Superconducting Circuits and Quantum Computing

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Overview

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. We read out the qubit state by detecting the switching events of an underdamped dc-SQUID magnetometer, which encloses the PC qubit. 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

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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 by using 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 (Oliver *et al.*, 2005); a regime of quasi-classical dynamics (Berns *et al.*, 2006); and microwave-induced cooling (Valenzuela *et al.*, 2006).

Further extending the driving amplitude to reach across several level-avoided crossings, 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. We call this approach “amplitude spectroscopy,” as we obtain spectroscopic information by monitoring the system’s response to amplitude rather than frequency. The resulting “spectroscopy diamonds” contain interference patterns and population inversion that serve as a fingerprint of the atom's spectrum, see Fig. 1 and the article by Berns *et al*. (2008). 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.

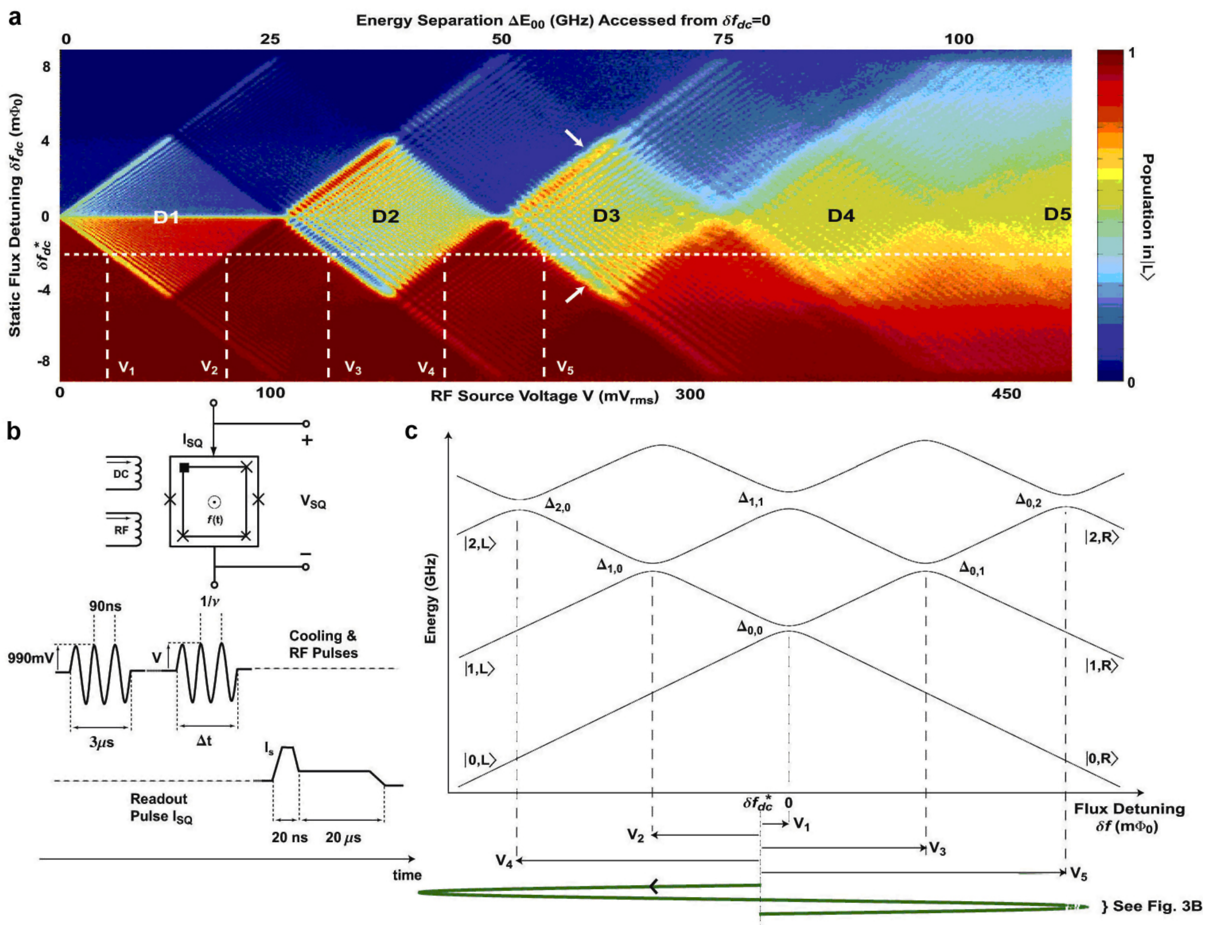

Figure 1: Amplitude spectroscopy. a, Diamonds. The qubit is driven at a fixed frequency ν=0.160 GHz, while the microwave amplitude *V* is swept for each static flux detuning δf_{dc}. Color scale: net qubit population in state $|q, L\rangle$, where $L\,(R)$ labels diabatic states of the left (right) well of the qubit double-well potential (or, equivalently, left- (right-) hand circulating current), and *q*=0,1,2,… labels the longitudinal modes. The diamond edges signify the driving amplitude *V* for each value of δf_{dc} when an avoided level crossing is first reached (amplitudes $V_1 - V_5$ for $\delta f_{dc} = \delta f^*_{dc}$). Top axis: the $|0, L\rangle - |0, R\rangle$ energy spacing $\Delta E_{0,0}$ accessed by *V* from δf_{dc} = 0. **b,** Schematic of the qubit surrounded by a dc-SQUID magnetometer readout. Static and radio-frequency (RF) fields control the state of the qubit: a 3-μs cooling-pulse followed by an amplitude spectroscopy pulse of duration Δ*t* and amplitude *V*. The qubit state is determined with a synchronous readout pulse applied to the SQUID. **c,** Schematic energy-level diagram illustrating the relation between the driving amplitude *V* and the avoided-crossing positions for a particular static flux detuning $\delta f_{dc} = \delta f^*_{dc}$. The arrows represent the amplitudes $V_1 - V_5$ of the RF field at which the illustrated avoided crossings are reached, marking the onset of the diamond regions in (a).

Adapted from Berns *et al.* (2008)

As shown in Fig. 2 and in the paper by Rudner *et al.* (2008), the two-dimensional Fourier transform of the diamond pattern in Fig. 1a is found to exhibit a family of one-dimensional curves in Fourier space. We interpret these images in terms of the time evolution of the quantum phase of a qubit state, and show that they can be used to probe dephasing mechanisms in the qubit. We call this method "quantum phase tomography," as the image of the phase evolution in time is reconstructed from sections, which cut through the energy-domain diamonds.

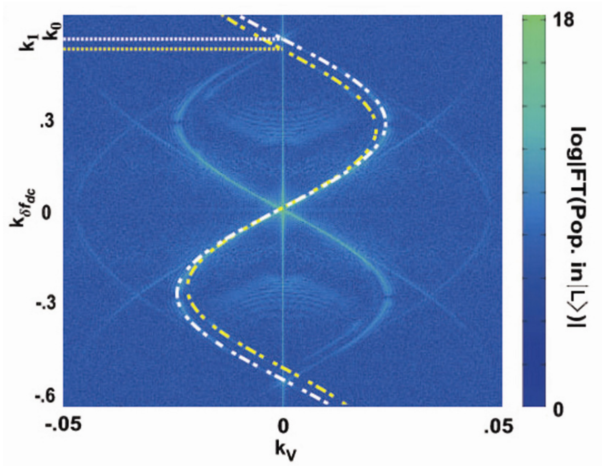

Figure 2: Quantum phase tomography. Two-dimensional Fourier transform of the diamonds D1 and D2 in Fig. 1a. The sinusoids with wavenumbers k_0 and k_1 are contributions from diamonds D1 and D2, respectively.

See Rudner *et al.* (2008)

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.

2. Pulse Imaging via Bi-harmonic Driving

Sponsors
The U.S. Government.

Project Staff
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Transitions in artificial atoms can be controlled by carefully engineering the driving protocol. This is particularly relevant for non-adiabatic control methods, 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. In this work, 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. By predistorting the waveform at the source, we were able to demonstrate the desired control even in the presence of dispersion, see the preprint by Bylander *et al.* (2008).

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

Sponsors
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J. Bylander, S. Gustavsson, F. Yan (MIT Dept. Nucl. Sci. and Eng.), L.S. Levitov (MIT Phys. Dept.), D. Cory (MIT Dept. Nucl. Sci. and Eng.), W.D. Oliver, and T.P. Orlando

In a project that started this year, 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 coherence through Rabi oscillations, Ramsey fringes, and spin-echo, with decay times up to 1 us that are limited predominantly by energy relaxation, see Fig. 3.

Using the results of these coherence measurements, we will develop noise models and NMR-based optimal control pulses for the persistent-current qubit in collaboration with David Cory's group at the Department of Nuclear Science and Engineering.

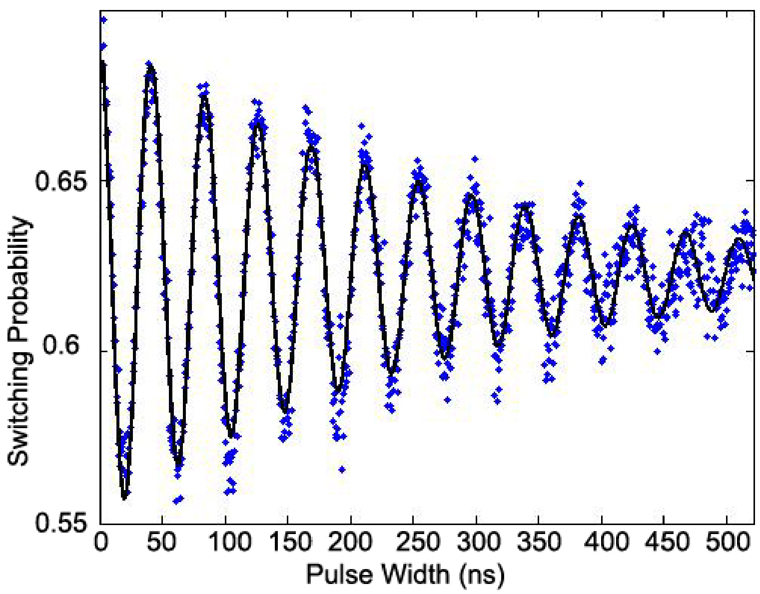

Figure 3: Rabi oscillations in a persistent-current qubit with an energy-level avoided crossing of 1.7 GHz, weakly driven by resonant microwaves. This device was made by shadow-evaporation of Al–AlOx–Al Josephson junctions.

Publications

Journal Articles

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Thesis

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