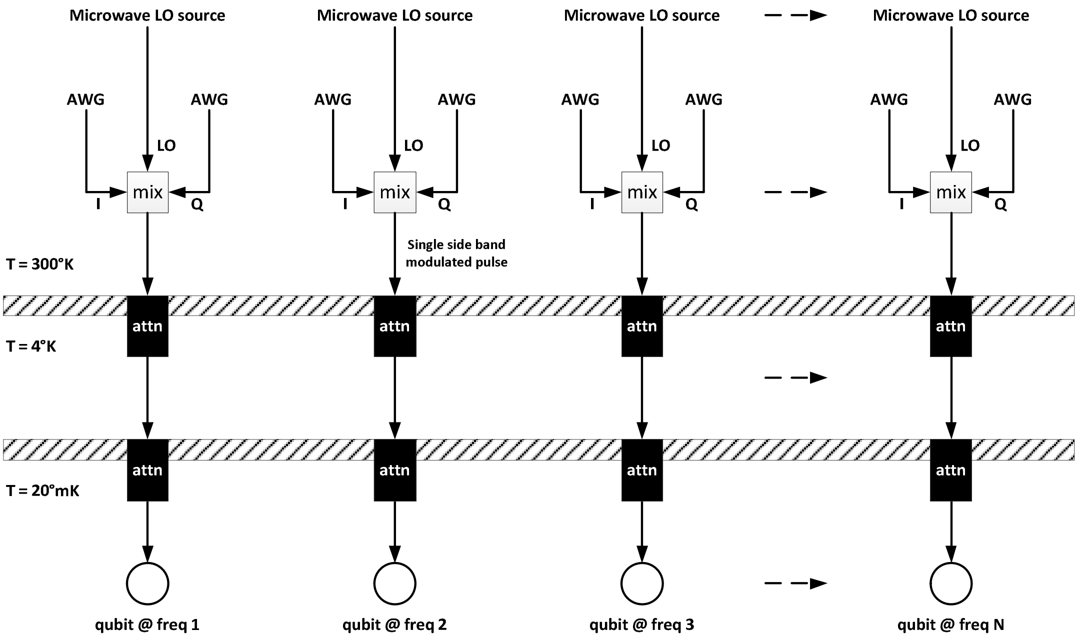

Figure 1: "Traditional" method for applying microwave pulses to perform operations on qubits. Each qubit (1 to N) is controlled with dedicated peripheral equipment.

To reduce the amount of peripheral equipment required we introduced the concepts of multiplexing and qubit frequency reuse, where one peripheral setup can be used to control multiple qubits at identical frequencies. This Duplexer (because of two outputs) is an example of what we generalized to **Microwave Vector Switch Matrix** and can be used to address two qubits with one AWG + RF-source setup or four qubits with two AWGs + two RF-sources. Both a reduction of a factor two compared to the traditional setup required.

Connecting the duplexer

First mechanically mount the duplexer by means of the grid of M3 screwing holes at the bottom side. Connect the dedicated mains power supply (laptop style type labeled with QuTech Duplexer) and the Ethernet cable to a local network switch/router. Connect the four SMA-SMA cables from the I/Q-mixers to the input ports of the duplexer and connect the two RF-output ports of the duplexer to the lines going into the fridge.

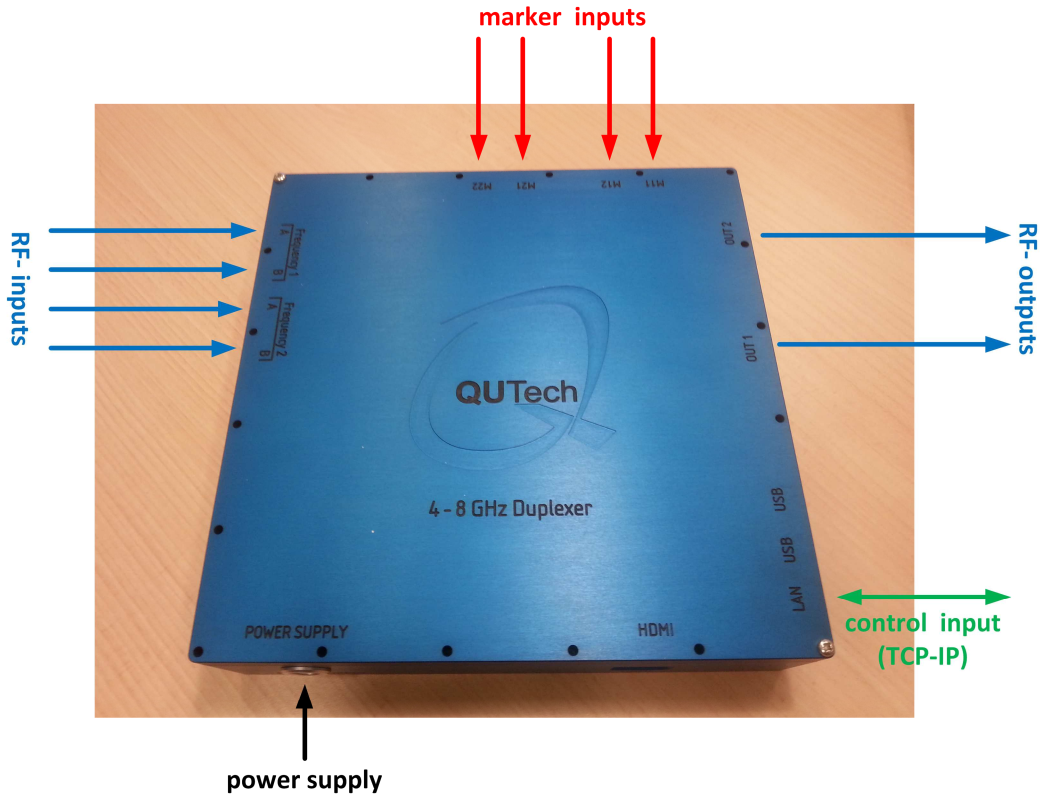

Figure 2 duplexer with the ports that are essential to connect (USB and HDMI are not essential).

Boot sequence

After plugging in the power cable of the adapter the duplexer will boot. After a max. 1 minute boot sequence the LEDs will flash when the daemon is up and running. You can now connect to it over TCP-IP, open the socket and send SCPI-command strings to the device. (This will be described in detail at the software control commands chapter)

Power down

Warning: Just unplugging the power cable might result in a corrupt SD-card image of the Linux OS (this is an open issue to be fixed in a next version firmware).

A better way to power down is to open a remote SSH-shell, login and perform a shutdown.

> sudo shutdown –h now

After a while the SSH connection gets lost and you can unplug the power cable without causing damage.

Software TCP-IP control

The duplexer has a lightweight Linux OS inside (Raspbian) which can be connected to in two ways: remote shell (SSH) and SCPI (Virtual GPIB port).The remote shell interface can be used to give commands actually **ON** the duplexer. The SCPI interface is a daemon running on the duplexer listening to command strings received over TCP-IP.

SSH-Remote shell connection

You can use a program like PuTTY to open a remote shell connection to the duplexer.

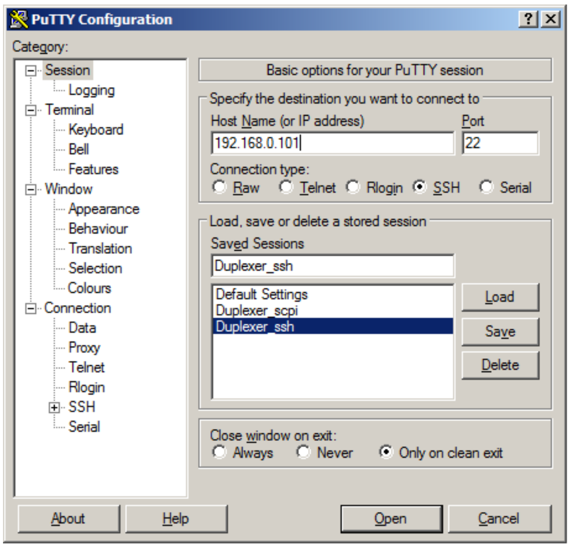

Figure 3 PuTTY program for SSH connection to Duplexer.

If you now press the PuTTY load button you will get a logon screen.

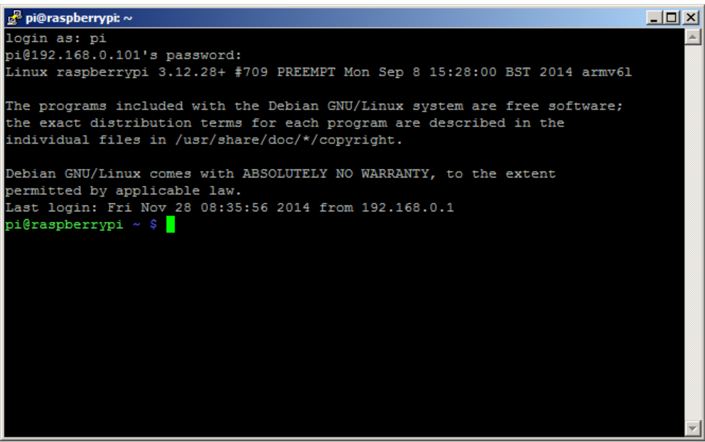

Figure 4 Remote logon (username = pi, password = raspberry).

You can now enter any Linux command. For a proper shutdown enter a **sudo shutdown –h now** command.

SCPI-Commands (manually entering at the command line)

When an SSH connection has been established you have access to the Duplexer Linux command shell. To enter the SCPI-commands to change the duplexer settings locally you can use the program **netcat**. Enter the following command at the shell:

≫ nc 127.0.0.1 5025

Now you can type the SCPI commands (explained later) at the command prompt.

This functionality is extremely useful if a keyboard and monitor are connected to the Duplexer.

SCPI-Commands (sending over Ethernet)

A more advanced way of duplexer control is to send SCPI commands over Ethernet (open port 5025 at the IP-address specified with a label on the duplexer).

Implemented command strings are:

- *IDN? (responds with the Duplexer serial number and software version)
- ch:in1:out2:att:raw 65535 (Attenuator DAC-value 0..65535 for input 1 to output 2)
- ch:in4:out1:ph:raw 65535 (Phase DAC-value 0..65535 for input 4 to output 1)
- ch:in3:out2:sw on (Turn RF-switch on for in3 to out2 connection.)
    - Valid options for the switch are: 'off', 'on' and 'ext'.

Wrapper functions have been written in Python (QT-lab) to send these commands over a TCP-IP connection to the Duplexer. A Python based duplexer object can be instantiated, which has high level functions for operations.

Qt-Lab (Python) driver

A wrapper/driver has been written in Python (Qt-lab) to send the SCPI-commands by means of high level functions.

Summary of system specifications

Block diagram

The Duplexer is a 4 to 2 Microwave Vector Switch Matrix is can functionally be described by:

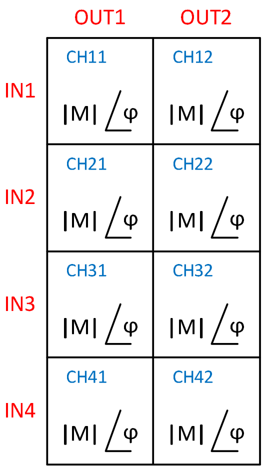

Figure 5 The microwave vector switch matrix of the duplexer. Four inputs can connect to two outputs with a programmable Magnitude (|M|) and Phase (φ)

Each of the inputs can get connectivity to each output, with a programmable magnitude *(switch for on/off + logarithmic attenuator for amplitude calibration)* and a programmable phase *(phase shifter for I/Q phase calibration)*. So each cell of the matrix has a complex number in polar form and the signal path of one of these cells is:

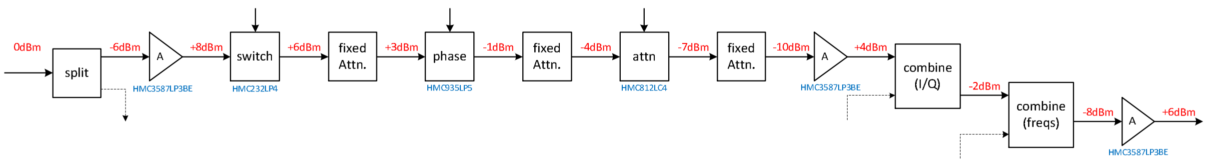

Figure 6 Signal path of one cell (channel) of the duplexer. Eight of these paths have been implemented.

In the signal path the input signal is first split (for the left OR right column of the matrix) then:

- Amplified
- Switched on/off
- Phase shifted (programmable phase)
- Attenuated (programmable magnitude)
- Amplified (mainly for channel isolation but also to compensate for insertion loss)
- Combined (channel 1 + 2 which are I/Q and 3 + 4 which are I/Q)
- Combined((1+2) + (3+4))
- Amplified (to compensate for total insertion loss)

At the output the four rows of a column are combined to one output. In between the components are 3dB attenuators to isolate parameter co-influence *(e.g. if S22 of the phase shifter is a function of its phase setting then the Attenuator "sees a phase dependent source" which influences it's attenuation.)* To keep a better orthogonal parameter control the chip reflections are "shielded" using these attenuators.

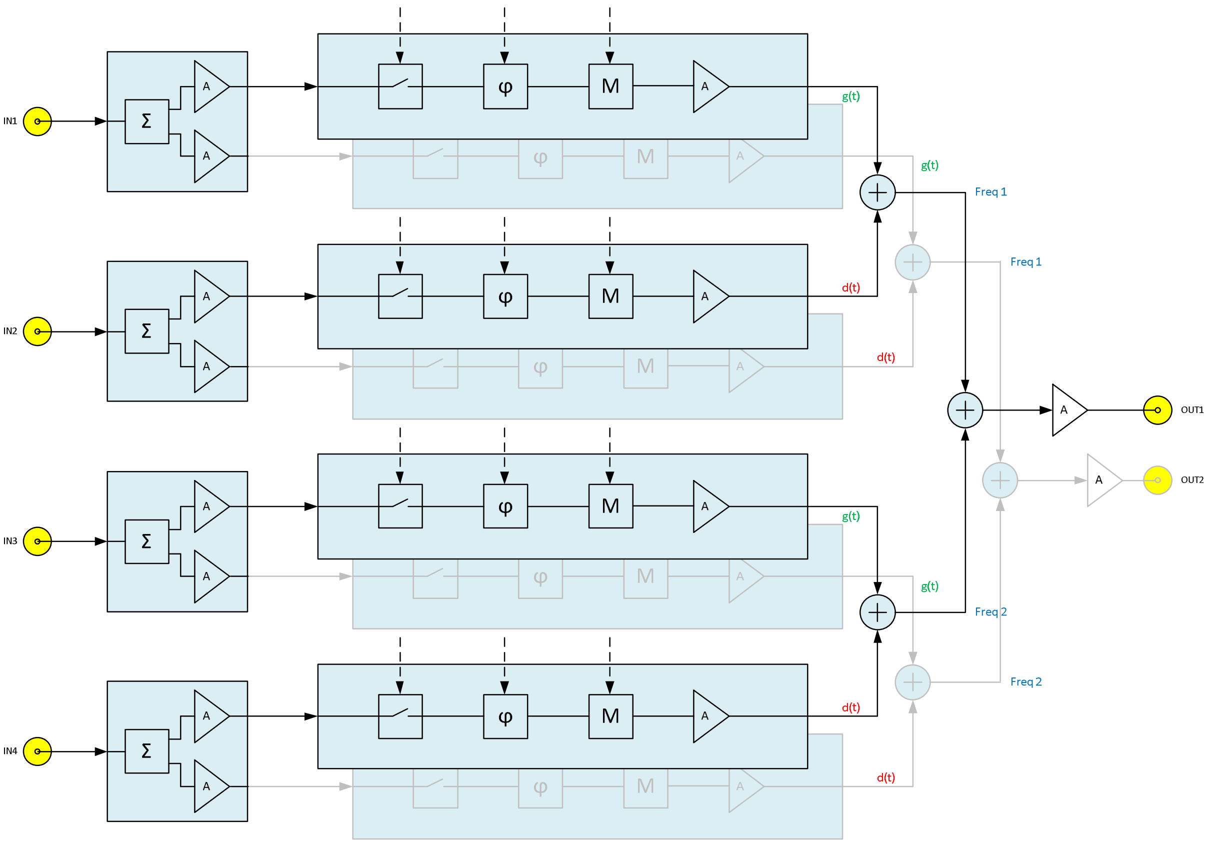

Figure 7 Block diagram of the duplexer (with the eight cells of the matrix visible).

A more detailed diagram of the switch, phase and amplitude control is given by the next drawing.

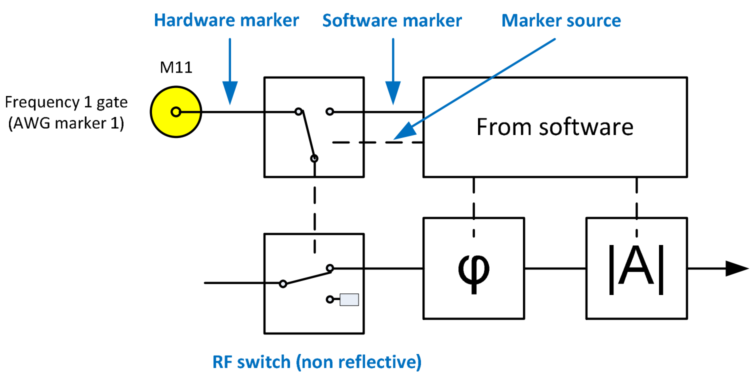

Figure 8 Detail of the control lines.

The source of the marker/gate can be set to hardware or software control. If set to software control the RF-switch can be ON or OFF, so there are three states possible form the driver side: OFF, ON, EXTernal. In EXT mode the external AWG trigger determines the state. The RF switch is of a non-reflective type at all ports and has approximately 50dB of isolation.

Input specifications

Table 1 RF-inputs (freq 1 A/B and freq 2 A/B)

Parameter	min	typ.	max	unit
frequency range	3.9		10.5	GHz
Input impedance		50		
maximum input power (linearity)		0		dBm
damage power		+5		dBm

Table 2 RF-outputs (out 1 and out 2)

Parameter	min	typ.	max	unit
frequency range	3.9		10.5	GHz
output impedance		50		
maximum output power (linearity)		+6		dBm
output IP3 (intercept point)		+25		dBm

Table 3 Marker/trigger/gate inputs (M11, M21, M12 and M22)

Parameter	min	typ.	max	unit
Marker voltage range	-0.5		+5.5	V
Marker threshold		2.8		V
RF-switching time			4	ns
Digital switching latency			6	ns

Table 4 Power supply

Parameter	min	typ.	max	unit
Mains voltage	100		240	V
Mains frequency	50		60	Hz
Duplexer power consumption		2		W

Table 5 Digital control

Parameter	value
TCP-IP address	SN1: 192.168.0.100 SN1: 192.168.0.101
SCPI port	5025

Performance specifications

Table 6 RF-gating (on/off switching)

Parameter	min	typ.	max	unit
Isolation (4 .. 8GHz)	48	52		dB
Isolation (3.9 .. 10.5 GHz)	48			dB
RF-turn on/off transition			4	ns
Latency marker in to RF-switched			10	ns

Table 7 Amplitude control

Parameter	min	typ.	max	unit
Dynamic range (4 .. 8GHz)		24		dB
Dynamic range (3.9 .. 10.5 GHz)			20	dB
Amplitude ripple (4 .. 8GHz)			4	dB
Amplitude ripple (3.9 .. 10.5 GHz)			5	dB

Table 8 Phase control

Parameter	min	typ.	max	unit
Dynamic range (4 .. 8GHz)	200			degree
Dynamic range (3.9 .. 10.5 GHz)	200			degree
Phase flatness (4 .. 8GHz)		20		degree
Group delay (4 .. 8GHz)		3		ns

Calibration graphs (Magnitude over frequency 4 to 8 GHz)

The next graphs show the frequency response between 4 and 8 GHz for the eight channels and for 9 different attenuation DAC values (0, 8192, 16384, 24576, 32768, 40960, 49152, 57344 and 65535).

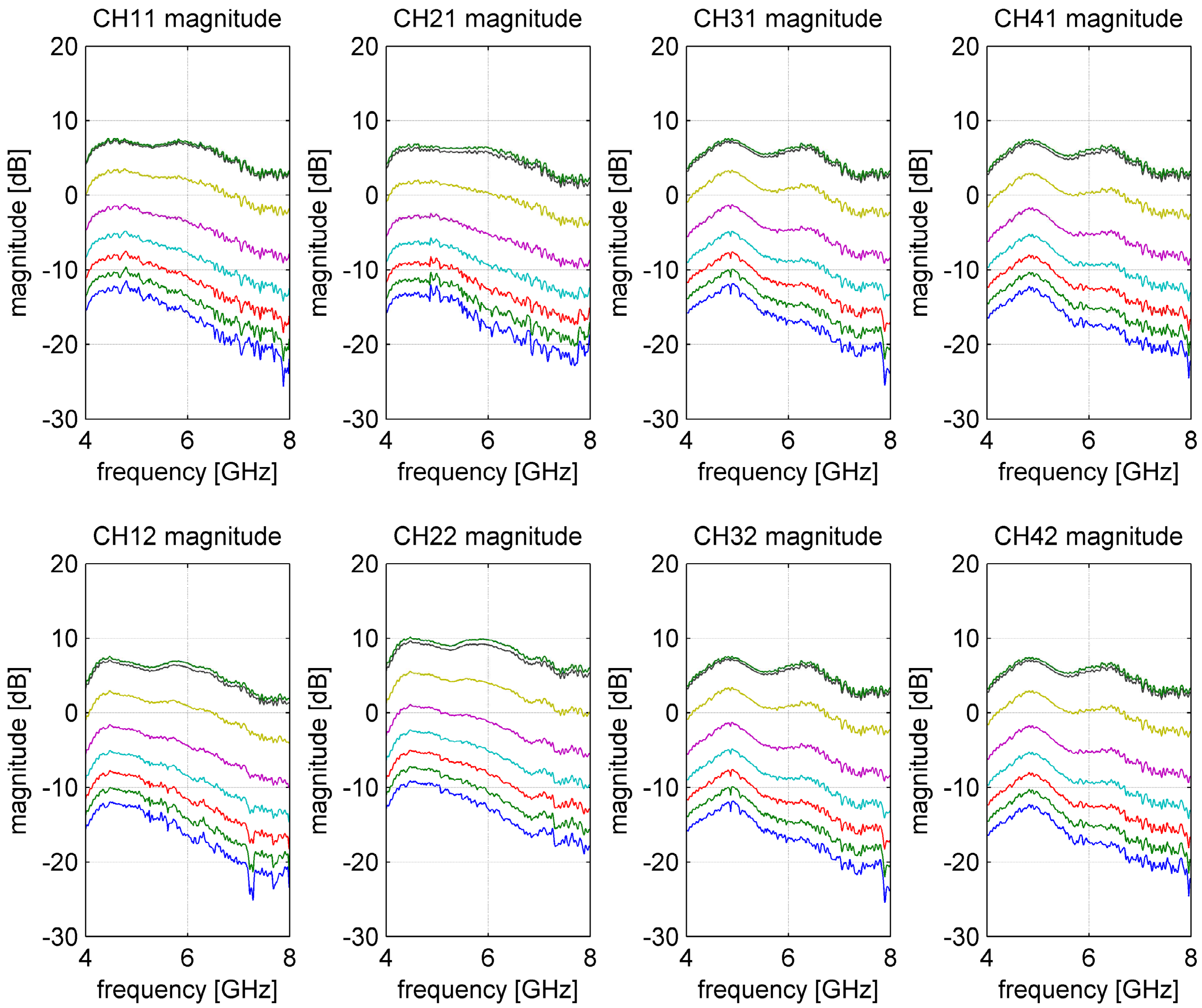

Figure 9 Attenuation over frequency for the eight channels and nine attenuation settings .

The graphs clearly show that channels have individual responses. (e.g. CH22, has for some reason more gain.). Common patterns are also visible, like the increasing attenuation for higher frequencies.

Calibration graphs (Magnitude vs DAC value at 5.8GHz)

A cross section has been taken at a frequency of 5.8GHz and the magnitude has been plotted against the DAC value sent to the attenuator.

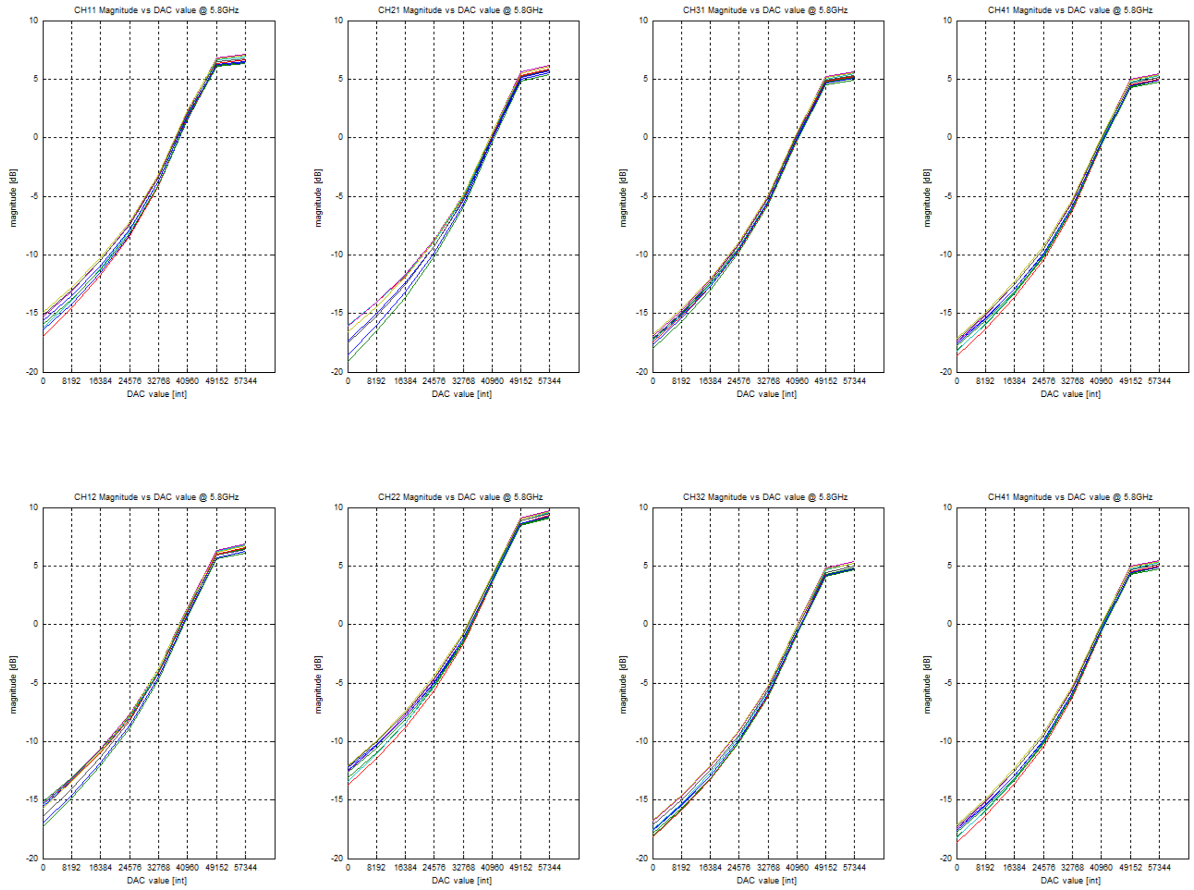

Figure 10 Attenuation vs DAC value for the eight channels and nine phase settings each .

In this cross section we can again conclude that CH22 has more gain. Also visible is that the magnitude is not fully independent of the phase setting (although the lines sort of overlap). At high DAC values we even see "compression" of attenuation control *(which is not the same as compression of the RF-signal. The RF signal is still attenuated without distortion)*

Calibration graphs ((unwrapped) Phase over frequency 4 to 8 GHz)

The next graphs show the phase response between 4 and 8 GHz for the eight channels and for 9 different phase DAC values (0, 8192, 16384, 24576, 32768, 40960, 49152, 57344 and 65535).

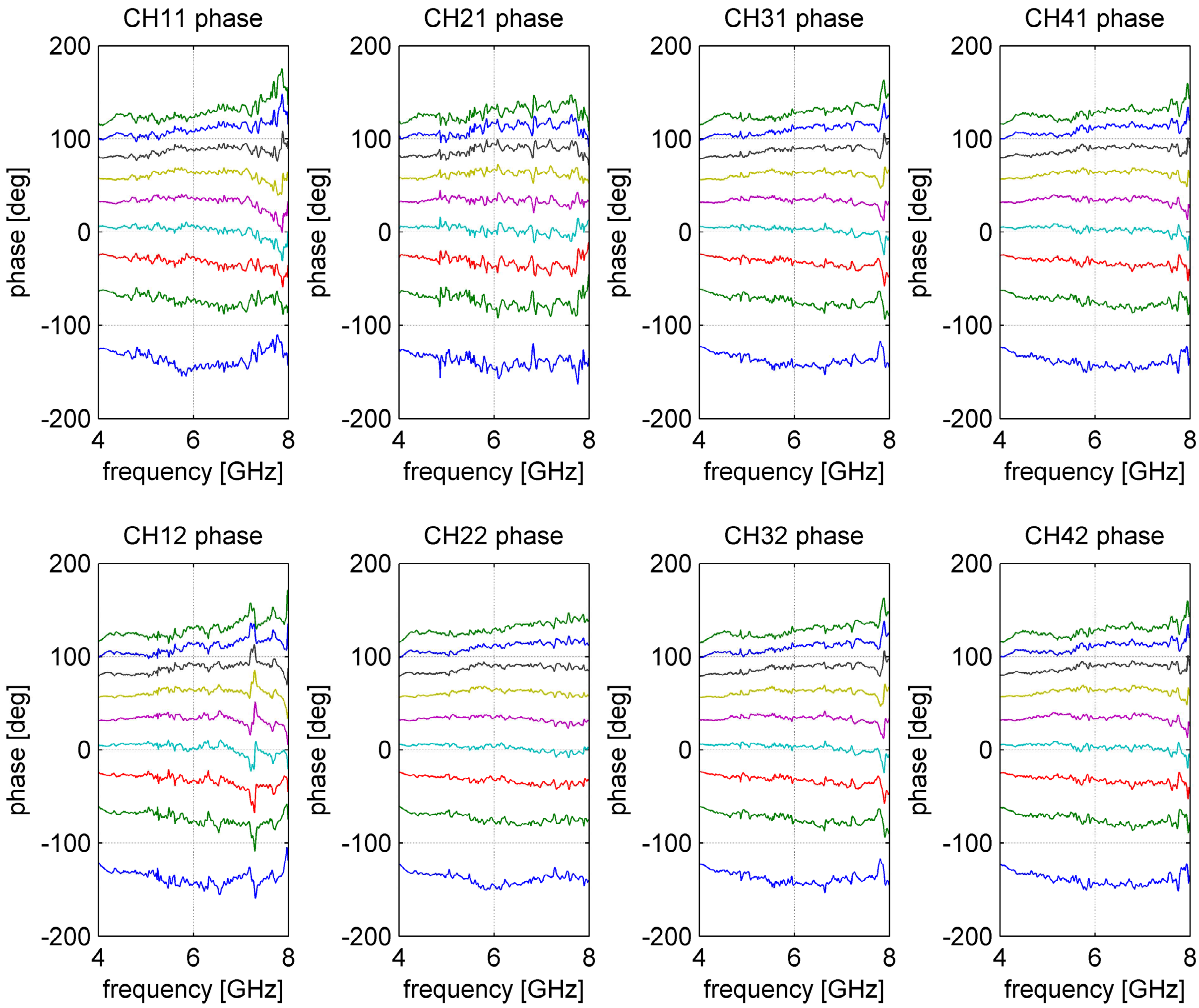

Figure 11 (unwrapped) phase over frequency for the eight channels and nine phase settings .

Because of phase unwrapping and relating to the mean phase line the phase is more or less a flat line over frequency. Again we see that channels are not perfectly identical and that there are some unexpected peaks (e.g. CH12 around 7.2GHz).

Calibration graphs (group delay over frequency 4 to 8 GHz)

All measurement have been performed using an Agilent PNA-X vector network analyzer, which has been calibrated at the reference planes of the connector cables mating the input and output connectors of the Duplexer. The next plot shows the absolute phase from input to output connector over (angular) frequency. This slope is a measure for the group delay from input to output.

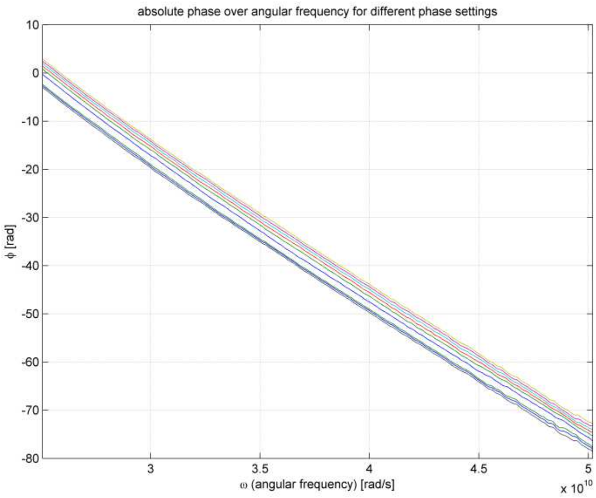

Figure 12 absolute phase (radians) over angular frequency (radians per second) nine phase settings (CH11) .

The group delay is defined as: $\tau = -\frac{d\phi}{d\omega}$

The average group delay is 3ns, but a histogram of all channels and phase settings shows 2 peaks.

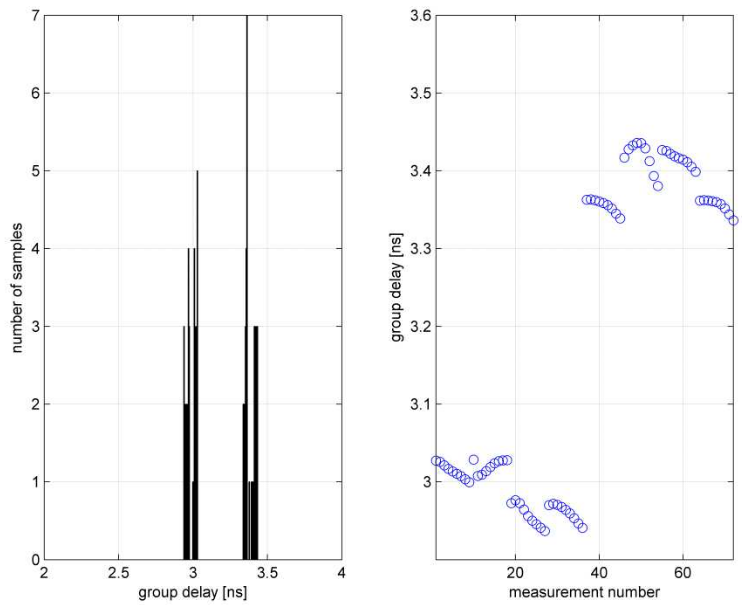

Figure 13 group delay histogram (left) and explanation of two peaks (right).

Surprisingly the group delay distributions has two peaks at 3.0 ns and 3.4 ns. The right plot of group delay vs measurement number also shows this distribution, which can only be explained by differences in the two boards (or their RF-cables) inside the duplexer. The left half of the measurements corresponds to board 1 (= output 1) and the right half of the measurements corresponds to board 2 (= output 2). It can be concluded that propagation to output 2 takes 400ps more time than output 1. Both connect to different qubits so this difference probably isn’t a problem (If it had been a difference between Gaussian and Derivative pulse propagation it might have been a problem, but fortunately these pair well).

Calibration graphs (Magnitude over extended frequency 2 to 12 GHz)

The Duplexer will be used between 4 and 8 GHz, but has more bandwidth (approx.. 3.9 to 10.5 GHz). The next graphs show this extended bandwidth.

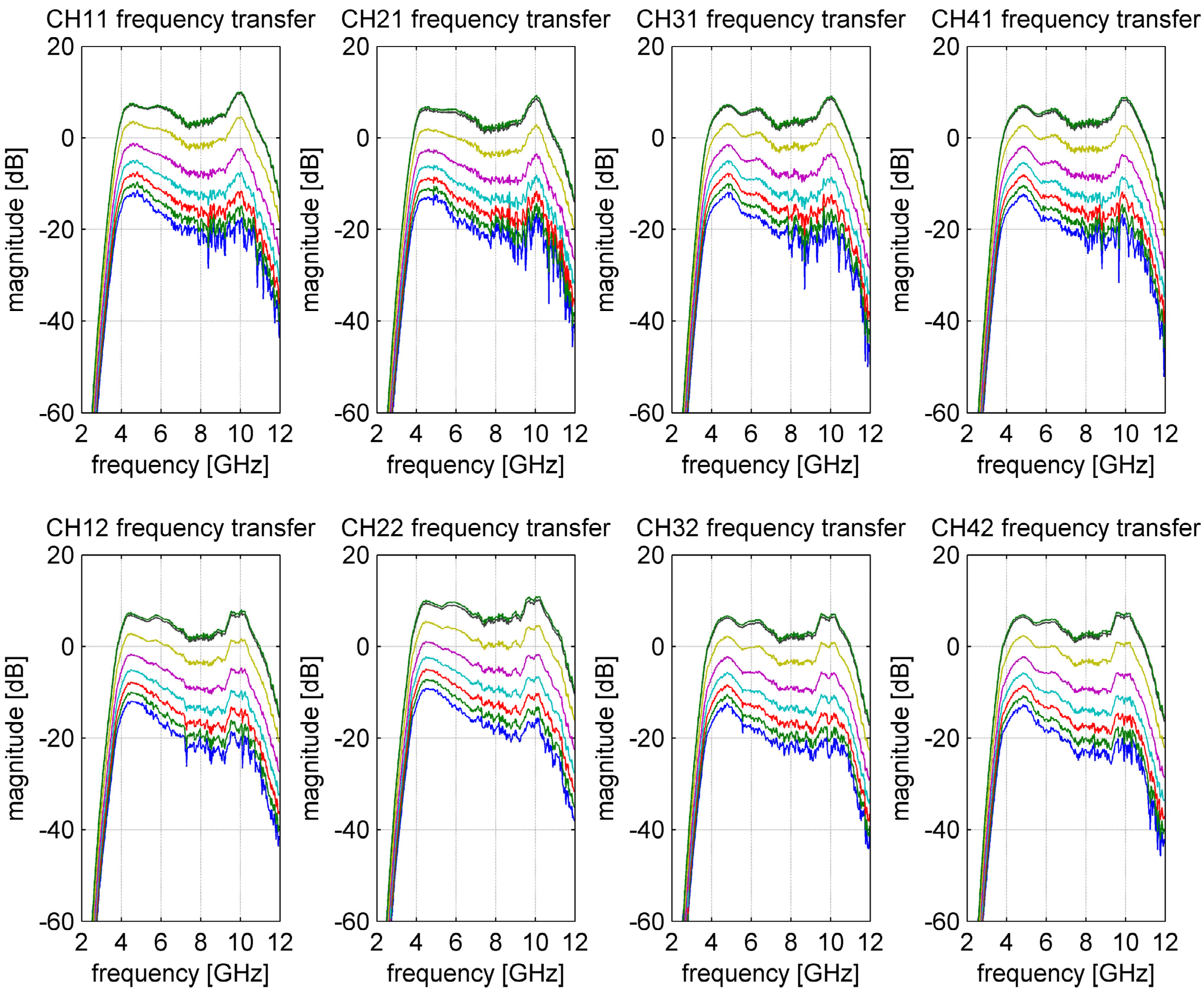

Figure 14 Attenuation over extended frequency range for the eight channels and nine attenuation settings .

Below 4GHz the input signals are blocked, there is some peaking around 10GHz and higher frequencies are blocked again.