Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Digital Phase Comparator for the characterization of a Superconductive Quantum System

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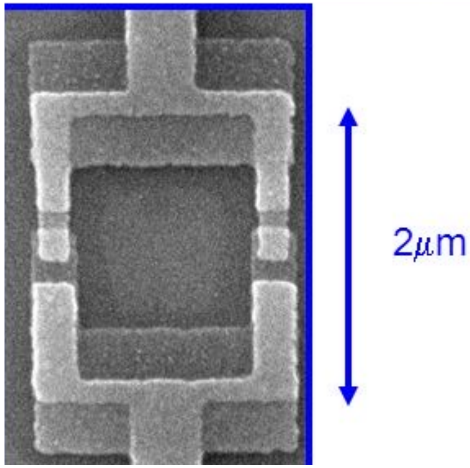
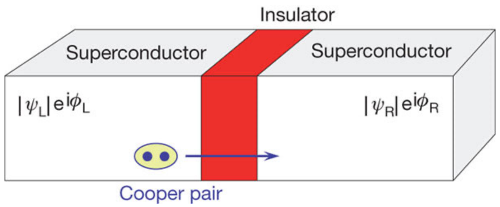
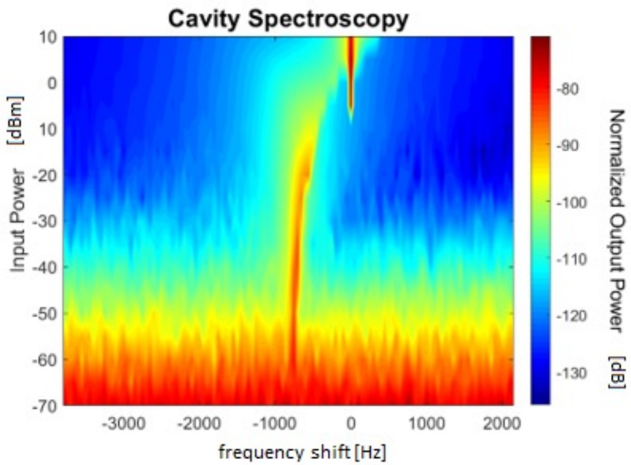
Summer Internship – Final Report

26 September 2018

Superconductive Qubits





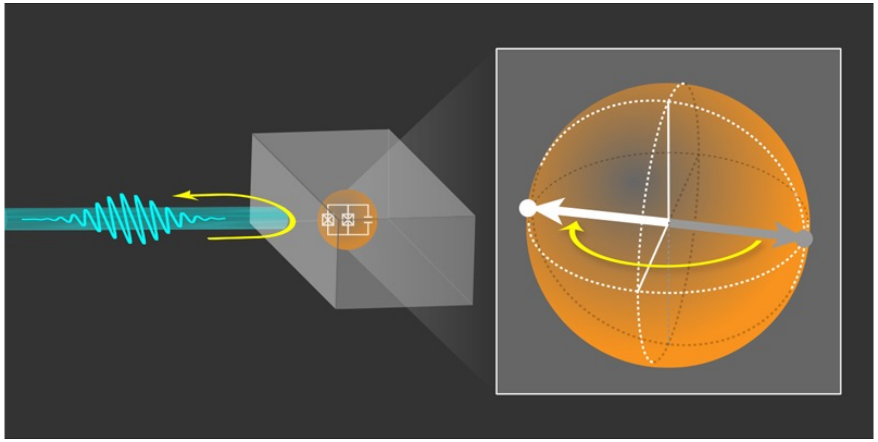


- **Qubit**: A two energy quantum system described by a state function. It carries information in Quantum Computing.
- In superconducting technology the qubit is a **Josephson Junction** that results in an unharmonic oscillator

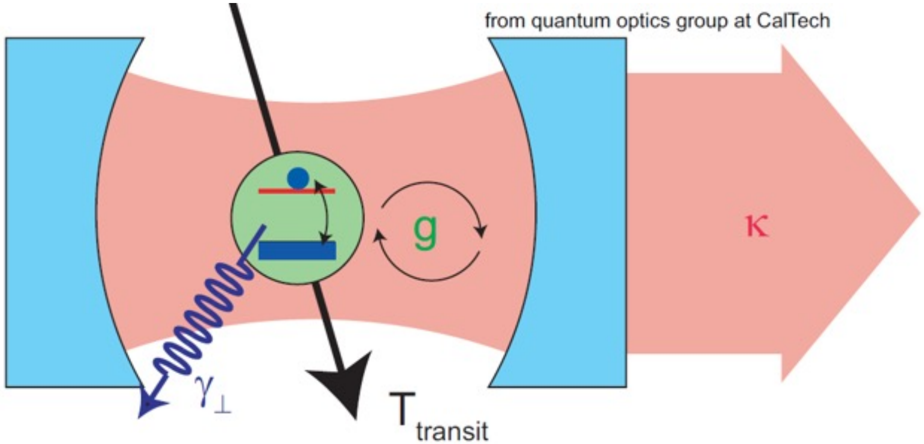
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \qquad \alpha, \beta \in \mathbb{C}$$

- Superconductive Radio Frequency (SRF) **Cavity** $f_r = 2.6\ \mathrm{GHz}$
- **Coherence time**: the state preserves its quantum coherence until interaction with the environment affects it. Research groups are trying to increase coherence times.

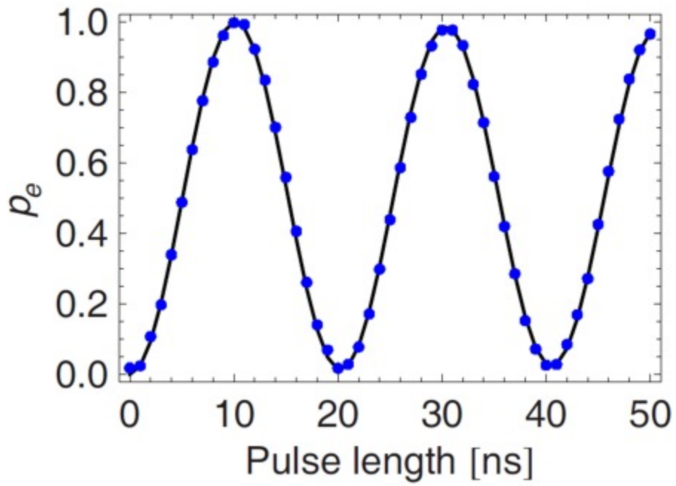
Rabi Oscillation



- Qubit state can be driven by sending **microwave pulses** of variable pattern and duration
- The Qubit inside the cavity alternately emits photons and reabsorbs them
- Its state switches giving rise to the «**Rabi Oscillation**»

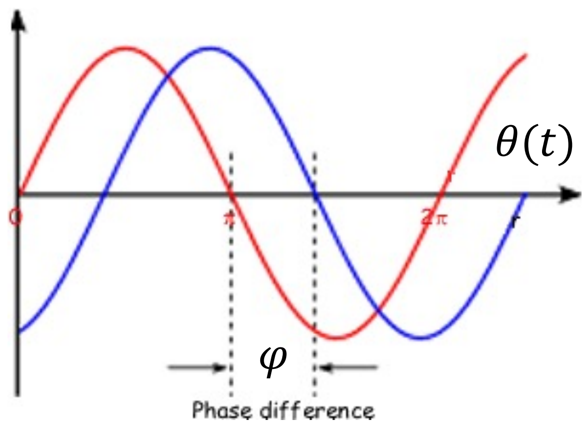


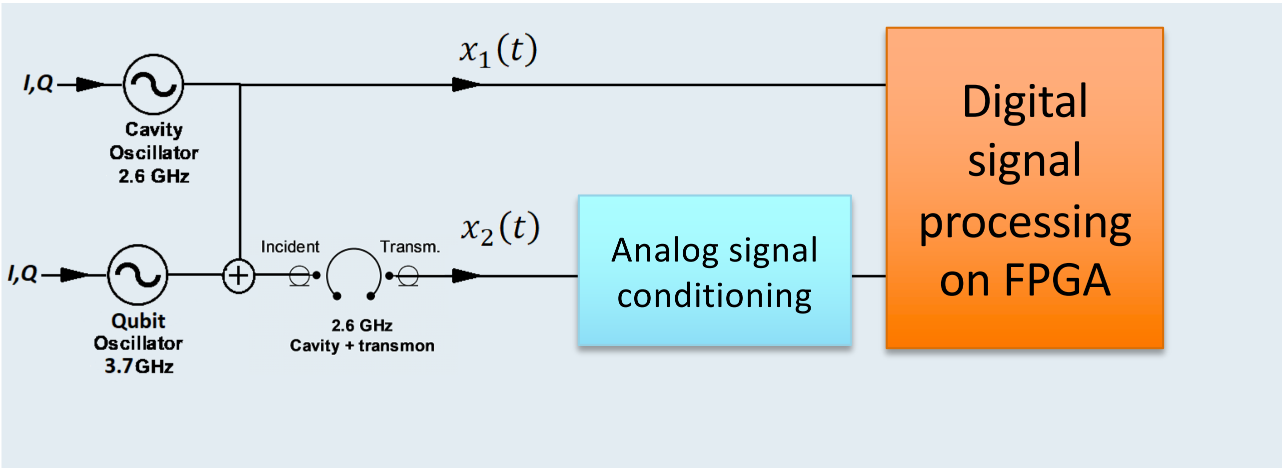
- Repeated measurements and statistics allow us to observe the **oscillation pattern** of the probability function



Phase Measurement

- **Phase shift** introduced by the cavity brings information on the probability of being in state $|0\rangle$ or $|1\rangle$
- **My task** is to design and implement a digital system to measure the phase difference between two sinewave signals.
- A **digital system** allows to perform real time analysis. It helps to perform statistical analysis on repeated measures always needed when dealing with quantum system.





Design Schematic - Hardware

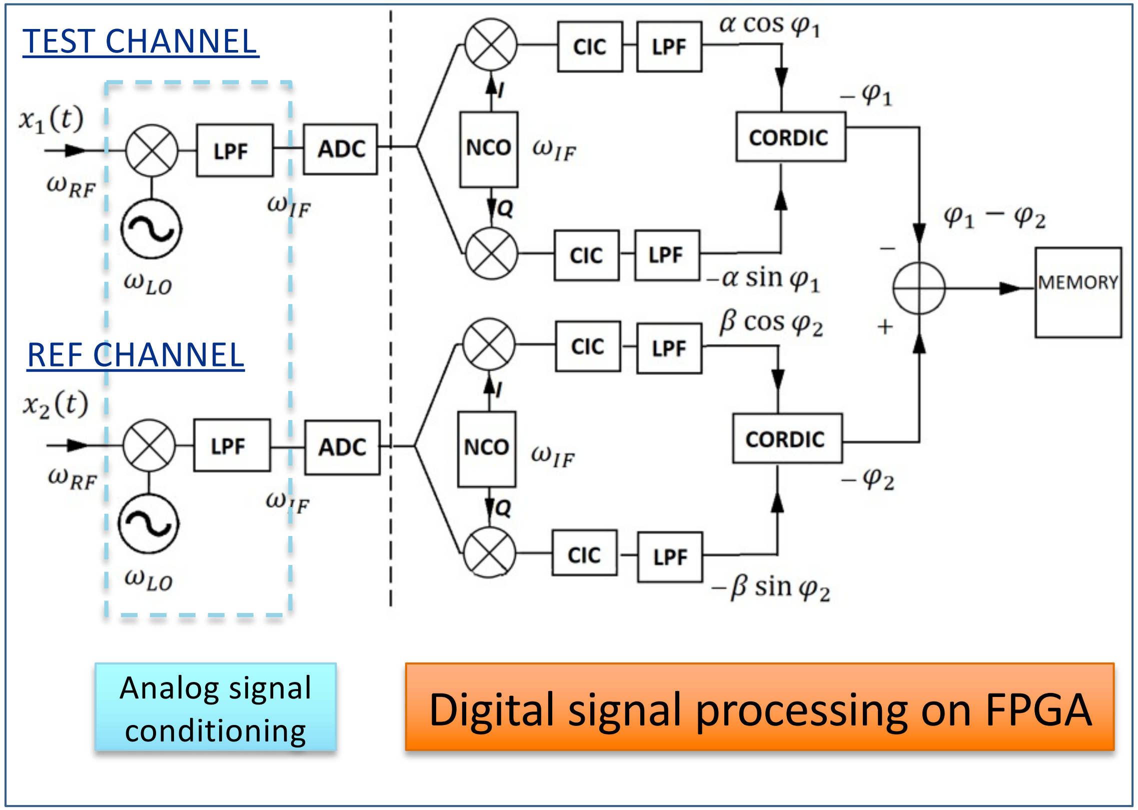
$$x_1(t) = A_1 \cos(\omega_{IF} t + \varphi_1)$$
$$x_2(t) = A_2 \cos(\omega_{IF} t + \varphi_2)$$

$\rightarrow$

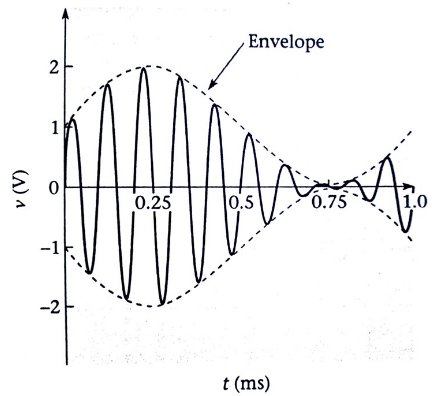
$$x_I^{(\gamma)} = A_\gamma \cos \varphi_\gamma$$
$$x_Q^{(\gamma)} = A_\gamma \sin \varphi_\gamma$$

$\rightarrow$

$$\varphi_\gamma\,, \qquad \gamma = 1{,}2$$



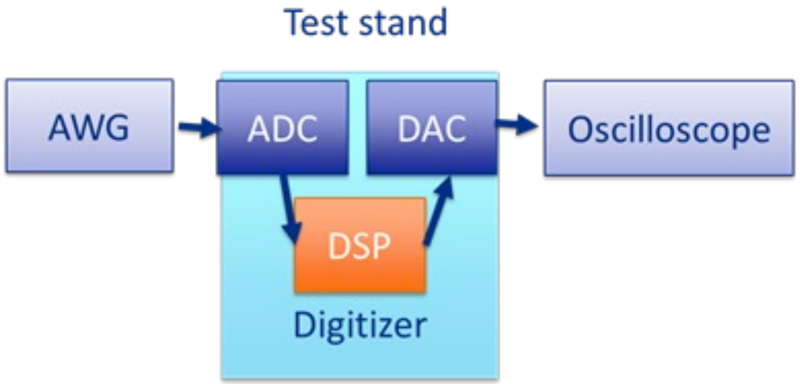
- $x_1(t)$ Readout from cavity
- $x_2(t)$ Cavity input (reference)
- ADC: **A**nalog to **D**igital **C**onversion
- CIC: **C**ascade **I**ntegrator-**C**omb
- LPF: **L**ow **P**ass **F**ilter
- CORDIC: **CO**ordinate **R**otation **DI**gital **C**omputer

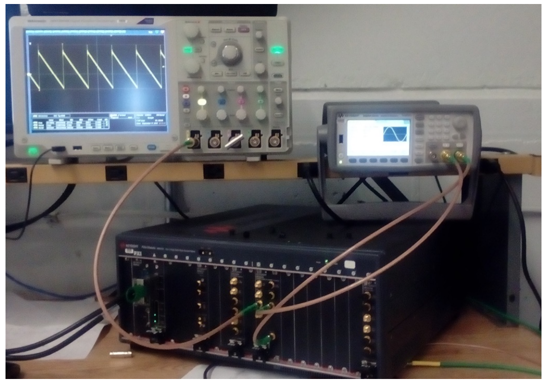


Analogy: AM Demodulator in a receiver

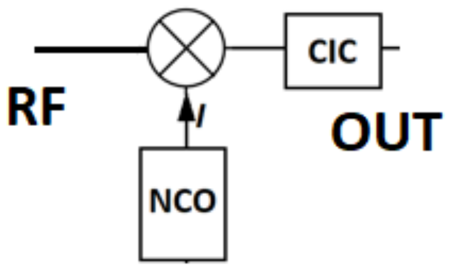
Our Setup

- Vivado – Running simulation of **VHDL** codes
- Keysight M3602A – **FPGA** design environment
- Keysight M3302A – **Digitizer** and Arbitrary Waveform Generator (**AWG**)
- Scope and waveform generator (**OS** and **WG**)
- Test and debug operations on the Keysight digitizer: new equipment in QCL.



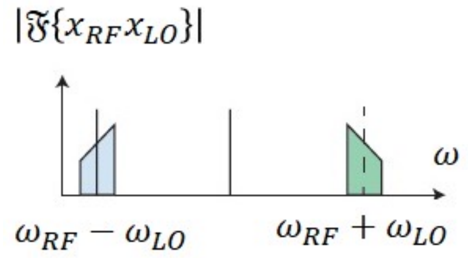


FPGA Programming – CIC Filter Test

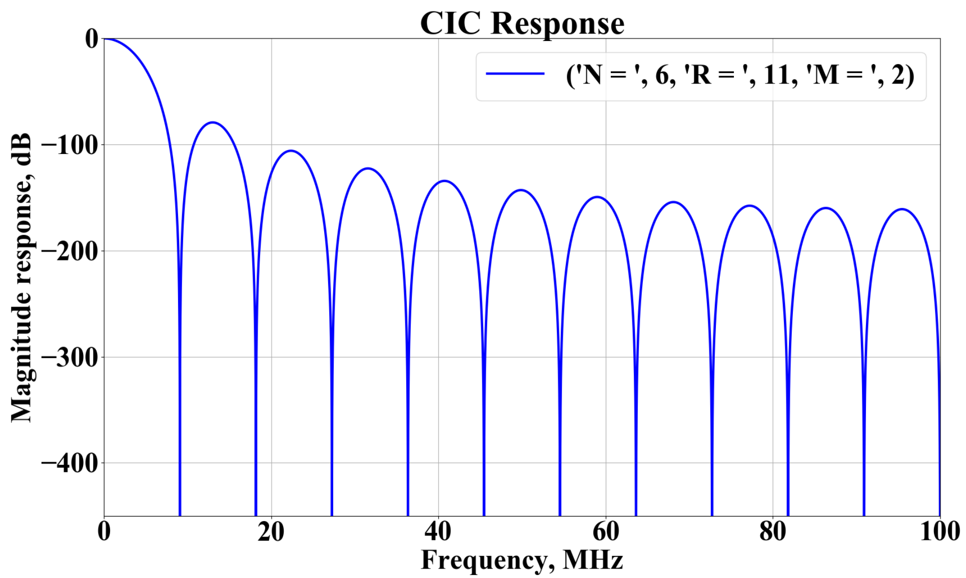


HARDWARE

System test of the CIC filter using the waveform generator and the oscilloscope



SPECTRUM

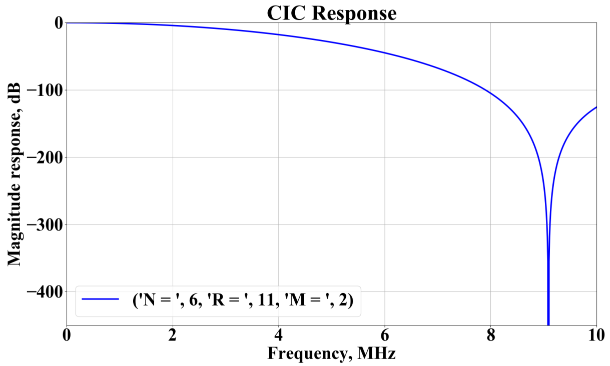


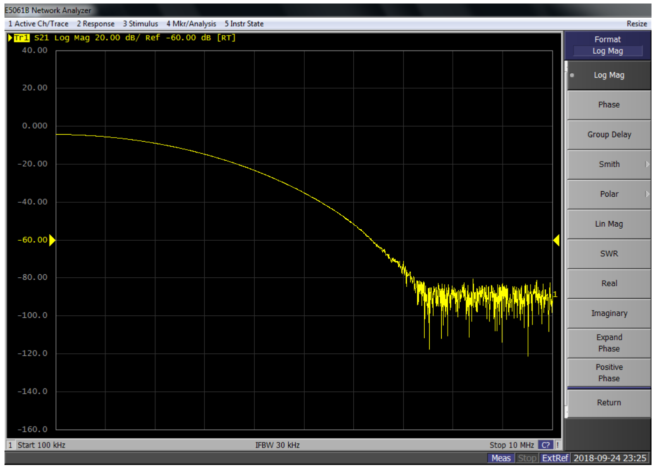
FILTER MAGNITUDE RESPONSE

Test setup

- $f_{RF} = 27.522$ MHz
- $f_{LO} = 27.8$ MHz
- $f_{OUT} = f_{RF} - f_{LO} = 278$ kHz

FPGA Programming – CIC Filter Test



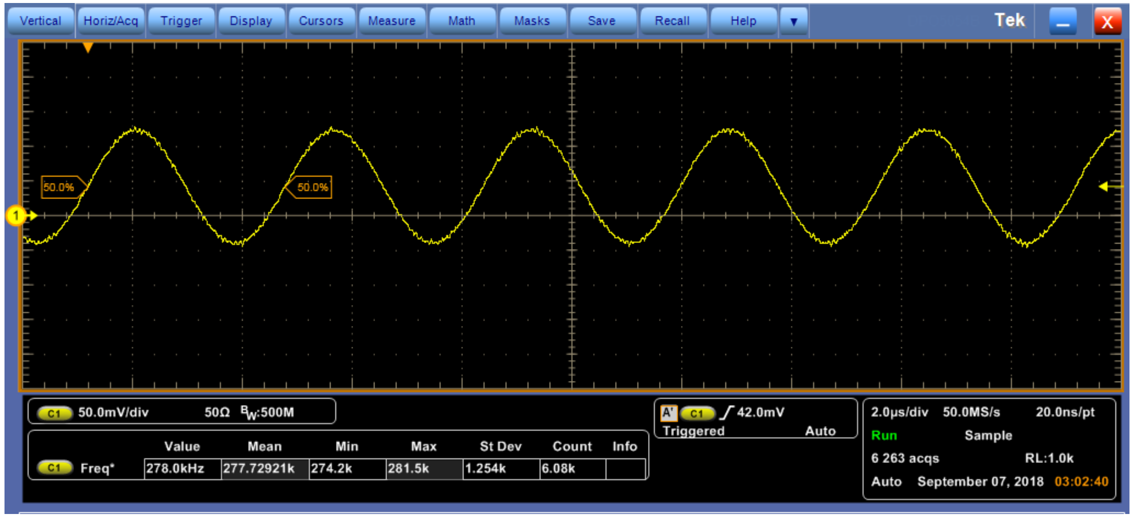


Simulation and VNA measurement comparison

$f \in [100\ \text{kHz}\ , 10\ \text{MHz}]$

Mixer output:

$$\cos(\omega_{RF}t)\cos(\omega_{LO}t) = \frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\cos(\omega_{RF} - \omega_{LO})t} + \frac{1}{2}\cos(\omega_{RF} + \omega_{LO})t$$

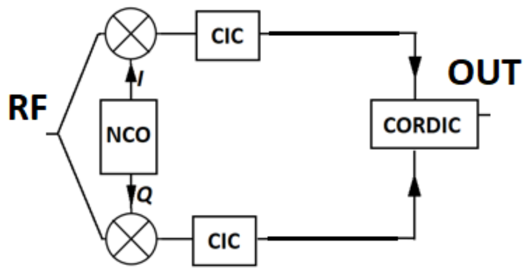


Output of a CIC filter

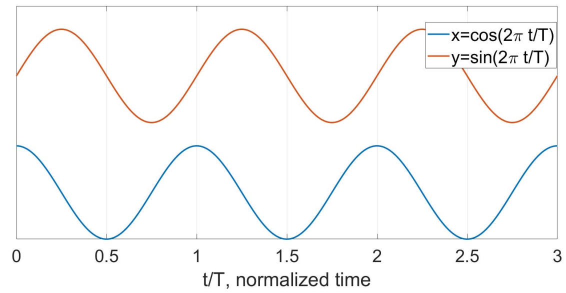
- $f_{RF} = 27.522\ \text{MHz}$
- $f_{LO} = 27.8\ \text{MHz}$
- $f_{OUT} = f_{RF} - f_{LO} = 278\ \text{kHz}$

FPGA Programming – Test Measurements

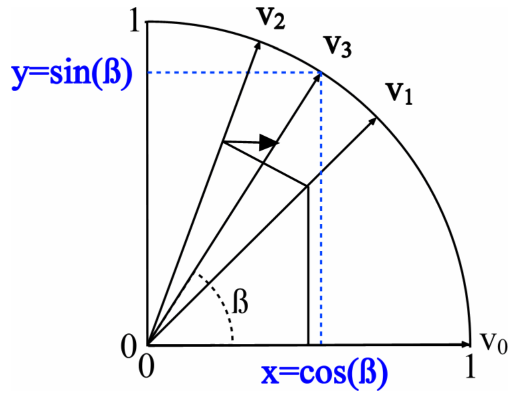
- System test of the CORDIC block using the waveform generator and the oscilloscope



HARDWARE

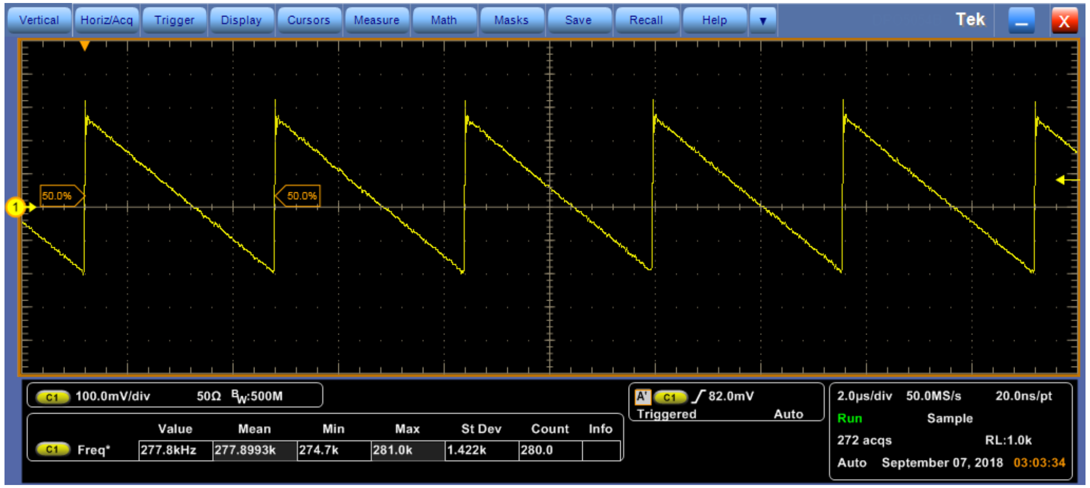


CORDIC INPUT

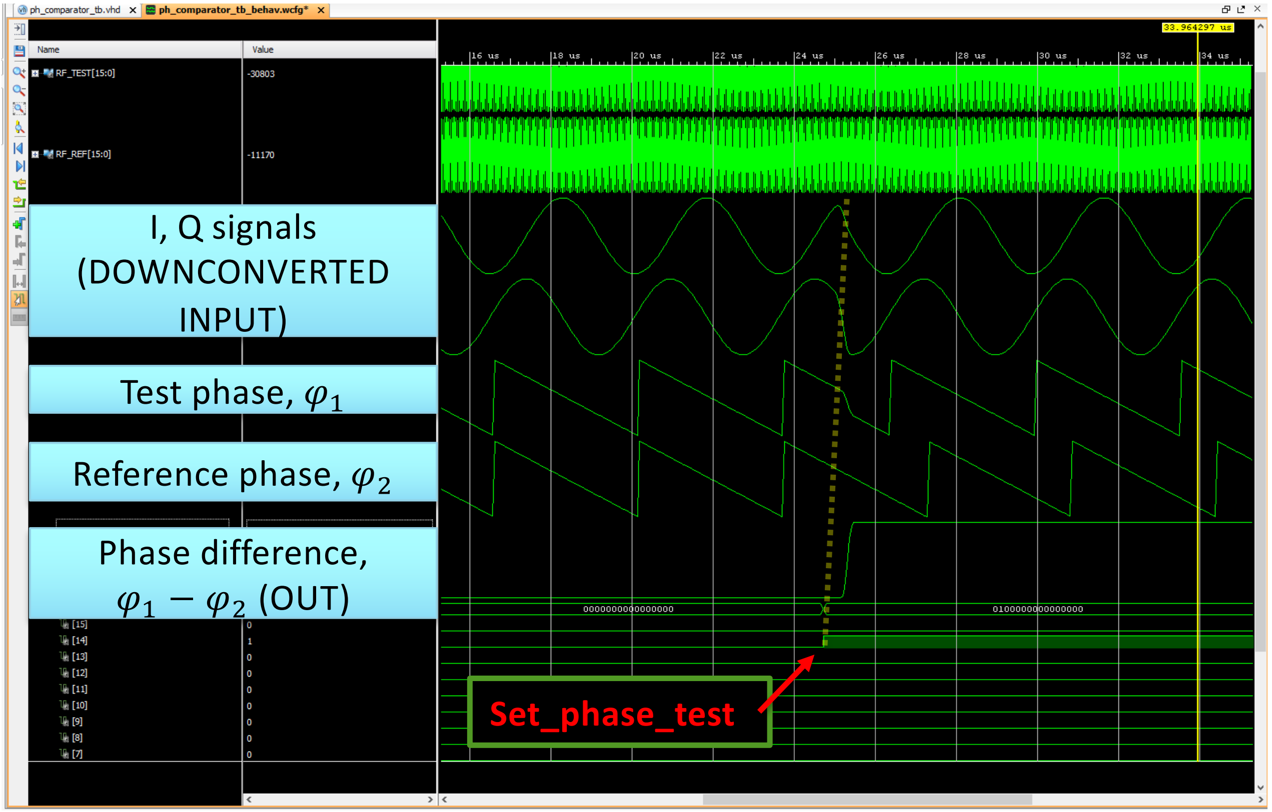


TWODIMENSIONAL VECTOR SPACE

Output of a CORDIC block: Phase is calculated once the cosine and the sine are given.

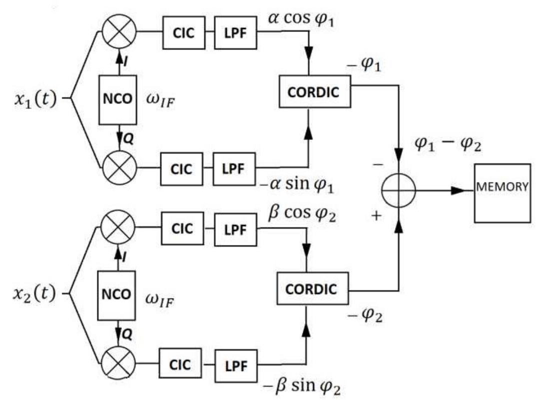


Behavioral simulation in Vivado – Overall System



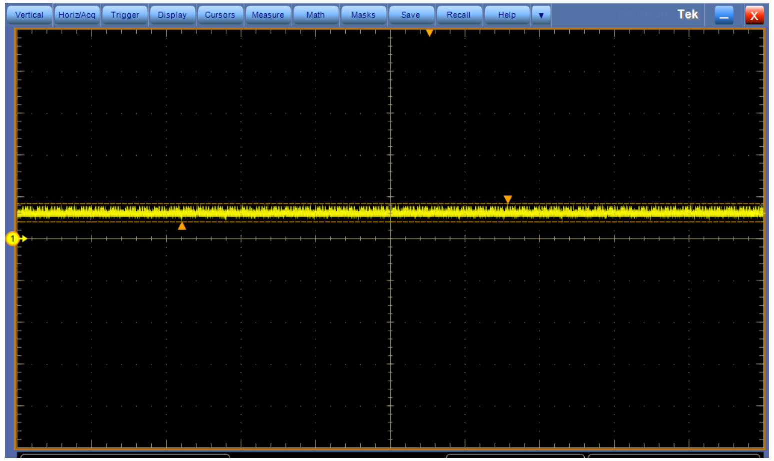
Showed output waveform:

- Output of the CIC **Filter** used as input for the **CORDIC**
- **CORDIC** output: argument of the sinewaves.
- **Phase** difference



The system is tested forcing values for the phase φ_1 of the TEST signal $x_1(t)$

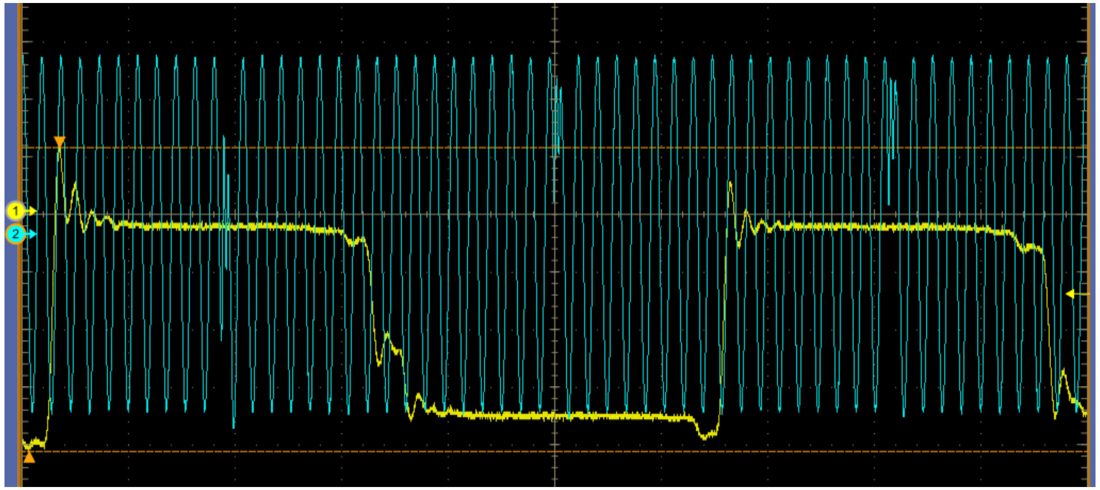
Phase Comparator on the FPGA



- Once implemented the system is tested:
We send two monochromatic waveforms with a given phase shift and we read their phase difference.
- The output signal is constant and its value is proportional to $\varphi_1 - \varphi_2$

$$f_{TEST} = f_{REF} = 27.522 \text{ MHz}$$

$$f_{LO} = 27.8 \text{ MHz}, \qquad \varphi_1 = -0.4 \text{ rad}$$



Phase Modulation Test

$$x_1(\mathrm{t}) = \cos(\omega_0 t + m(t))$$

$m(t)$ → SQUARE WAVE

Test signal's phase has been modulated by a square wave so it changes abruptly between two values that the system is able to detect after some delay.

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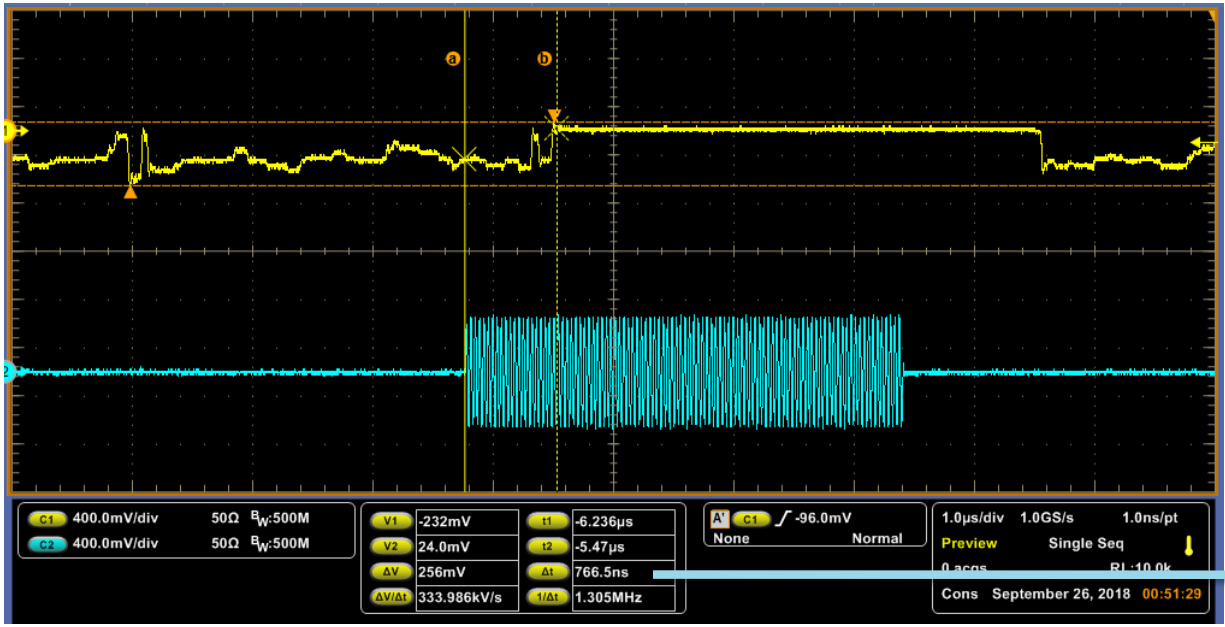
Phase Comparator on the FPGA - Latency

- Latency is the time that the system requires between the stimulation and the response
- We want this time to be short to get higher speed and faster signal processing



LATENCY TEST

Latency is measured applying a pulsed signal on the test channel and reading the time elapsed before a change in the phase difference occurs.

$$\tau_L = 766.5 \text{ ns}$$

Criticalities

Test and debug of the new equipment identified some criticalities reported to the group:

- Triggering is limited by the software we are using

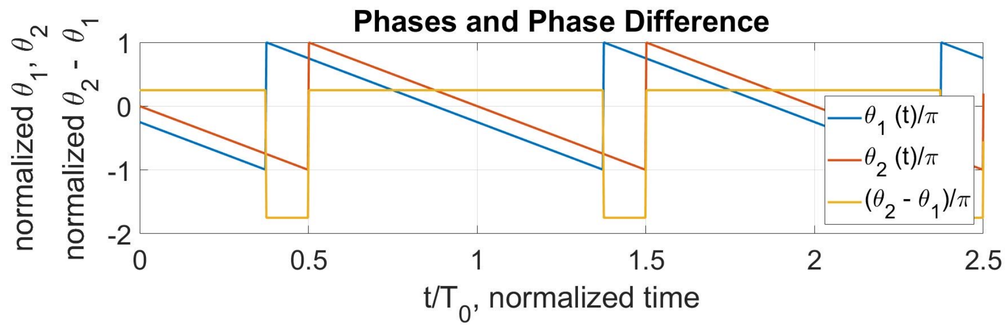
  Data representation works properly only when using the **full capacity** of our channels → It would require too **large data** width and this is not convenient.

- Reading data stored in memory from registers inside the FPGA has to be understood

  We want to build an **user interface** for real time data reading → It is still **not intuitive** how to write data to registers and has to be figured out

- The CORDIC algorithm provided by the SW needs a calibration to avoid double interpretation of the phase difference

  Representing phases in the interval $\varphi \in [-\pi, \pi)$ introduces artificial jumps of 2π giving rise to **incorrect values** when subtracted.



Conclusions and Outlooks

CONCLUSIONS

- The new digitizer has been installed and I figured out how to synthesize a project even if I identified some weaknesses
- The digital system for measuring the phase difference is implemented and has shown good results to input test signals
- Once the criticalities will be fixed it can be included in the instrumentation test bench for the Qubit characterization in the Quantum Computing Laboratory

FUTURE IMPROVEMENTS

- Improve trigger settings in order to have the best data representation
- Implement a user interface for reading and writing data in the firmware registers

Thank you for the attention, if you have any question
I would be glad to answer