Development and experimental study of fluxonium qubits in planar architecture

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Quantum superconducting circuits based on Josephson tunnel junctions are a flexible platform for building artificial atoms. Rapid progress has been made in the last decade due to appearance of new types of qubits [1, 2] and improvements in coherence of qubits [3]. Various types of superconducting qubits [4, 5] governed by a variety of Hamiltonians can be implemented by choosing the proper combination of capacitors, inductors, and Josephson junctions. In a recent work [6] promising coherence times have been obtained on fluxonium qubits in a 3D cavity, but for performing quantum computation, error correction and simulation it is necessary to create large-scale systems with two-qubit gate operations which is possible when using planar architecture.

In this work we present the results of the development and experimental study of fluxonium qubits capacitively coupled to a transmission-line resonator, which have been implemented as a planar integral electric circuit. Experimental design requires accurate description of the dependence of the Hamiltonian parameters on fabrication parameters. A successful approach for this problem is finding an effective superconducting circuit Hamiltonian with sufficient detail to accurately predict device behavior. Hamiltonians should still be simple enough for efficient diagonalization. Here, experimental results are compared numerical simulations of an extended model of the system at various magnetic fluxes.

The fluxonium qubit consist of a tunnel Josephson junction shunted by a large capacitance with the charge energy E_C and the Josephson energy E_J in parallel with a superinductance L [7], which are all organized in a single closed loop geometry. The Josephson inductance of a series of large ($E_J \gg E_C$) Al–AlOx–Al Josephson junctions is used in this work as the superinductance. The equivalent circuit of a fluxonium qubit capacitively coupled to a coplanar resonator is shown in Fig..

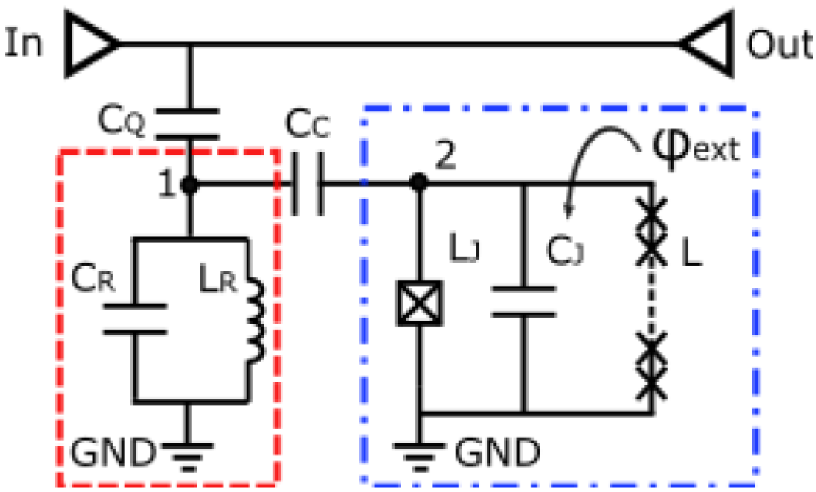

Figure 1: Equivalent circuit

The total Hamiltonian of the full system is given below.

$\hat{H}_{\mathrm{FR}} = \hbar\omega_{\mathrm{R}}\hat{a}_1^{\dagger}\hat{a}_1 + 4E_c\hat{n}_2^2 + E_{\mathrm{J}}\left(1-\cos\left(\hat{\phi}_2\right)\right) + \frac{E_{\mathrm{L}}}{2}\left(\hat{\phi}_2 - \frac{2\pi\Phi_{\mathrm{ex}}}{\Phi_0}\right)^2 + \hbar g\hat{n}_2\left(\hat{a}_1 + \hat{a}_1^{\dagger}\right)$, where $\hat{a}_1^{\dagger}$ and $\hat{a}_1$ are the creation and annihilation operators of photons in the resonator, respectively; $E_{\mathrm{C}} \approx \frac{e^2}{2(C_{\mathrm{J}}+C_{\mathrm{C}})}$,

$E_J = \frac{(\Phi_0/2\pi)^2}{L_\mathrm{J}}$, $E_\mathrm{L} = \frac{(\Phi_0/2\pi)^2}{L}$; Φ_0 is the magnetic flux quantum; Φ_ex is the external magnetic flux in the contour; $g \approx \frac{C_\mathrm{C}\omega_\mathrm{R}}{(C_\mathrm{J}+C_\mathrm{C})}\sqrt{\frac{4}{\pi}Z_0}$ is the coupling constant between the fluxonium and resonator.

Parameters of fluxonium devices obtained from spectroscopy fits in this work are shown in Table 1.

Table 1: Parameters of fluxonium devices obtained from spectroscopy fits

Qubit	E_c	E_J	E_L	g	N	$l \times s$
	GHz	GHz	GHz	MHz	-	nm
A	2.09	7,05	0.346	200	70	700 x 200
B	1.63	2.89	0.295	380	140	1000 x 200
C	0.99	3.8	0.247	10	140	1000 x 200

References

[1] *W. D. Oliver and P. B. Welander*, MRS Bull. 38, 816 (2013).

[2] *Z. L. Xiang, S. Ashhab, J. Q. You, and F. Nori*, Rev. Mod. Phys. 85, 623 (2013).

[3] *Y. Wang, Y. Li, Z. Yin, and B. Zeng*, Quantum Inform. 4, 1 (2012).

[4] *V. E. Manucharyan*, PhD Thesis (Yale Univ., New Haven, 2012).

[5] *N. A. Masluk*, PhD Thesis (Yale Univ., New Haven, 2012).

[6] *Long B. Nguyen, Yen-Hsiang Lin, Aaron Somoroff, Raymond Mencia, Nicholas Grabon, and Vladimir E. Manucharyan*, Phys. Rev. X 9, 041041 (2019).

[7] *Vladimir E.Manucharyan, Nicholas A. Masluk, Archana Kamal, Jens Koch, Leonid I. Glazman, and Michel H. Devoret*, Phys. Rev. B 85, 024521 (2012).