DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS

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May 14, 2015

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INTRODUCTION

Part I

Deep-reactive ion etched resonators

TODO:

- Explain heterodyne detection
- Explain VNA

Part II

Muxmon experiment

TODO: Explain surface code architecture

Introduction

At this moment circuit QED is at the stage where multi-qubit experiments are being realized.

Chapter 1

Muxmon chip architecture

Topics that should be explained in this section:

- The Muxmon0 and Muxmon1 chip are designed with two purposes
  1. Testing multiplexing using the Duplexer
  2. Explore qubit frequency re-use
- Explain similarities of chips
  - Three qubits per chip
  - All three qubits have individual flux tuning
  - Air bridges are used, not only for connect the ground planes, but also such that the feed line can pass over other coplanar waveguides without contact
- Explain differences between Muxmon0 and Muxmon1.
  - The Muxmon0 chip has a driving line connected to each of the qubits.
    It has two resonator buses at 4.9 GHz and 5.0 GHz.
    These could also be used for two-qubit gates.

    Advantage Able to fully control each qubit individually, even when multiple qubits share the same frequency.

    Advantage Less coupling between data qubits.

    Disadvantage Requires more driving lines.

    Disadvantage Adds extra source of dissipation for the qubits.
  - The Muxmon1 chip has two driving lines, each capacitively coupled to one of the two data qubits, and to the ancilla qubit.

    Advantage Less driving lines required

    Advantage Less dissipation due to capacitive coupling

Disadvantage Cannot individually control data qubit and ancilla qubit when they share the same frequency

Disadvantage More coupling between qubits

- Simplified model of the surface code

- Explain concepts of cross-coupling and readout cross-talk

Cross-coupling The coupling between qubits.
Cross-coupling leads to transfer of excitation.
An associated coupling strength **g** can be associated to cross-coupling.
Can be determined by driving one qubit extremely hard, and measuring signal from other qubit.
TODO: Show values of cross-coupling found, or do this in characterization section
TODO: Leads to coherent errors?
TODO: Two types of cross-coupling? Direct leakage of pulse pulse, and transfer of excitation? cross-driving?

Readout cross-talk Coupling between a qubit and a resonator that are not directly coupled.
A part of the signal measured from one resonator is then due to the state of another qubit
TODO: Understand more behind readout cross-talk

Left to think about:

- Should I already include items such as coherence times, the fact that Muxmon0 performs better than Muxmon 1?
- Where should I include coherence times versus frequency?
- Should the part on cross-coupling and readout cross-talk not be in characterization section?
- Should the section on the Duplexer go in here?

Figures that need to be included:

- Muxmon0 and Muxmon1 chip, preferably optical microscopy
- SEM image of air-bridges such that coplanar wave-guides cross without intersecting
- schematic of cross-coupling and readout cross-talk
  It could be good to create this using the actual Muxmon chip as background, with arrows indicating how the different effects operate

Chapter 2

Qubit characterization

This chapter gives a step-by-step description of how to find a resonator and qubit, and subsequently how to tune the qubit's parameters.

In the design of cQED chips, the parameters of the qubits and resonators are always targeted which are ideal for the experiment. For coplanar waveguide resonators one can already obtain relatively good parameters for the required dimensions from simple formulae **TODO:** refer to formula. For superconducting transmon qubits, however, finding the right dimensions that correspond to the desired parameters is a much more complicated process. The qubit's frequency, for instance, depends on the qubit's coupling energy $E_{\mathrm{c}}$and Josephson energy E_{J}. The coupling energy E_{c}can be reasonably estimated from classical simulations. Finding the right dimensions for the Josephson junction that result in the desired Josephson energy E_{J}, however, is difficult, and usually physically testing different junctions is necessary to determine an accurate conversion from the desired $E_{\mathrm{J}}$to the Josephson junction dimensions.

Nevertheless, the actual parameters of the sample are almost never where one expects them to be. Once the sample is cooled in the dilution refrigerator, an inevitable hide-and-seek game follows with the goal of finding the frequency of the resonators and qubits, and subsequently determining their properties. This chapter describes the measurements that were performed to characterize the MuxMon samples.

2.1 Part I: Continuous-wave measurements

Once a sample is properly cooled down it is ready to be measured. At this stage the sample is still an unknown terrain, where the experimenter only has a rough map, containing the sample's targeted parameters, and the specific properties of the resonators and qubits.

The first step is to look for signs of life. These manifest themselves as resonance frequencies of the resonators and the qubits that are coupled to them. As we are not yet interested in the properties of the resonators and qubits which can only be obtained through measurements with accurately timed pulses, we send continuous tones through the feedline, and measure deviations in the transmission. These measurements are known as continuous-wave measurements

2.1.1 Scanning for resonators

Since communication with the qubits is mediated through their coupling to resonators, the first step is to find these resonators. This is done using heterodyne detection, and has been explained in section **TODO:** Create section in Resonator chapter.

TODO: Explain why using a high power is good.

Figures:

- Figure of transmission showing all three Muxmon0 resonators

2.1.2 Powersweeping the resonators

Once the resonators have been located, the next stage is to find the qubit that is capacitively coupled to each of the resonators. Due to this capacitive coupling the frequency of the resonator experiences a shift dependent on the state of the qubit. This shift disappears when the resonator is driven with sufficient power, in which case its resonance frequency shifts to the bare cavity frequency f_{bare}. If this frequency shift is observed, it indicates that the qubit is alive. A powersweep additionally provides information about at what power the resonator enters the **TODO:** nonlinear? regime. For measurements involving the qubit the readout power must be below this threshold power.

TODO:

- Explain better theory behind resonator shift χ
- Explain theory behind transition to bare cavity frequency
- Refer to thesis for more info on frequency shifts

Figures:

- Powersweep of ancilla qubit

2.1.3 Scanning for qubits

2.2 PART II: TIME-DOMAIN MEASUREMENTS

Chapter 3

Calibration routines

Chapter 4

Randomized benchmarking