Schemes for improvement of design, control, and readout of Transmon qubits

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Abstract:
The Transmon qubits are the most popular superconducting qubits in the past few years. As a representative of NISQ quantum device, various techniques for design, fabrication, measurement, and control of Transmon have been developed. Implementation of these existing schemes and exploration of new schemes is the main job, which serves the core objective of exploring more and more application scenarios of the engineered Transmon qubits platform. From theoretical research assistant points of view, we aim to build a series of frameworks on the design, control, and readout of Transmon to direct the fabrication, chip selection, and calibration experiments. In this presentation, we will go through the basic procedure of Transmon structures design, calibration experiments, and chip selection, and take two examples on gate implementation and readout optimization to explain why these ideas are crucial in the development of superconducting qubits platform.

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Assembly Lines for Quantum Chips Upgrade

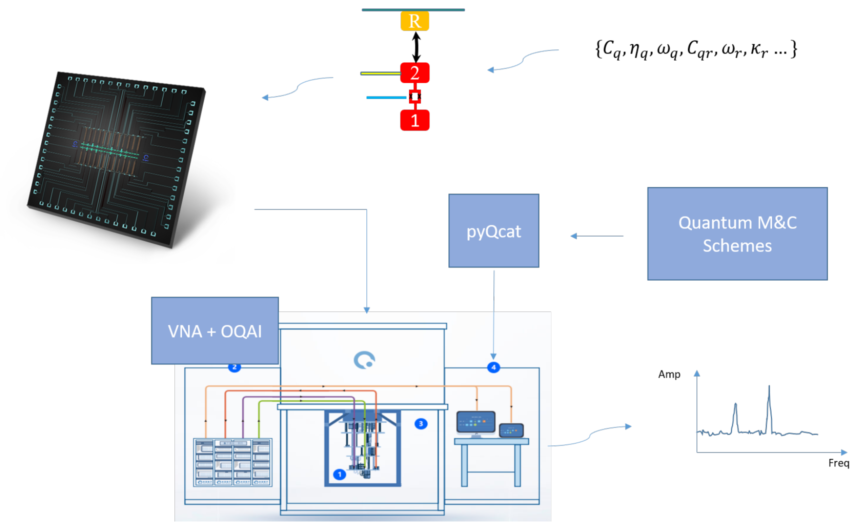
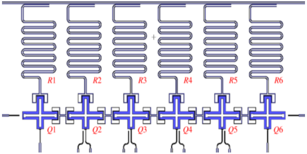


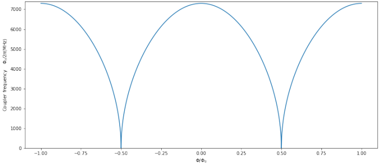
Figure: Work streamline in Origin Quantum

Design Parameters:

$\{C_{qi},\ \eta_{qi},\ \omega_{qi},\ C_{q,ij},\ \omega_{ri},\ \kappa_{ri},\ g_{qr,i}\ldots\}$



(a) Origin's 6-bit Transmon chip[2]



(b) Frequency bias: $\omega_q(\Phi)$

Control & Readout lines

- XY control(rf): $H_{d,\mathrm{eff}} = -\frac{\hbar\Omega}{2} V_0 f(t) \left(\cos\phi\ \sigma_x - \sin\phi\ \sigma_y\right)$
- Z control(DC&AC): $\omega_q(\Phi) = \left(\sqrt{8E_C E_{J\Sigma}\cos\left(\pi\frac{\Phi}{\Phi_0}\right)} - E_C\right)/\hbar$
- Readout(rf): $H_{\mathrm{eff}} = \frac{\hbar\tilde{\omega}_q}{2}\sigma_z + \hbar(\Delta_r + \chi_{\mathrm{eff}}\sigma_z)a^\dagger a + \hbar\left[\varepsilon_d(t)a^\dagger + \varepsilon_d^*(t)a\right]$

Part 1: Tunable Coupler

We would like to design a multi-qubit chip, for which the leaders prefer the tunable coupler scheme as structure units. Following the architecture of [7], we would like to explore the implementation scheme of two-qubit gate in this architecture.

Object: Prove that CZ gate of fidelity>99% is possible under this scheme

$$H = \sum_{j=1,c,2} \omega_j a_j^\dagger a_j + \frac{\eta_j}{2} a_j^\dagger a_j^\dagger a_j a_j + \sum_{i<j} g_{ij}(a_i - a_i^\dagger)(a_j - a_j^\dagger) \quad (1)$$

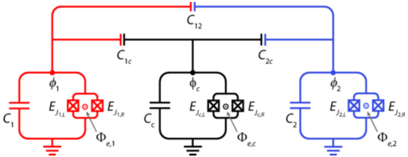


Figure: The tunable coupler shceme of Transmon[7]

Implementation of CZ gate: SWAP effect between $|200\rangle - |101\rangle$

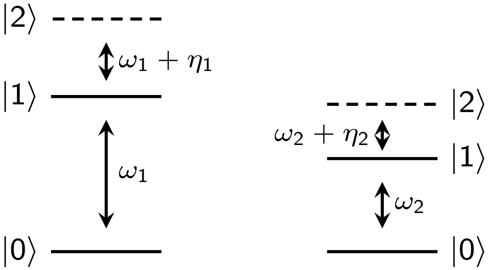


Figure: energy level bias for CZ gate

Hamiltonian in $\{|200\rangle, |101\rangle\}$ subspace: $H_{eff} = \begin{pmatrix} \tilde{\omega}_1 + \tilde{\omega}_2 & \sqrt{2}\tilde{g} \\ \sqrt{2}\tilde{g} & 2\tilde{\omega}_1 + \eta_1 \end{pmatrix}$

Simulation procedure:

Step 1: Design frequency range: Qubit< Coupler<Resonator
Step 2: make sure $g_{\text{eff}}(\omega_c)$ =+5~-30 MHz

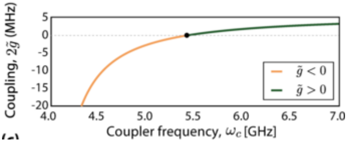


Figure: Effective coupling between q1 and q2[7]

Step 3: Construct the Hamiltonian
Step 4 $|11\rangle - |20\rangle$ swapping condition: $\omega_1 + \eta_1 \approx \omega_2$
Step 5: Caclculate the propogator + single-qubit phase calibration

Step 6: Wrap up the step 1-4 to optimize $\{\omega_{qi},\ C_{q,ij},\ \omega_{\text{on}}...\}$ by Nelder-Mead algorithm with cost function=QPT result
Step 7: Verify the optimized design and control parameters, add decoherence and initial thermalization to quantify the reduction of fidelity...

Project 1: Design and control of Transmon(Further work)

Obstacles in calibration of tunable-coupler-based qubits

- 'Coupler' $\rightarrow$ more decoherence channel
- (Long-time)Distortion correction $\rightarrow$ time cost
- Fast gate operation $\rightarrow$ strong effective coupling
- strayling coupling from neighbours$\rightarrow$ spectator error

Part 2: Implementation of CZ gate with net-zero pulse

Following the methods[6], we do some simple simulations on:

- Spectral analysis of noise
- Add Gaussian noise to z-line flux with varying amp, and compare sensitivity of CZ fidelity between the cases of NZ and unipolar
- Model the non-Markovian noise by sampling the $1/f$ flux noise amp with different standard deviations

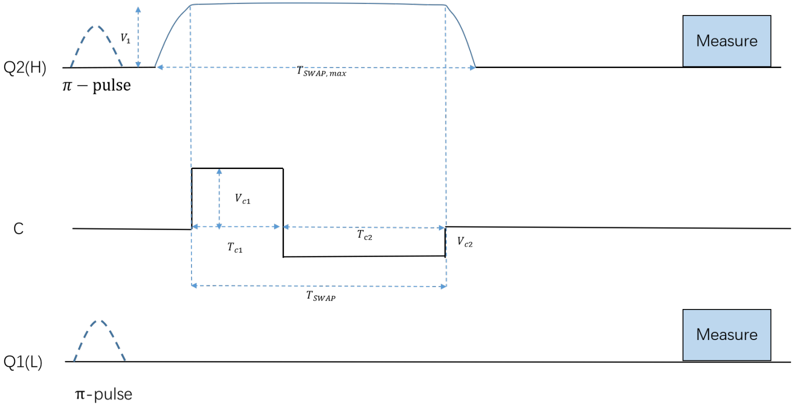
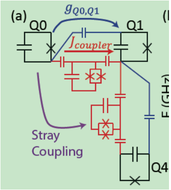


Figure: The Net-zero pulse scheme of SWAP experiment

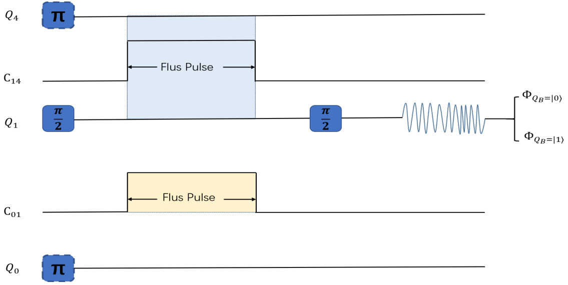
Part 3: Spectator error

In 2021, the IBM present their study on straying coupling [8] as shown in (a). In this paper, they present a scheme with 4 steps to calibrate the 'spectator error':

- Calibrate a standard CZ gate when the spectator qubit is in $|0\rangle$
- Calibrate a standard CZ gate when the spectator qubit is in $|1\rangle$
- Repeat the both of above procedures, but sweeping the flux of spectator coupler



(a) Stray coupling effect



(b) Pulse sequence of spectator calibration

Rough picture of readout: $H_{\text{eff}} = \frac{\hbar\tilde{\omega}_q}{2}\sigma_z + \hbar(\Delta_r + \chi_{\text{eff}}\ \sigma_z)a^\dagger a + \hbar\left[\varepsilon_d(t)a^\dagger + \varepsilon_d^*(t)a\right]$

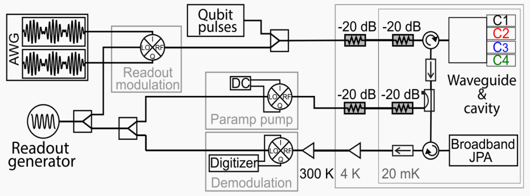
Part 1: Readout Simulator for IQ-Result

Probe signal $f_d(t) = A\sin(\omega_d t + \phi)$: from input port of resonator through the digitizer.

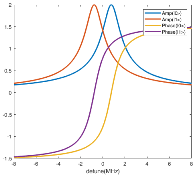
State-dependent response of resonator to f_d:

$$S_{21} = \frac{\kappa}{\kappa/2 - i(\delta - \chi\sigma_z)} \tag{2}$$

Added noise: 2D Gaussian noise



(c) Device[3]



(d) Resonator response to probing

Project 2: Optimize the Qubit Readout

Aims: {Parameters of qubit, resonator, and readout system} $\rightarrow$ IQ-result of single-qubit readout compatible to our experiment data.

Parameter space:

- Qubit Parameters: $\{\omega_q, \eta\}$
- Resonator Parameters: $\{\omega_r, g, \kappa\} \rightarrow \chi_{\mathrm{eff}} = -\frac{g^2}{\Delta}\frac{1}{1+\Delta/\eta}$
- Readout Parameters: $\{\omega_d, P_{rf}, t_{delay}, t_{total}, SNR, NoisePower\} \rightarrow \mathcal{F}_{|0\rangle/|1\rangle}$
- $|1\rangle$ Preparation rate: $\{p\} \rightarrow$ estimate the readout backaction on qubit T_1

Project 2: Optimize the Qubit Readout

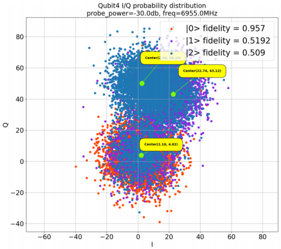
Part 2: Readout by $|2\rangle$

Readout in $|2\rangle$ in place of the traditional $|1\rangle$ readout.

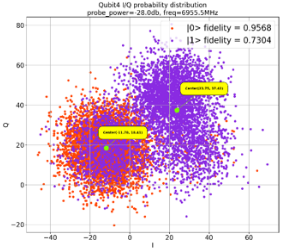
The paradigm of higher-level excited state readout take two advantages:

- Longer T1
- Improve seperability(with $f_d \approx f_{r,|0\rangle}$, and high χ_{eff})

A preliminary result to verify $|2\rangle$ readout scheme working:

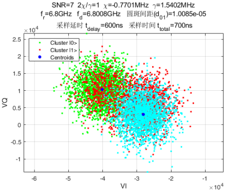


(e) 2-means discriminator

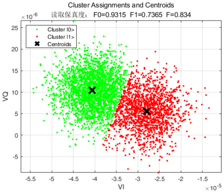


(f) 3-means discriminator

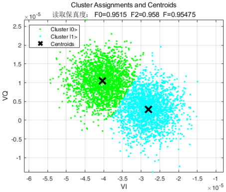
Comparison between experimental result and simulator prediction(without JPA and Purcell filter in this case, fidelity limited by short T1):



(g) IQ representation of $|0\rangle$, $|1\rangle$, $|2\rangle$



(h) $|0\rangle$, $|1\rangle$ discriminator



(i) $|0\rangle$, $|2\rangle$ discriminator

Error Sources

One can directly read from readout IQ result:

- Overlap Error
- Initialization Error
- Outliers

Project 2: Optimize the Qubit Readout(Further work)

Part 3: Readout backaction on qubits

From the qubits' point of view, the backaction from readout signal may has negative impact on both their T_1 and T_2:

- Flucutaion of intraresonator photons$\rightarrow$ lower T_2
- Noise carried by readout pulse and added by amplifiers
- Purcell effect $\rightarrow$ lowering T_1
- High-power probing $\rightarrow$ non-RWA transition[1][5]

Project 2: Optimize the Qubit Readout(Further work)

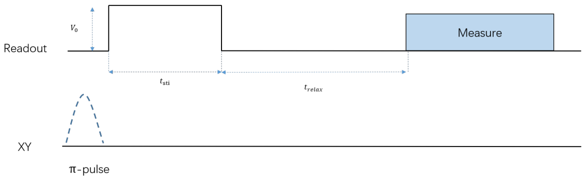


Figure: Pulse sequence for readout backction on T_1[1]

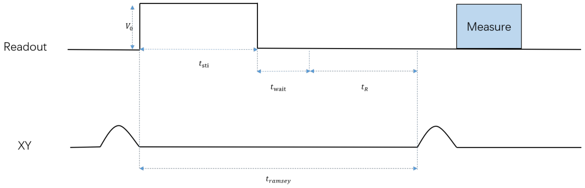


Figure: Pulse sequence for readout backction on T_2

Further work

- Puse amplitude shaping with smooth functions
- Perform single-shot readout under IMPA, redo the backaction experiment
- Cavity-reset & pre-measurement[4]
- Multiplexed readout

Calibration of Transmon

Calibration: All qubits parameters and theoretical predictions must be verified by step-by-step operatioins on qubits.

Core ideas of calibration

- only three(or less) control lines for each qubit
- outside in: inspect the unknown from the known
- probe ≈ ideal value

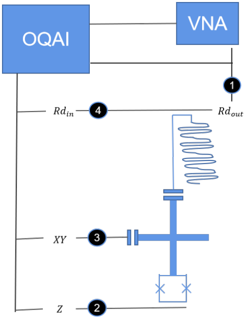


Figure: Single-qubit calibration

Step.1: VNA→ $S_{21}(\omega_d)$
Step.2: Vary DC → Resonator spectrum
Step.3: Vary X_{rf} → Qubit spectrum
Step.4: Readout parameters optimization

Step.5: Accurate calibration, multi-qubits calibration.....

Summary: Errors on multi-qubits

Classification of error sources? ★ Simulation, Calibration, Benchmarking...

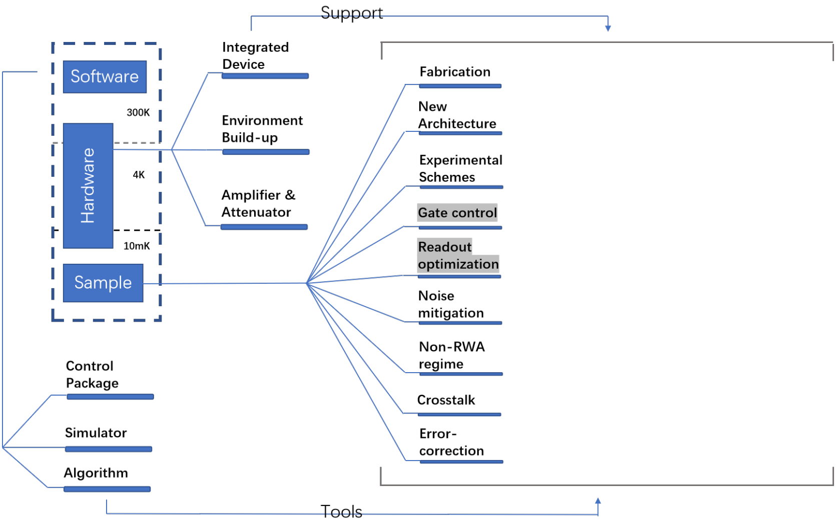
Error Source

In superconducting qubits, error sources can be roughly divided into two types: coherent and incoherent errors. For example, this tunable-coupler-based qubits chip tells us...

$$
\begin{array}{cccccccc}
\textit{Feedline} & --- & --- & --- & --- & --- & --- & --- \\
\textit{Purcell} & P_0 & & P_2 & & P_4 & & P_6 & \ldots\ldots \\
\textit{Resonators} & R_0 & & R_2 & & R_4 & & R_6 & \ldots\ldots \\
\textit{Qubits} & Q_0 & C_1 & Q_2 & C_3 & Q_4 & C_5 & Q_6 & \ldots\ldots \\
\mathrm{XYZ}-\textit{line} & | & & | & & | & & | & \ldots\ldots
\end{array}
$$

Various types of crosstalk!

Summary: Problems of so-called quantum engineering



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