Tunable coupling between a superconducting charge and phase qubit

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Introduction

Last decade: new experiments in quantum mechanics using superconducting quantum circuits

- two level system: superconducting qubit

\[
\begin{align*}
|e\rangle & \quad h\nu \\
|g\rangle & \quad \uparrow
\end{align*}
\]

\[|\Psi\rangle = \alpha|g\rangle + \beta|e\rangle\]

- multi quantum levels systems

- qubit coupled to high Q cavity

\[
\begin{align*}
|e_1\rangle & \quad h\nu_1 \\
|g_1\rangle & \quad \uparrow
\end{align*}
\]

qubit 1

\[
\begin{align*}
|e_2\rangle & \quad h\nu_2 \\
|g_2\rangle & \quad \uparrow
\end{align*}
\]

qubit 2

\[|\Psi\rangle = \frac{|g_1e_2\rangle + |e_1g_2\rangle}{\sqrt{2}}\]
Motivation for a tunable coupling

Quantum algorithm

2-qubits operations

On coupling

1-qubit operations

Off coupling

Tunable coupling
Outline

- Description of the circuit
- dc-SQUID: phase qubit
- Asymmetric transistor: charge qubit
- Tunable coupling between the charge and phase qubit
- Summary
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Hybrid superconducting two-qubits system

Asymmetric Cooper pair transistor (ACPT)
Superconducting island \( \sim 0.12 \, \mu m^2 \)

Charge qubit

Phase qubit

dc-SQUID: superconducting loop interrupted by 2 Josephson junctions

Nanofab

3-angle shadow evaporation
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dc-SQUID: phase qubit

\[ V = 2\Delta_{Al} \]

\[ \nu_p(I_b, \Phi_S) \]

\[ \Delta U(I_b, \Phi_S) \]

\[ |0\rangle \rightarrow |1\rangle \rightarrow \frac{\hbar \nu_S(I_b, \Phi_S)}{2} \]


E. Hoskinson et al., cond-mat/0810.2372v1 (2008)

Escape probability
Phase qubit spectroscopy

\[ \Phi_S = 0.02 \Phi_0 \]

\[ I_{\text{bias}} = 1890 \, \text{nA} \]

\[ P_{\text{esc}} \]

\[ \nu_S \]

\[ C_S = 454 \, \text{fF} \]

\[ I_C = 2.712 \, \mu\text{A} \]
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Charge qubit spectroscopy

\[ \nu = \frac{C_{gg} \delta}{2e} \]

\[ \delta(\Phi_T, \Phi_S, I_b) \]

\[ h\nu_t(\delta, n_g) \]

\[ P_{\text{esc}} \]

\[ \nu_T = 8.779 \text{ GHz} \]
Charge qubit frequency versus $n_g$

\[ E_C = \frac{(2e)^2}{2C_\Sigma} \sim 26.7 \text{ GHz} \]
Charge qubit frequency versus $\delta$

**Josephson asymmetry**

$$\mu = \frac{E_{j1} - E_{j2}}{E_{j1} + E_{j2}} = 41.9\%$$

$$E_j / E_C \approx 0.8$$

**Graphical Representation**

- **Optimal point** $$(\delta = 0, n_g = 0.5)$$
- **Optimal point** $$(\delta = \pi, n_g = 0.5)$$

- $E_{j1} + E_{j2} \approx 21.8 \text{ GHz}$
- $E_{j2} - E_{j1} \approx 8.8 \text{ GHz}$
Rabi oscillations (charge qubit)

\[ |+\rangle \quad \uparrow \nu_{\mu w} = \nu_T \quad \downarrow |-\rangle \]

\[ V_g \]

\[ \mu \text{wave duration} \]

\[ A_{\mu w} \]

\[ T_{2}^{\text{Rabi}} \sim 110 \text{ ns} \]

\[ \nu_{\text{Rabi}} = 20.4 \text{ MHz} \]

\[ \nu_{\text{Rabi}} \propto A_{\mu w} \]
Relaxation (charge qubit)

\[ P_{\text{ech}} \propto e^{-\frac{t}{T_1}} \]

\[ T_1 \sim 0.8 \, \mu s \]
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Coupled qubits spectroscopy

Spectroscopy at $I_{\text{bias}} = 1890$ nA

![Graph showing frequency vs. $\Phi_s/\Phi_0$ for phase qubit and charge qubit.](image)
Entangled qubits

Transistor $|0, +\rangle$

SQUID $|1, -\rangle$

$g \sim 110$ MHz

$|1, -\rangle - |0, +\rangle \over \sqrt{2}$

$\nu_S$

$|1, -\rangle + |0, +\rangle \over \sqrt{2}$

$P_{esc}$

Frequency (GHz)

$\nu_S = 18.97$ GHz

$nn_g \approx 1.2$
Spectroscopy versus $n_g$

Resonant coupling at $n_g = 0.5$

$\nu_S$ does not depend on $n_g$

$\nu_T$

$\nu_r = 18.98$ GHz

$g \sim 110$ MHz

dc-SQUID

$\nu_S$
Spectroscopy versus flux

Two qubits can be in resonance from 9 GHz to 20 GHz.

Strong variation of the coupling strength.
Resonant coupling

Coupling varies from 60 MHz to 1100 MHz, a factor of 18.
Electrical schematic of the circuit

\[ \hat{H} = \hat{H}_{ACPT} + \hat{H}_{SQUID} + \hat{H}_{COUPL} \]
Hamiltonian of the coupled qubits

\[ \hat{H} = h\nu_S \hat{\sigma}_z^S + h\nu_T \hat{\sigma}_z^T + \frac{1}{2} hg \left( \hat{\sigma}_S^+ \hat{\sigma}_T^- + \hat{\sigma}_S^- \hat{\sigma}_T^+ \right) \]

\[ hg = \frac{E_{c,c}}{2} - E_{c,j} \cos(\delta/2 + \mu \tan(\delta)) \]

Capacitive coupling

\[ E_{c,c} = (1 - \lambda) \sqrt{\frac{E_S}{h\nu_p} h\nu_p} \]

Capacitance asymmetry

\[ \lambda = \frac{C_1^T - C_2^T}{C_1^T + C_2^T} \]

Josephson coupling

\[ E_{c,j} = (1 - \mu) \sqrt{\frac{E_S}{h\nu_p} E_J^T / 2} \]

Josephson energy asymmetry

\[ \mu = \frac{E_{J,1}^T - E_{J,2}^T}{E_J^T} \]
We consider $\lambda = \mu = 41.6\%$.
Resonant coupling

We consider $\lambda = 37.7\%$ and $\mu = 41.6\%$

If transistor was symmetric ($\lambda = \mu = 0$) coupling would be zero
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Two different qubits

Strong tunable coupling between a charge and phase qubit (x18)

Zero coupling and non-zero coupling
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Energy levels

Measurement

Flux pulse

$I_{50\%} (\mu A)$

$\Phi_s/\Phi_0$

$\gamma$ (GHz)

$|-, 1\rangle$

$|+, 0\rangle$

Flux pulse

Measurement
Landau-Zener and adiabatic passage

\[ P_{LZ} = e^{-2\pi \frac{g^2}{\hbar \dot{\epsilon}}} \]

\[ \dot{\epsilon} = \frac{d(E_b - E_r)}{dt} \]

- \( g^2 \ll \dot{\epsilon} \)  
  - LZ passage  
  - \( P_{LZ} \sim 1 \)

- \( g^2 \gg \dot{\epsilon} \)  
  - Adiabatic passage  
  - \( P_{LZ} \sim 0 \)
Measurement of the ACPT

Flux pulse

Adiabatic passage

\[ P_{LZ} = e^{-2\pi \frac{\phi^2}{\hbar \dot{c}}} \approx 0\% \]

\[ \dot{c} \approx 2.9 \text{ GHz/ns} \]
\[ g \approx 800 \text{ MHz} \]

Phase qubit

Charge qubit

\[ |1\rangle \]

\[ |0\rangle \]

\[ |+\rangle \]

\[ |\rangle \]

\[ \langle \Psi | +, 0 \rangle^2 \]

\[ \langle \Psi | -, 1 \rangle^2 \]