Application Note

Bell State preparation of superconduction qubits

Zurich Instruments

Applications: Quantum Computing
Products: UHFQA, HDAWG

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Motivation

Most recent approaches to build a large-scale quantum computer face the challenge of controlling a high number of qubits. Especially, systems based on superconducting circuits demand a high number of microwave control- and readout-channels [1]. Traditional solutions with low-channel count AWGs are not only unfavorable with respect to costs and physical size, but also have drawbacks regarding the system complexity and synchronization. With Zurich Instrument's High-Density AWG (HDAWG) and Ultra-High Frequency Quantum Analyzer (UHFQA), it is possible to provide an highly integrated platform for control and readout, which is ready for scaling up the number of qubits. This application note shows the benefits controlling a 4-qubit experiment with Zurich Instruments hardware, as implemented in the Quantum Device Lab at ETH Zurich, Switzerland.

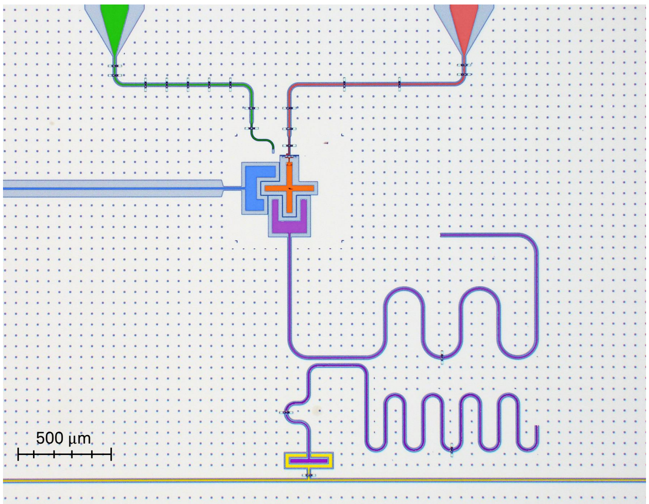

Figure 1. Colored microscope picture of a qubit unit cell: charge-line (green), flux-line (red), qubit island (orange), coupling resonator (blue), readout circuitry with Purcell-filter (violet) and feed-line (yellow). The chip substrate is Silicon with Niobium as a superconducting metal layer. [3]

Sample and Setup

We start by considering single qubit operations and the associated control hardware and then proceed to the multi-qubit case. In superconducting circuit technology, a qubit consists of a non-linear LC circuit, like the structure shown in Figure 1 [2, 3]. The capacitance for this LC circuit is provided by a cross-shaped metal island etched out of the superconducting metal plane (orange). Together with a loop of two small Josephson-junctions connected to this island, a weakly non-linear resonator is created. The total qubit inductance depends on the magnetic flux through this loop. Hence, the qubit resonance frequency can be tuned by adjusting the local magnetic field through the current carried by the flux-line (red) shorted nearby.

The anharmonicity of this resonator leads to an uneven spread of energy levels. Individual energy transitions are addressed by stimulating the circuit with a resonant microwave tone through the capacitively coupled charge line (green). Qubit states are manipulated by modulating this tone with short microwave pulses provided by one channel pair of the HDAWG, upconverted to mircowave frequency using an IQ mixer [4].

The sample shown in Figure 1 is installed in a dilution refrigerator to provide a well isolated low-temperature environment protecting the quantum properties of the circuit.

Qubit readout is achieved by dispersively coupling a transmission-line resonator to the qubit and driving this readout circuitry with a resonant tone (violet) [5].

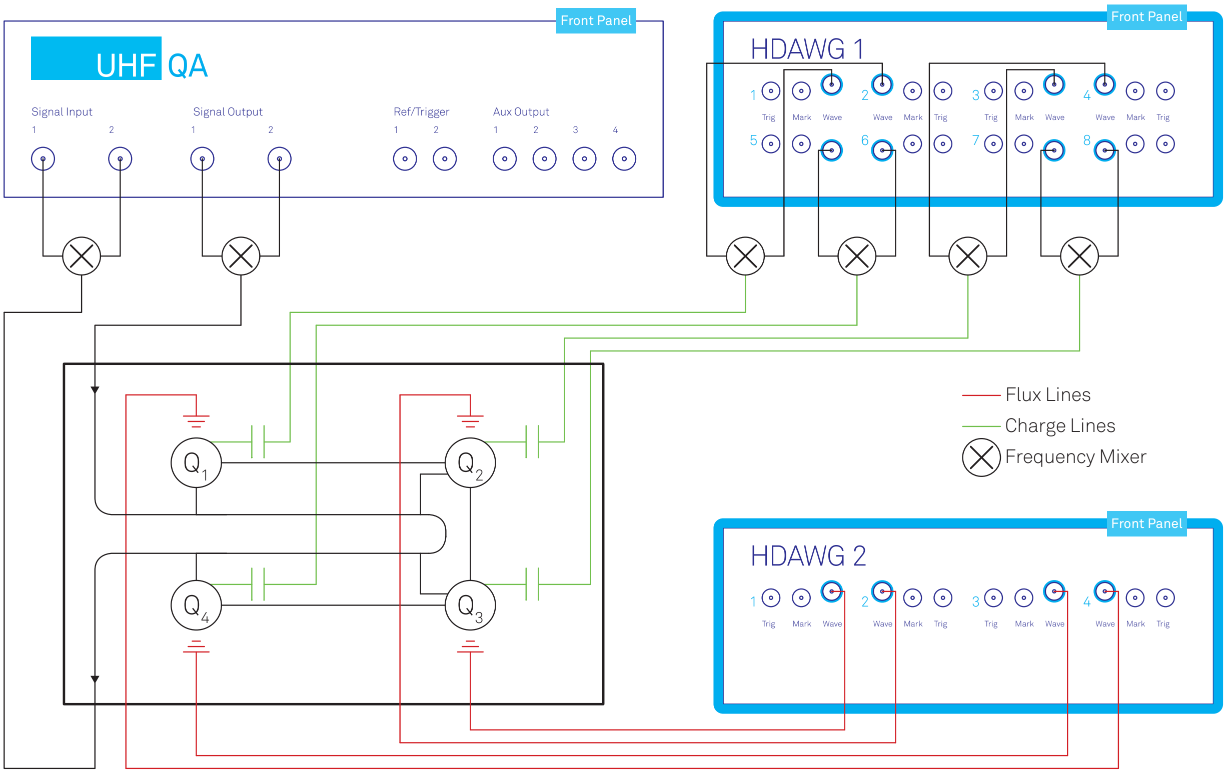

Figure 2. Simplified sketch of the 4-qubit experiment. Qubit readout is carried out by the UHFQA, qubit state manipulation by HDAWG 1 and qubit-qubit coupling is activated by HDAWG 2. For simplicity the local-oscillators, microwave amplifiers, filters and attenuators are not included in this sketch; see [4] for further details.

Depending on the qubit state, this readout resonator will now have a slightly different frequency response, which is evaluated by the UHFQA through the yellow colored feedline. A second transmission-line resonator (Purcell-filter) is placed in between readout resonator and feedline to suppress any additional decay of the qubit state through the readout circuitry [6]. Furthermore, reading out multiple qubits at the same time is possible by using one common feedline for all read out circuits and implementing a frequency multiplexed pulse scheme [7]. For this purpose a tone containing all readout resonator frequencies is generated by the UHFQA and is subsequently analyzed to discriminate the individual qubit states.
Quantum computing applications generally require interactions between qubits. Here, a coupling resonator (blue) is used to connect two neighboring qubits that are brought temporarily into resonance by adjusting the DC current through the respective flux-line. Typical coupling strengths lead to an exchange of the qubit states within hundreds of nano-seconds. The high time resolution signals required at the flux-line inputs can be provided by a 4-channel HDAWG as sketched in Figure 2.

Measurements

Single Qubit Characterizations

A successful set up of any qubit experiment requires the initial characterization of all elements and all operations to be calibrated. As a first step, the UHFQA is used to conduct a spectroscopy over the common feedline to determine the exact resonance frequencies of all four read-out resonators. For this measurement, the frequency of a continuous wave tone (CW) at the feedline input is swept and we evaluate the amplitude of the transmitted signal with the quantum analyzer. Subsequently, the qubit frequencies are asserted by observing the dispersive frequency shift in the readout circuitry. This is accomplished by using a two-tone microwave spectroscopy, where the first tone is fixed in frequency and drives the readout resonator and the second tone is applied through the qubit charge line and swept until the resonant excitation of the qubit leads to a dispersive shift of the readout resonator. The DC currents through the individual qubit flux-lines are set to achieve the desired qubit target frequencies. As a next step, the pulse parameters for single qubit gates are calibrated and qubit coherence characterized through time-resolved measurements where the HDAWG 1 generates the required pulse sequences. First, a Rabi experiment is set up by uploading a sequence of Gaussian pulses at an intermediate fre-

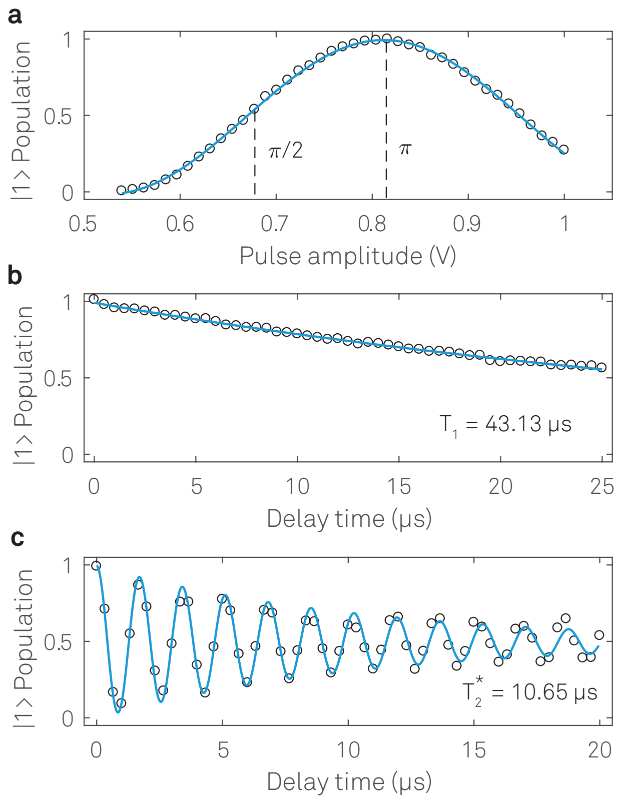

Figure 3. Single qubit characterizations: (**a**) Rabi-oscillation, (**b**) Qubit lifetime T_1 measurement and (**c**) Ramsey fringe measurement to extract T_2^*.

quency and subsequently up-converting it to qubit frequency with an analog IQ mixer. Additionally, the marker output of HDAWG 1 can be used to trigger the UHFQA the qubit readout. The qubit's probability for being in the excited state follows a sinusoidal response which is proportional to the control pulse amplitude and duration, see Figure 3 (a). Thus, sweeping the amplitude within the pulse sequence allows to calibrate the pulse amplitudes necessary for the so-called π- and $\pi/2$-pulses. A π-pulse will bring the qubit exactly from the ground $|0\rangle$ to its excited state $|1\rangle$ similar to a logical inversion in classical computing, whereas the $\pi/2$ will bring the qubit to an equal coherent superposition of both states.

Since any decay from the excited to the ground state will limit the gate performance, the lifetime of all four qubits has to be characterized. For this purpose, the qubit lifetime T_1 is measured by bringing the qubit to its excited state with a π-pulse and sweeping the delay until the qubit readout with the UHFQA occurs. The obtained data, shown in Figure 3 (b), is fitted to an exponential function $\exp(-T/T_1)$ to extract $T_1 = 43.13$ μs. Similarly, the T_2^* qubit coherence time is measured by a Ramsey experiment, which is accomplished by uploading the required pulse sequence to the HDAWG 1. It consists of two $\pi/2$ -pulses separated by a variable delay time followed by the qubit state readout. An additional small detuning of the pulse frequency relative to the qubit frequency causes oscillations in the qubit population. From the measurement shown in

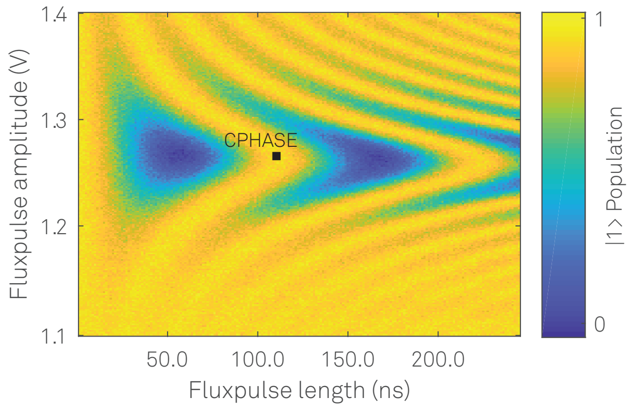

Figure 4. Chevron-Pattern of the CPHASE gate. A first π-pulse on both qubits is used to bring the system in the $|11\rangle$ state and then a flux pulse with variable amplitude and length is applied, followed by the readout of qubit 2.

Figure 3 (c), a T_2^* of 10.65 μs can be extracted by fitting the signal with an exponential decaying cosine function.

The CPHASE Gate

A common way to implement a two qubit gate is the controlled phase (CPHASE) gate, where the interaction of the $|11\rangle$ with the two-photon energy level $|20\rangle$ is exploited [8]. By bringing these two levels on resonance the CPHASE gate is activated and the second qubit will pick up a phase dependent on the state of the control qubit. When a total phase of π is accumulated a logical inversion of the qubit's state has taken place. The characterization of the flux-pulse length and amplitude which is necessary for such a gate operation requires the measurement of the so-called Chevron-pattern. For this purpose, both qubits are first prepared in their excited state by applying a single qubit gate on both (π_x-pulse). By varying the amplitude and length of a subsequent flux pulse on one qubit, the gate operation is conducted and the population exchanges coherently between the ground $|0\rangle$ and the excited state $|1\rangle$. At the end, the state of the second qubit is read out and compiled to the data plot shown in Figure 4. Now, we can calibrate the flux-pulse parameters for the CPHASE gate as indicated by the black marker in Figure 4 and determine the qubit-qubit coupling rate as an inverse of the required gate length. Please note, that for this experiment the flux pulse can be processed with the integrated HDAWG Predistortion filter to compensate for the frequency dependent transmission through the flux-line.

Bell State

We demonstrate the two-qubit gate performance by preparing two neighboring qubits in a maximally entangled state, a Bell state. The sequence of gate operations required is shown in Figure 5 (a). Both qubits are initially brought into an equal superposition by applying single qubit $\pi/2$-rotations. The subse-

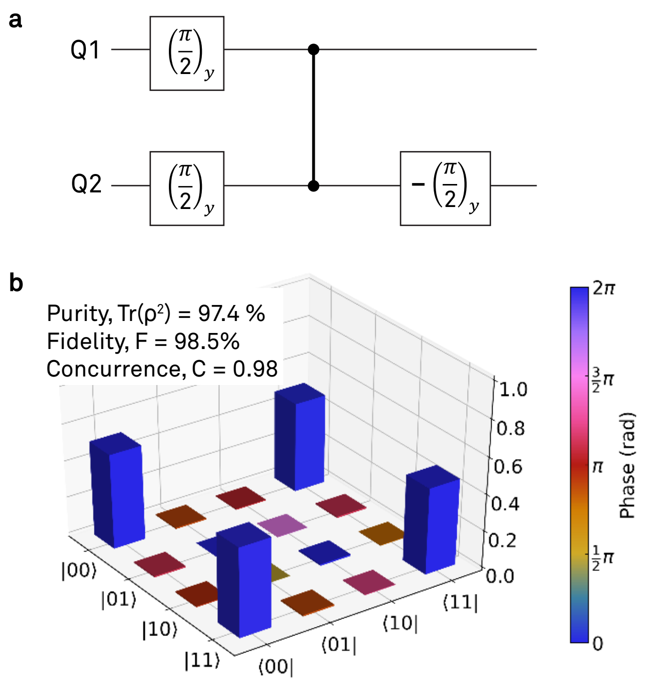

Figure 5. Bell state tomography: (**a**) Pulse Sequence for preparing the Bell state. The state was prepared with the aid of a CPHASE gate, illustrated by a vertical line. (**b**) Density matrix measured by state tomography. The obtained raw data was fitted with a Maximum-Likelihood estimation.

quent CPHASE gate operation entangles both qubits, followed by a final qubit rotation to obtain the targeted Bell state $(|00\rangle + |11\rangle)/\sqrt{2}$. To measure the density matrix ρ of the two qubit system, quantum state tomography is performed [7]. The raw measurement data were fitted to a Maximum-Likelihood estimation to ensure a physically meaningful result. To calculate the fidelity F of our state, we compare the fitted data to the ideal density matrix σ of the Bell state by evaluating,

$$\mathrm{F} = \left[\mathrm{Tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right]^2 = 98.5\,\% \tag{1}$$

In this calculation a single-shot readout fidelity of $\mathrm{F_R} = 98.85\%$ was taken into account.

Outlook

Ranging from essential qubit characterizations to complex multi-qubit gate operations, the combination of HDAWGs and UHFQAs form an effective platform for quantum computing applications. Scaling up to higher number of qubits will demand a well-thought-out device synchronization concept. Zurich Instruments' Programmable Quantum System Controller PQSC facilitates this task and enables the rapid construction of large-scale quantum computing systems.

Acknowledgments

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