Superconducting qubit: Circuit Quantum Electrodynamics - Leonardo DiCarlo

Hi! Last time, we introduced our superconducting qubit of choice in QuTech, the transmon. We focused on a transmon in isolation, studying its weakly anharmonic spectrum. Today, we will add the remaining ingredients that we need to perform qubit readout and two-qubit gates.

These ingredients are transmission-line resonators. The resulting architecture for quantum hardware, combining qubits and resonators, goes by the name of circuit quantum electrodynamics, or circuit QED. As this name suggests, circuit QED is a solid-state version of cavity QED, an older field of physics that studies the interaction between light and matter at its most fundamental, with flying atoms and single photons trapped inside three dimensional cavities.

In circuit QED, qubits play the role of atoms and transmission-line resonators play the role of cavities.

We build these resonators from coplanar waveguide transmission lines that are terminated with either open- or short circuits. For example, the resonator I show you here has a short at the far end, and an open termination at the close end. Well, it's not exactly open. The resonator at this end couples capacitively to a feedline that will be used later to interrogate the scattering properties of the resonator near its fundamental frequency.

This fundamental mode corresponds to the length matching approximately one quarter of the wavelength. For this reason, we call it a quarter-wave or lambda over four resonator. Resonators have higher modes of resonance as well, but most of the time, we focus exclusively on the fundamental.

The capacitive coupling between the qubit and the resonator is most clearly visualized by performing spectroscopy of the combined system. As this typical image shows, as we tune the qubit through resonance with the resonator, we observe the emergence of an avoided crossing. This avoided crossing is known as the vacuum Rabi splitting. The minimum splitting is equal to twice the coupling constant, g, in the celebrated Jaynes-Cummings Hamiltonian describing the system quantum mechanically.

Most of the time, however, we avoid this resonant regime. We tend to focus on the so-called dispersive regime in which the detuning Delta of the qubit with respect to the resonator is several times larger than g in magnitude.

In this dispersive regime, there is a small but finite remnant of the avoided crossing. If we consider the avoided crossings arising between qubit-resonator levels with equal total number of excitations, we learn something very useful: the ladder of photon excitations remains harmonic, but the resonance frequency depends on the state, |0> or |1> of the qubit. This dependence of the resonator frequency on qubit state is the key ingredient allowing qubit readout. We can interrogate the resonator, and thereby also the qubit, by measuring the transmission properties of a microwave pulse applied to the feedline with a frequency close the bare fundamental. Niels will cover this in greater detail in his video.

Moving on, when two qubits couple to a common resonator, an avoided crossing is also observed when one qubit is tuned through resonance with the other qubit. Compared to the vacuum Rabi splitting, which you can see here, the qubit-qubit avoided crossing is smaller, by a factor (g/Delta)

These qubit-qubit interactions mediated by a dispersively coupled common 'bus' resonator are the key to doing two-qubit gates. Adriaan will discuss the specific avoided crossing that we use to implement two-qubit conditional-phase gates. Hint: it is not this one!

So, let's now see examples of how transmons and resonators can be combined to build simple quantum processors. This is the first one I built, back in 2008, together with collaborators at Yale. It has two transmon qubits and only one resonator. This resonator is used for both qubit-qubit coupling and readout functions.

The resonator has capacitive terminations at both ends, so it's a half-wave or lambda over two resonator.

The optimal parameters of a resonator for readout and for coupling are often in conflict with one another. For this reason, the next generation of processors that we built in Delft uses different resonators for these functions.

Here's an example two-qubit processor from 2013. Note the common lambda over two bus resonator in the middle, and the lambda over four readout resonators, one per qubit, coupled to the common feedline.

Here we see the same concept in a four-qubit processor. The planar constraints required us to have two feedlines. Hopefully, you can easily recognize the bus resonator common to all 4 qubits, and the dedicated readout resonators, one for each qubit.

So, as a simple exercise, I challenge you to identify the bus resonators and readout resonators in this five-qubit processor from 2015. How many of each are there? In this more complex processor, we could get away with one feedline for all readout resonators! You will see the trick or the *astuce* in the next video!

To motivate this next video on scalable circuit QED, note that all of these processors have a common form factor (roughly 2 mm by 7 mm) and a common location of the up to eight ports connecting them to the external world. This reflects the use of a common printed circuit board throughout all these years! Surely a new approach must be taken to increase the qubit count! And indeed, the third generation of quantum processors completely rethinks the approach, with extensibility to hundred qubits as the top priority! I can't wait to show you!