Superconducting Circuits and Quantum Computing

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Overview: Superconducting Qubits

Our research addresses the scientific and engineering challenges of building a solid-state quantum computer. Our qubit species of choice is the superconducting persistent-current (PC) qubit (also known as the flux qubit), in which the two quantum states are represented by currents circulating in opposite directions around a superconducting loop interrupted by Josephson junctions. These qubits are multi-level artificial atoms with a Hamiltonian that we can engineer. They are fabricated on a chip, can be connected together, and couple strongly to external fields which we apply by using standard and custom microwave components, and on-chip control wires. We read out the qubit state by detecting the switching events of an underdamped dc-SQUID magnetometer, which encloses the PC qubit. The experiments are performed in a dilution refrigerator at a temperature of 0.01 K above absolute zero, in order for the ambient thermal energy to be much smaller than the energy-level spacing of our artificial atoms, and also reducing the noise being channeled into the device through the control wires.

Our research aims at characterizing and mitigating the sources of decoherence in such devices; at developing means of quantum control; and towards using the qubit as a model quantum system to perform experiments analogous to phenomena in, *e.g.*, optics and atomic physics.

1. Quantum Coherence of a Persistent-Current Qubit under Large-Amplitude Driving – Pulse Imaging via Bi-harmonic Driving

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In the presence of large-amplitude excitation by a microwave field, the artificial atom's quantum state can be driven through one or more of the constituent energy-level avoided crossings. The resulting Landau–Zener–Stückelberg (LZS) transitions mediate a rich array of quantum-coherent phenomena, as experimentally demonstrated in our group during the last few years, see the review paper below by Oliver and Valenzuela (2009). Using a niobium device, fabricated at MIT Lincoln Laboratory in a planarized three-layer process and deep sub-micron photolithography, we demonstrated Mach–Zehnder-type interferometry between repeated LZS transitions and multi-photon (up to n=50) spectroscopy; a regime of quasi-classical dynamics; and microwave-induced cooling. We introduced the concept of "amplitude spectroscopy", in which we probed the artificial atom's energy spectrum over the bandwidth 0.01 – 120 GHz, while driving at a fixed frequency of only 0.16 GHz, but with large driving amplitude, reaching across several level-avoided crossings. This method is in contrast with conventional frequency spectroscopy, whereby the frequency ν of a harmonic driving field is varied to fulfill the resonance conditions $\Delta E=h\nu$, where ΔE is the level separation and h is Planck's constant. Although this latter technique has been successfully employed in a variety of physical systems, including natural and artificial atoms and molecules, its application is not universally straightforward, and becomes extremely challenging for frequencies in the range of 10's and 100's of gigahertz. The novel amplitude-spectroscopy approach provides a means to manipulate and characterize systems over a broad bandwidth, using only a single driving frequency that may be orders of magnitude smaller than the energy scales being probed.

Transitions in artificial atoms can be controlled by carefully engineering the driving protocol. This is particularly relevant for non-adiabatic control methods, such as the ones described above, where the qubit response is very sensitive to the driving waveform. It is important to construct a precisely calibrated waveform such that when it reaches the device after frequency-dependent dispersion in a coaxial waveguide, the desired control is still obtained. By applying a bi-harmonic waveform generated by a digital source, we demonstrated a mapping between the amplitude and phase of the harmonics produced at the source and those received by the device. This technique allowed us to image the actual waveform that arrived at the device, akin to having an on-chip oscilloscope. By predistorting the waveform at the source, we were able to demonstrate the desired control even in the presence of dispersion, see Figs 1-2 below and the paper by Bylander et al. (2009).

These experiments all exhibit a remarkable agreement with theory, and are extensible to other solid-state qubit modalities. In addition to our interest in these techniques for fundamental studies of quantum coherence in strongly driven solid-state systems, we anticipate that careful engineering of the driving protocol will find application to non-adiabatic qubit control and state-preparation methods for quantum information science and technology.

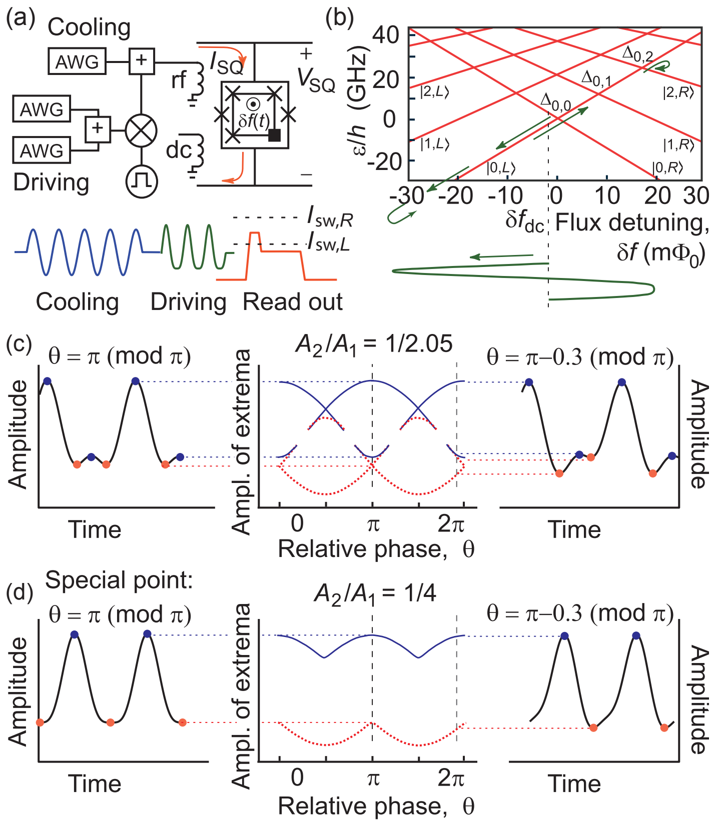

Figure 1: Pulse-imaging via bi-harmonic driving of a superconducting artificial atom.

(a) Schematic experimental setup.

(b) Energy diagram of the artificial atom.

(c-d) Examples of the bi-harmonic waveforms that are being applied to the device in order to control its quantum state.

From the paper by Bylander *et al.* (2009).

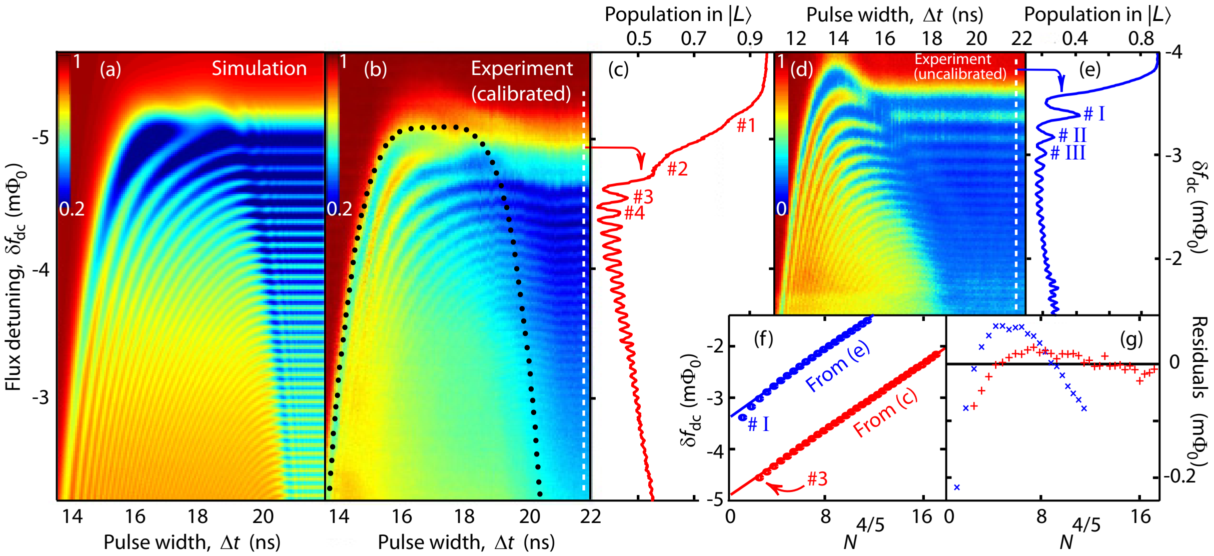

Figure 2: Time-dependent response of the artificial atom to a bi-harmonic driving signal (Stückelberg interference fringes).

The color scale represents the population in one of the qubit's quantum states at the final time Δ*t* of a pulse of the shape in Fig. 1(d). **(a-b)** The edges of the curved fringes provide a direct image of the pulse (black dotted line), obtained experimentally. **(d)** Fringes resulting from an un-calibrated waveform.

From the paper by Bylander *et al.* (2009).

2. Coherent Control, Characterization and Noise Mitigation for Persistent-Current Qubits

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We are investigating the quantum coherence of persistent-current qubits made of aluminum thin films, in collaboration with the group of Y. Nakamura and J.S. Tsai at the NEC Corporation, Japan and MIT Lincoln Laboratory. We have demonstrated quantum coherence through Rabi oscillations, Ramsey fringes, and spin-echo refocusing. Our qubits have shown decay times exceeding 1 us, limited predominantly by energy relaxation, see Fig. 3.

In one design, we have demonstrated wide tunability of both terms (ε and Δ) in the qubit's Hamiltonian $H = \varepsilon\sigma_Z + \Delta\sigma_X$, thus allowing for controlled qubit-qubit coupling through $\sigma_X\sigma_X$, $\sigma_Z\sigma_Z$ as well as $\sigma_X\sigma_Z$. The device is realized by replacing one of the Josephson junctions in the qubit with an additional loop which forms a dc SQUID. By applying different fluxes in the main qubit loop and in the additional SQUID loop, we can change the qubit energy-level separation (ε) and the tunnel coupling (Δ) independently.

Using the results of these coherence measurements, we are developing noise models and NMR-based refocusing schemes for the persistent-current qubit in collaboration with David Cory's group at University of Waterloo.

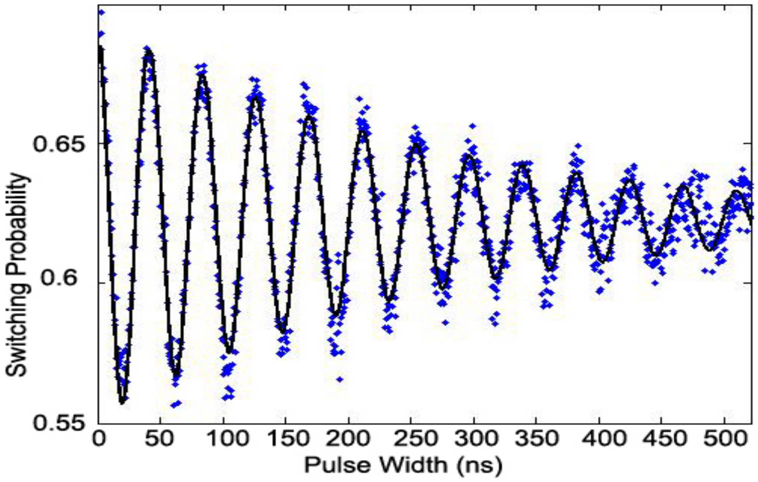

Figure 3: Rabi oscillations in a persistent-current qubit with an energy-level avoided crossing of 1.7 GHz, weakly driven by resonant microwaves. This device was made by shadow-evaporation of Al–AlOx–Al Josephson junctions.

Publications

Journal Articles

J. Bylander, M.S. Rudner, A.V. Shytov, S.O. Valenzuela, D.M. Berns, K.K. Berggren, L.S. Levitov, and W.D. Oliver, *Pulse imaging and non-adiabatic control of solid-state artificial atoms*, Physical Review B **80**, 220506(R) (2009).

W.D. Oliver and S.O. Valenzuela, *Large-amplitude driving of a superconducting artificial atom. Interferometry, cooling, and amplitude spectroscopy*, Quantum Inf. Process. **8**, 261-281 (2009).