Engineering the quantum
probing atoms with light & light with atoms in a transmon
circuit QED system

Nathan K. Langford

OVERVIEW

• Transmon circuit QED experimental hardware
• Finding your qubit: where to start when the fridge gets cold
• Getting things pulsing
• Getting control of your qubit
• Fast frequency tuning: making your qubit dance
• Using your qubit as a…

Acknowledgements
Ramiro Sagastizabal, Florian Luthi
and the rest of the DiCarlo lab at TU Delft
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A typical transmon circuit QED setup

microwave electronics

data acquisition

dilution refrigerator & cryogenic components

amplification chain

chip

Risté et al., Nat Comm 2015
A typical transmon circuit QED setup

- Microwave electronics
- Amplification chain
- Microwave components
- Dilution refrigerator & cryogenic components
- Data acquisition
- Chip
A typical transmon circuit QED setup

Cavity QED in electronic circuits
Haroche group (2000s)

- “cavity” – \( \mu \)w coplanar waveguide resonator
- “atom” – frequency-tunable transmon qubit
- “input/output” - \( \mu \)w feedline for control/read

Rabi interaction: field-dipole coupling

\[
H = \hbar \omega_r \sigma_a + \frac{1}{2} \hbar \omega_q \sigma_z + \hbar g (\sigma_+ + \sigma_-) (a + a^\dagger)
\]

Jaynes-Cummings interaction: strong coupling regime

\[
H = \hbar \omega_r \sigma_a + \frac{1}{2} \hbar \omega_q \sigma_z + \hbar g (a\sigma_+ + a^\dagger \sigma_-)
\]
RWA: \( \gamma, \kappa < g, \Delta \ll \omega_q, \omega_r \)

Jaynes-Cummings interaction: dispersive regime

\[
H = \hbar \omega_r \sigma_a + \frac{1}{2} \hbar \omega_q \sigma_z + \hbar \chi \sigma_z a^\dagger a
\]
\( g \ll \Delta \)

Component frequencies
\( \omega_{\text{qub}} : E_C \) (geometry)  \( \omega_{\text{res}} : \) length (geometry)
\( : E_J \) (junctions)  \( : \) materials

Rabi, Phys Rev 49, 324 (1936)
Jaynes & Cummings, Proc IEEE 51, 89 (1963)
A typical transmon circuit QED setup

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Component frequencies
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Rabi, Phys Rev 49, 324 (1936)
Jaynes & Cummings, Proc IEEE 51, 89 (1963)
The transmon qubit

- superconducting thin-film circuit → low-loss operation
- Josephson junctions → nonlinearity without loss

large dipole moment (capacitive coupling)

almost harmonic (a bit anharmonic)
harmonic

- a variety of junctions: single vs split, break junctions, nanowire junctions
- a variety of geometries: 2D vs 3D, xmon, gmon, three-island
- focus here: Al-AlOx SIS tunnel junction, standard transmon
OVERVIEW

- Finding your qubit: where to start when the fridge gets cold
A typical transmon circuit QED setup

Microwave setup

microwave electronics

microwave components

dilution refrigerator & cryogenic components

data acquisition

amplification chain
Resonator spectroscopy

Microwave setup

- Microwave components
- Dilution refrigerator & cryogenic components
- Microwave electronics
- Data acquisition
- Amplification chain
Resonator spectroscopy

What do you see with?

- digitise, demodulate & integrate
- frequency down-mixing

IQ Mixers

- nonlinearity provides signal multiplication
- IQ mixers multiply both carrier quadratures (cos and sin terms)
- can up-convert and down-convert signals
- typically used to move between microwave regime (for our experiments) and radio frequencies (where the electronics is good and cheap)

- microwave equivalent of Mach-Zender
- homodyne: $\omega_{RF} = \omega_{LO}$
- heterodyne: $\omega_{RF} = \omega_{LO} + \omega_{IF}$
- nonlinearity provided by IQ mixers
Step 1: Find your resonators

First look at your device...
Step 1: Find your resonators

What should you see?

Quality factors

- energy stored / energy loss per cycle

\[ Q = \frac{\omega}{\kappa} \]

\[ \frac{1}{Q} \propto \kappa = \frac{1}{\tau_{\text{decay}}} = \text{decay rate} \]

\[ \frac{1}{Q_{\text{total}}} = \sum_j \frac{1}{Q_j} \]

Asymmetry arises from impedance (unwanted inductance) mismatching in the feedline and coupler.
Step 2: It’s alive!

The first signature of your qubit

- low power: linear regime
- high power: nonlinear regime
- very high power: saturation regime (bare resonator response)
- frequency shift: $\frac{g^2}{\Delta}$
  
  (same as dispersive shift for a two-level qubit)
- for most purposes, you want to operate in the linear regime

Note: $\text{dBm} = \log \text{scale unit of power}$
Step 3: Change the tune…

Can you tune the qubit frequency?

Qubits with matched junctions
Koch et al., PRA 2007

\[
f_q^{\text{bare}} = \sqrt{8E_C E_J(\Phi_I) - E_C}
\approx f_q^{\text{max}} \sqrt{|\cos (\pi \Phi_I / \Phi_0)|}
\]

\[
f_r = f_r^{\text{bare}} + g^2 / \Delta_{q,r}
\]

\((\Phi_0 = h/(2e) = \text{magnetic flux quantum})\)

- identify sweet spots (top and bottom)
- calculate flux scaling
- identify qubit-resonator crossing points and calculate coupling strengths
Qubit spectroscopy

Microwave setup
Qubit spectroscopy

Microwave setup

![Microwave setup diagram](image-url)
**Measurement signal**

- uses two microwave tones (resonator readout and qubit excitation)
- detects qubit-state-dependent frequency shift of the resonator
- dispersive regime:

\[
H = \hbar \omega_r a^\dagger a + \frac{1}{2} \hbar \omega_q \sigma_z + \hbar \chi \sigma_z a^\dagger a = (\hbar \omega_r + \hbar \chi \sigma_z) a^\dagger a + \frac{1}{2} \hbar \omega_q \sigma_z
\]

excitation OFF

excitation ON
Step 4: Find your qubit…

Where do you start looking?

- move to a sweet spot or near a crossing
- use a power shift to estimate the qubit detuning
- start scanning…

*find resonator*
Step 4: Find your qubit…

Where do you start looking?

- move to a sweet spot or near a crossing
- use a power shift to estimate the qubit detuning
- start scanning…

![Graphs showing amplitude and phase](image)
Step 4: Find your qubit…

Where do you start looking?

- move to a sweet spot or near a crossing
- use a power shift to estimate the qubit detuning
- start scanning…

But is it your qubit??
Step 5: It don’t mean a thing if it ain’t got that swing…

**Flux tuning a split-junction qubit and tracked qubit spectroscopy**

- as you move the qubit, both resonator and qubit frequency move
- at each step, find the resonator and then find the qubit
**Step 5: It don’t mean a thing if it ain’t got that swing…**

**Flux tuning a split-junction qubit and tracked qubit spectroscopy**

- as you move the qubit, both resonator and qubit frequency move
- at each step, find the resonator and then find the qubit

But this does not look like this!!

- asymmetric qubits have two “sweet spots”
- frequency gradient vs flux (and therefore flux noise) also reduced

\[
E_{J,\text{max}} = E_{J1} + E_{J2} \\
E_{J,\text{min}} = E_{J1} - E_{J2}
\]
Step 6: Estimating qubit-resonator couplings

Variety of different methods

- **Power Shift**
- **Fit Resonator & Qubit arches**
- **Avoided Crossing**
- **Flux Pulsing**

DiCarlo et al., Nature (2010)
Step 7: Estimating qubit anharmonicity

Transmons are weakly anharmonic

- linked to low charge dispersion (charge noise insensitivity)
- higher levels affect photon-number dispersive shift
- limits speed of control pulses
- can be used to implement qubit-qubit entangling gates
- can also cause unwanted spurious system interactions

DiCarlo et al., Nature (2009)

High-power spectroscopy

“Two-tone” spectroscopy
(warning: uses three microwave tones)

Courtesy of F. Luthi (2016)
Engineering the quantum

OVERVIEW

• Getting things pulsing
**CW vs Pulsed spectroscopy**

**Continuous spectroscopy: all sources always on**

- readout cavity full of photons during qubit excitation

- **Photon-number splitting**

- **Qubit broadening/shifting**
  Schuster et al., PRL (2005)

**Pulsed spectroscopy**

- half ‘n’ half: pulse the readout tone
  - requires little calibration, works with short lifetimes, can be messier

- all the way: pulse both excitation and readout tones
  - requires more calibration (e.g., excitation power, excitation and readout resolution), can be cleaner
  - can use both saturation and pi pulses for excitation pulses
Pulsed spectroscopy

Microwave setup
Pulsed spectroscopy

Microwave setup: half ‘n’ half
Pulsed spectroscopy

Microwave setup: all the way
**Pulsed spectroscopy**

**Live Fourier transform of a square pulse**

- Readout pulse length sets readout resolution
- Excitation pulse sets qubit resolution

Decreasing pulse amplitude
Engineering the quantum

OVERVIEW

- Getting control of your qubit
Microwave setup: all the way
Basic calibration steps

- **Step 1** mixer
  - -- allows full control of:
    - drive pulse envelope and drive pulse phase
      - (rotation axis)
    - -- mixers require careful calibration to compensate for imperfections

- **Step 2** pulse timings (RO, drive)
  - -- timing critical at qubit and digitization (ADC)
  - -- delays are calibrated in AWG sequencing

- **Step 3** drive frequency
  - mixer

- **Step 4** pulse amp
Basic calibration: pulse frequency and amplitude

Find qubit frequency

- good starting sequence: most tolerant to inaccuracies

\[ \text{scan for resonator} \] \[ \text{scan for qubit} \]

Warning: frequency may be significantly inaccurate if the spec readout power is too high!!

Calibrate pulse amplitude using Rabi oscillations

- traditional Rabi oscillations (vary pulse length)
- Rabi calibration sequence (vary amplitude for target pulse length)

Wallraff et al., PRL (2005)
Basic qubit characterisation sequences

*T1: qubit relaxation time*

- well-characterised pulse not required
- calibration points allow conversion from I/Q data to probability
Basic qubit characterisation sequences

*T2 star (Ramsey time): qubit dephasing time*

- need reasonably well characterised pulse, or the data will look strange
- e.g., frequency detuning can give data outside the range of the calibration points
- artificial detuning allows better fitting of the decay time and frequency
- very versatile sequence with many applications
Basic qubit characterisation sequences

T2 echo: decoupled qubit dephasing time

- insensitive to low-frequency phase noise
- not so sensitive to detuning because of echo effect
Fine-tuning your pulses

Optimal single-qubit control with DRAG
Fine-tuning your pulses

Optimal single-qubit control with DRAG

• 1-2 transition is quite close to 0-1 transition, especially for short drive pulse durations (~ 10 ns)
• leakage errors: pulses driving qubit into 2 state
• phase errors: qubits temporarily populate 2 state during pulse, leading to phase errors
  \(\rightarrow\) use “derivative removal by adiabatic gate (DRAG)"

Motzoi et al., PRL (2009)
Chow et al., PRA (2010)

Reed, PhD thesis, Yale (2013)
Fine-tuning your pulses

**Qubit frequency with Ramseys**

- sensitivity to frequency increases with step size
- start small, zooming in after each step, until you reach target accuracy
- robust technique, limited mainly by T2 coherence time

50 ns step

10 ns step

**Qubit amplitude with flipping sequences**

- small amplitude errors may only become significant after many pulses
- diagnosed best with a long pulse sequence
Fine tuning your pulses: going further?

State of the art

These techniques should allow you to get near fidelities sufficient for fault-tolerant single qubit control in surface code.

Amplifying errors for accurate benchmarking

- Randomized Benchmarking: targets gate errors independently of “preparation-and-measurement” errors; rigorous benchmarking, limited diagnostic capabilities
- Gate-Set Tomography: complete characterisation of everything, long and arduous

Operational approaches

- Your application is the most important yardstick
- Use algorithm specific diagnostics
- Amplify errors that are relevant to your application
- e.g., Martinis benchmarking

Engineering the quantum

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• Getting things pulsing
• Getting control of your qubit
• Fast frequency tuning: making your qubit dance
• Using your qubit as a...
Fast frequency tuning: let’s dance!

Why do you want to be able to pulse your qubit frequency?

Controlled excitation swapping with bus resonators and other qubits

Fast qubit-qubit entangling gates and arbitrary interactions

DiCarlo et al., Nature (2010)
Majer et al., Nature (2007)
Salathé et al., PRX 2015
DiCarlo et al., Nature (2009)
Fast frequency tuning: let’s dance!

Microwave setup
Fast frequency tuning: let’s dance!

Microwave setup

"bias tee"
Fast frequency tuning: a distorted reality

How you want flux pulsing to look

Digital simulation of the quantum Rabi model

Fast frequency tuning: a distorted reality

But what’s the real story?

AWG: finite BW, sampling rate, resolution, amplitude

frequency-dependent cable loss (skin effect)

“bias tee”

low-pass filtering

on-chip response??

Fast frequency tuning: a distorted reality
Fast frequency tuning: a distorted reality

Pre-compensating non-ideality with “predistortion” filters

[Graph showing target and predistorted waveforms over time]
Fast frequency tuning: a distorted reality

Inside the fridge: the qubit is your signal

Flux-controlled excitation swapping: the flux chevron

What you see when you first get inside the fridge
Fast frequency tuning: a distorted reality

RamZ: measuring your flux pulse with a Ramsey sequence

- use a Ramsey pulse pair to sense residual frequency error after the down step of a flux pulse
- increase/decrease pulse separation to control detector sensitivity
- adjust step size to probe different timescales
OVERVIEW

- Using your qubit as a…
Using your qubit as a... photon meter

Measurement of a bus resonator via an ancilla “meter” qubit

- study interaction between “Rabi” qubit and (quarter-wave) “Rabi” resonator
- measure Rabi qubit directly and measure Rabi resonator via the “Wigner” qubit
- resonator could be loaded with photons via resonant interaction with the Rabi qubit (g ~ 2 MHz) and coherently driven via a classical input line
- Wigner qubit strongly coupled (~ 70 MHz) but dispersively (detuning ~ 1.4 GHz)
- Wigner qubit state read out independently using a dedicated readout resonator

Using your qubit as a... photon meter

Photon-dependent qubit frequency: the ac Stark effect

Schuster et al., PRL 2005

Dispersive-regime Hamiltonian

\[
H = \hbar \omega_r a^\dagger a + \frac{1}{2} \hbar \omega_q \sigma_z + \hbar \chi \sigma_z a^\dagger a = (\hbar \omega_r + \hbar \chi \sigma_z) a^\dagger a + \frac{1}{2} \hbar \omega_q \sigma_z
\]
Using your qubit as a... photon meter

Photon-dependent qubit frequency: ac Stark effect

Schuster et al., PRL 2005

Dispersive-regime Hamiltonian

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\]

\[
\chi = \frac{g^2 \alpha}{\Delta (\Delta + \alpha)} \quad \alpha = \text{anharmonicity}
\]
Using your qubit as a… photon meter

Photon-number splitting of the qubit peak

Size of dispersive shift depends on how photons are created!!

- chi varies linearly with drive frequency
- the standard value is only true on resonance (dressed-state frequency)
- chi -> 0 at bare resonator frequency minus cavity shift

Gambetta et al., PRA 2006
Using your qubit as a... photon meter

**Ramsey-based average photon meter**

- $\pi/2$ pulse
- delay $\tau$ (sets range)
- $\pi/2$ pulse

**Ramsey-based parity meter**

- $\pi/2$ pulse
- delay $\tau = 1/4\chi$
- $\pi/2$ pulse

Using your qubit as a... photon meter

The dark (bright?) side of qubit-resonator “chevrons”

Recall qubit “chevron”:
Using your qubit as a... photon meter

The dark (bright?) side of qubit-resonator “chevrons”

**photon meter**

**parity meter**
Using your qubit as a… photon meter

Direct Wigner tomography via a parity measurement

- requires resonator input coupler for displacement pulse
- ancilla qubit for parity operation and readout

\[
W(\alpha | \rho) = \frac{2}{\pi} \text{Tr} \left[ \Pi D(\alpha)\dagger \rho D(\alpha) \right]
\]

**Measuring flux noise**

- tuning a qubit away from its sweet spot increases its sensitivity to flux noise
- $T_1$ and $T_2$ echo measurements give estimate of pure dephasing

\[
\frac{1}{T_2^\varphi} = \frac{1}{T_2^{\text{echo}}} - \frac{1}{2T_1}
\]

From the change in pure dephasing with flux gradient, can calculate $1/f$ flux noise:

\[
A = 1/f \text{ flux noise @ 1 Hz}
\]
Using your qubit as a… noise spectrum analyser

**Measuring charge noise**

- in transmons, charge noise is exponentially suppressed with increasing $E_J/E_C$
- environmental charge noise causes qubit to wander along the offset charge axis
- transmon dipole oscillations mediated by Cooper pair tunnelling through junction
- quasiparticle (unpaired electron) tunnelling events shifts energy curves by half a pair
- this causes shot-to-shot switching between two frequencies, which shows up as beating in a Ramsey experiment and can be tracked

Koch *et al.*, PRA 2007 (transmon bible)
Risté *et al.*, Nat Comm 2013
**Measuring charge noise**

- In transmons, charge noise is exponentially suppressed with increasing $E_J/E_C$.
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- Quasiparticle (unpaired electron) tunnelling events shift energy curves by half a pair.
- This causes shot-to-shot switching between two frequencies, which shows up as beating in a Ramsey experiment and can be tracked.

Koch *et al.*, PRA 2007 (transmon bible)
Risté *et al.*, Nat Comm 2013
Charge noise in a nanowire “dmon”

- shows very different noise behaviour from the standard SIS junction transmon
- conduction channels in the semiconductor nanowire may be very sensitive to environmental charges
- exact source of frequency noise unknown
- we use a parity meter to study the shot-to-shot switching dynamics

Courtesy of F. Luthi, T. Stavenga (2016)

random telegraph noise
Summary in pictures...
Asymmetric qubits and why you might want ’em…

Effect of mismatched junctions on qubit frequency

- matched junctions ($E_{J1} = E_{J2}$):

  \[ f_q = (f_q^{max} + E_C) \sqrt{\cos(\pi \Phi/\Phi_0)} - E_C \]

- mismatched junctions ($E_{J1} > E_{J2}$):

  \[ f_q = (f_q^{max} + E_C) \left[ \alpha^2 + (1 - \alpha^2) \cos^2 \left(\pi \Phi/\Phi_0\right) \right]^{1/4} - E_C \]

![Graph showing qubit frequency vs. bias flux]

asymmetry $\sim 0.86$
Asymmetric qubits and why you might want ’em…

**Effect of mismatched junctions on qubit frequency**

- matched junctions \((E_{J1} = E_{J2})\):
  \[
  f_q = (f_{q}^{\text{max}} + E_C) \sqrt{|\cos (\pi \Phi/\Phi_0)|} - E_C
  \]

- mismatched junctions \((E_{J1} < E_{J2})\):
  \[
  f_q = (f_{q}^{\text{max}} + E_C) \left[ \alpha^2 + (1 - \alpha^2) \cos^2 \left( \frac{\pi \Phi}{\Phi_0} \right) \right]^{1/4} - E_C
  \]

![Graph showing qubit frequency as a function of bias flux with different asymmetry values](image)

**asymmetry \(\sim 0.68\)**
Asymmetric qubits and why you might want ’em…

Effect of mismatched junctions on qubit frequency

- matched junctions ($E_{J1} = E_{J2}$):

$$f_q = (f_{q}^{\max} + E_C) \sqrt{\cos(\pi \Phi/\Phi_0)} - E_C$$

- mismatched junctions ($E_{J1} < E_{J2}$):

$$f_q = (f_{q}^{\max} + E_C) \left[ \alpha^2 + (1 - \alpha^2) \cos^2 \left( \pi \Phi/\Phi_0 \right) \right]^{1/4} - E_C$$

asymmetry $\sim 0.68$
Pulsing with an IQ mixer

- Single sideband modulation of a microwave carrier tone
- Pulse envelope allows switching of pulses on/off
- RF modulation of IQ envelopes allows control of drive pulse phase
- Also compensation for mixer imperfections: leakage, skewness

Square pulse (e.g., for saturation pulses)

Qubit pulses (DRAG)

SB modulation in frequency domain
**Basic calibration 1: mixer leakage and skewness**

**Calibrating single-sideband pulse modulation**

Mixer leakage: Adjust DC offset voltages of the I & Q channels of the AWG to minimise leakage of the carrier tone.

Mixer skewness: Adjust relative phase and amplitude of I/Q modulation envelopes to minimise power in the (unwanted) spurious sideband.

“spurious sideband” can cause errors such as “leakage” out of the qubit basis.
Basic calibration 2: pulse timings

Getting your pulses in sync

- Pulse timings controlled by the AWG through analogue and digital (marker) outputs
- Latency (internal delays) in electronics, filtering and cabling introduce different signal delays
- Timing is critical “on chip” and at the ADC
- Delays, once calibrated, are easily compensated in the pulse sequences.

Direct calibration: Signals transmitted through the feedline show up in the measurement signal. Remember: Always look at the start times!!

Indirect calibration: Other signals must be calibrated by looking at the response of other elements, like qubits. Ramsey-based pulse sequences are the most sensitive way of detecting frequency shifts.
Fast frequency tuning: a distorted reality

What it looks like in reality…

Step response of an isolated AWG
Fast frequency tuning: a distorted reality

What it looks like in reality...

Step response of an isolated AWG

Corrected step response from AWG
Fast frequency tuning: a distorted reality

What it looks like in reality…

Step response of an isolated AWG
Corrected step response from AWG
Step response after bias tee
Fast frequency tuning: a distorted reality

What it looks like in reality…

Step response of an isolated AWG

Corrected step response from AWG

Step response after all corrections before entering fridge

Step response after bias tee
Fast frequency tuning: a distorted reality

What it looks like in reality…