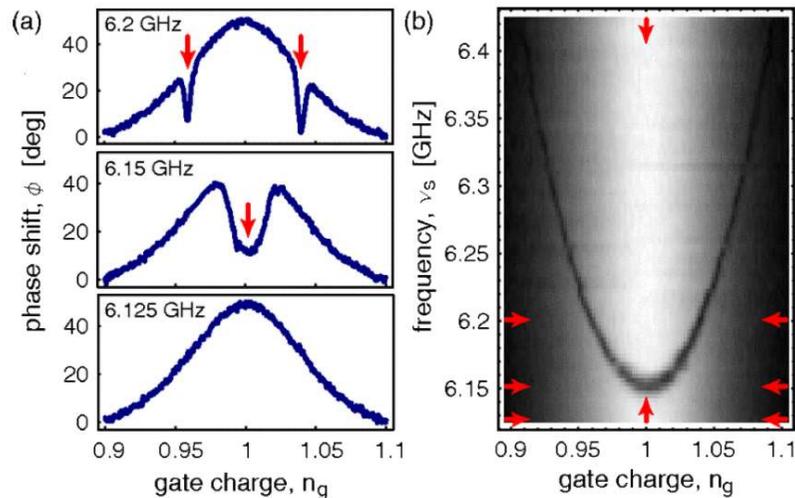


Two-tone spectroscopy

Thursday, February 18, 2016 7:36 PM



Schuster, D. I., Wallraff, A., Blais, A., Frunzio, L., Huang, R.-S., Majer, J., Girvin, S. M., and Schoelkopf, R. J. 2005. ac Stark Shift and Dephasing of a Superconducting Qubit Strongly Coupled to a Cavity Field. *Physical Review Letters*, 94(12), 123602

When the qubit is effectively excited it will rotate alternating between positive and negative phase shifts, which average to zero

* Goal: to do full spectroscopy of the qubit when it is protected = far off resonance from the resonator

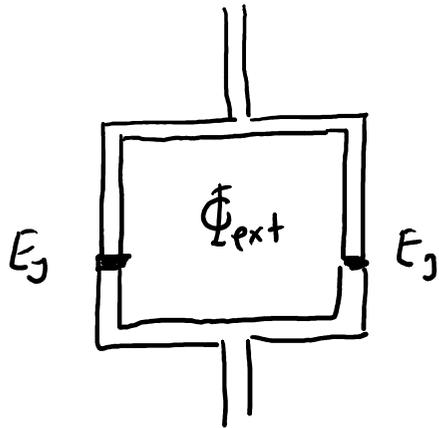
* Protocol:

- 1) Fix one microwave "beam" at a freq. that is transmitted by the cavity when qubit is in g. state. For instance just " ω "
- 2) Apply a simultaneous drive, either on the qubit, or on the cavity, w. the freq. that will excite the qubit
- 3) Monitor the phase of the outgoing field

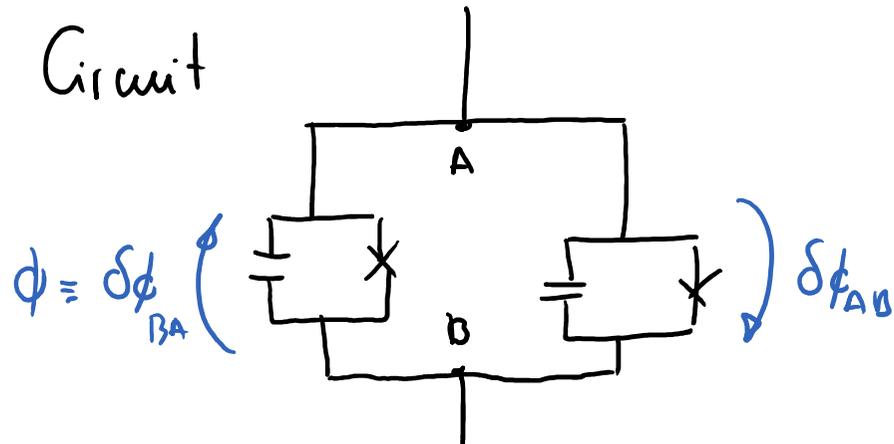
DC-SQUID

lunes, 22 de febrero de 2016 18:56

Design



Circuit



$$\delta\phi_{AB} + \delta\phi_{BA} = \Phi_{ext}$$

Effective model

$$\mathcal{L} \sim 2 \times \frac{1}{2} (\dot{\phi})^2 C_J + E_J \left[\cos\left(\delta\phi_{AB} \frac{2\pi}{\Phi_0}\right) + \cos\left(\delta\phi_{BA} \frac{2\pi}{\Phi_0}\right) \right]$$

$$\sim \frac{1}{2} 2C_J (\dot{\phi})^2 + E_J 2 \cos\left(\phi_+ \frac{2\pi}{\Phi_0}\right) \cos\left(\phi_- \frac{2\pi}{\Phi_0}\right)$$

$$\phi_+ = \frac{1}{2}(\delta\phi_{AB} + \delta\phi_{BA}) = \frac{\Phi_{ext}}{2} = \text{ct.} \quad \phi_- = \frac{(\delta\phi_{BA} - \delta\phi_{AB})}{2} \text{ is our dynamical variable}$$

$$\mathcal{L} \sim \frac{1}{2} 2C_J (\dot{\phi}_-)^2 + \tilde{E}_J(\Phi_{ext}) \cos\left(\phi_- \frac{2\pi}{\Phi_0}\right) \quad \tilde{E}_J(\Phi_{ext}) \approx 2E_J \cos\left(\frac{\Phi_{ext}}{2} \frac{\pi}{\Phi_0}\right)$$

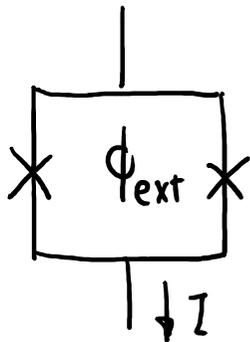
$$J \sim \frac{1}{2} 2t_J (\phi_-)^2 + E_J (\phi_{\text{ext}}) \cos \left(\phi - \frac{2\pi}{\Phi_0} \right)$$

$E_J(\phi_{\text{ext}}) \approx \langle E_J(0) \rangle \left(\frac{2\pi}{\Phi_0} \right)$
acts as a tuneable junction

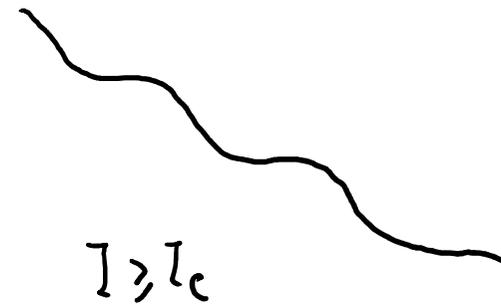
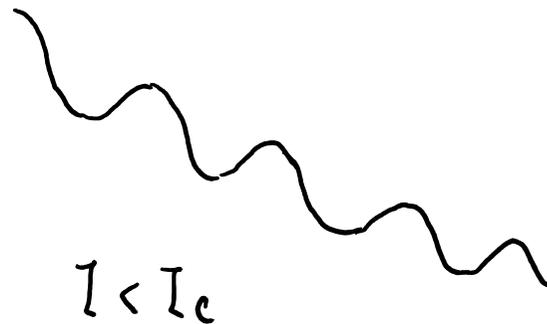
Applications

lunes, 22 de febrero de 2016 19:24

a) Magnetic field sensing : } we bias the squid, we get an unstable potential



$$E_{ind} \sim E_J(\Phi_{ext}) \cos\left(\phi - \frac{2\pi}{\Phi_0}\right) - I\phi$$



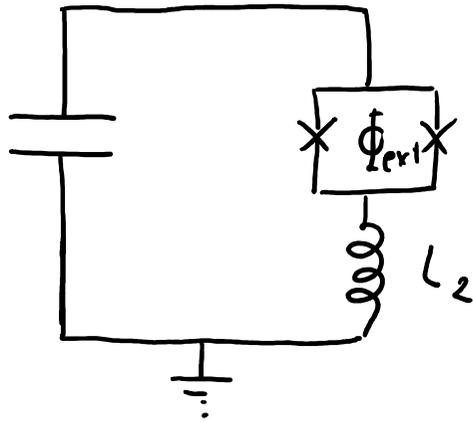
Apart from spontaneous quantum tunneling events, when $I > I_c = \frac{E_J(\Phi_{ext}) 2\pi}{\Phi_0}$ the system enters a delocalized state $\psi(\phi) \sim e^{i\phi}$ which corresponds to a well defined value of voltage, ever growing. In practice, the junction resistance stabilizes

this, giving rise to a very sensitive magnetometer with a fraction of Φ_0 precision.

Applications (2)

lunes, 22 de febrero de 2016 19:14

b) Tuneable inductor



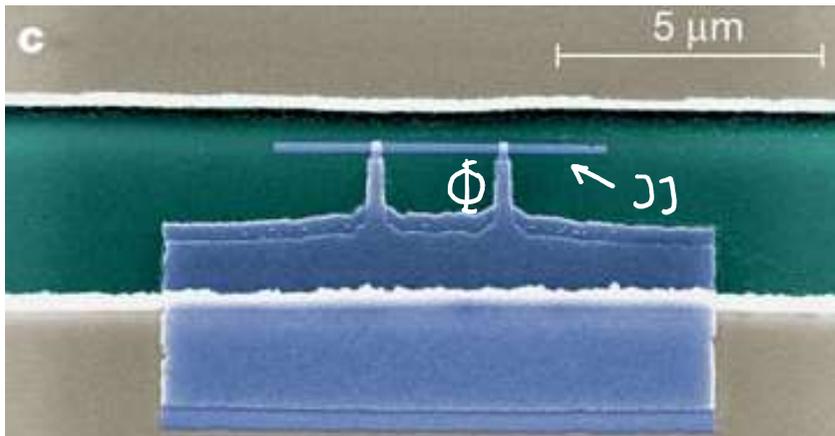
Working in the linear regime, we can insert the SQUID in an LC resonator to use it as a tuneable inductance

$$E_{\text{inductive}} \sim -E_J(\Phi_{\text{ext}}) \cos\left(\phi \frac{2\pi}{\phi_0}\right) \\ \sim \frac{1}{2L_J(\Phi_{\text{ext}})} \phi^2$$

with

$$L_J(\Phi_{\text{ext}}) \sim \frac{\phi_0^2}{4\pi^2} \cdot \frac{1}{2E_J \cos(\Phi_{\text{ext}} \pi/\phi_0)}$$

c) Tuneable Josephson junction



We use this element in circuit designs in the nonlinear regime (e.g. charge qubit) to allow tuneability of tunneling amplitudes

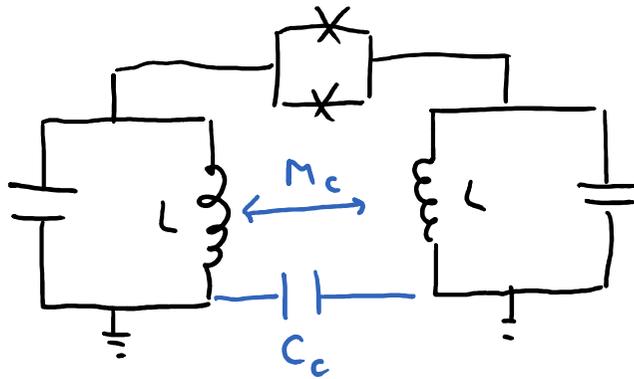


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Applications (3)

martes, 23 de febrero de 2016 9:27

d) Negative inductance / tuneable interaction



Let us take any two circuits with some direct coupling, inductive or capacitive (M_c or C_c)

This coupling may arise because of proximity effects, geometry considerations, shared antennae, ...

In the circuit eigenbasis that coupling typically reads $g (a_1^\dagger a_2 + a_2^\dagger a_1)$ with fixed g

In our circuit model the spin inductive energy reads $\tilde{E}_J(\Phi_{\text{ext}}) \cos(\phi \frac{2\pi}{\phi_0})$

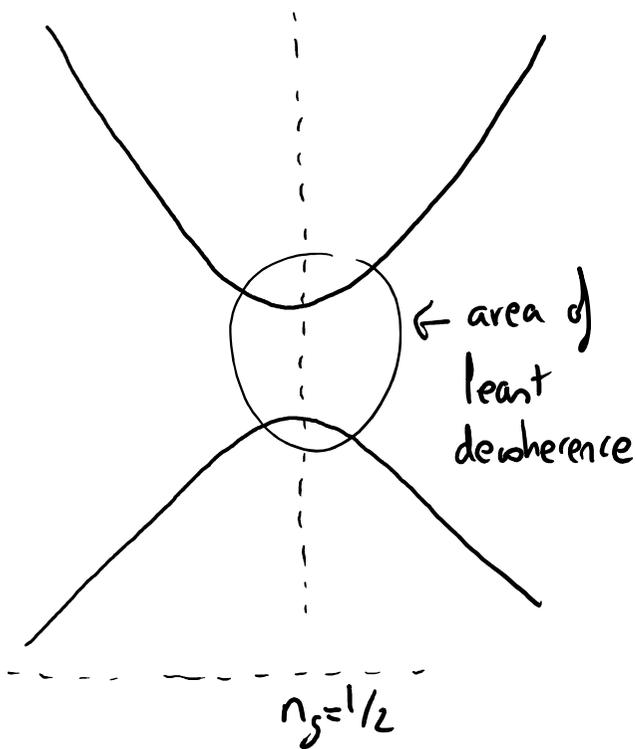
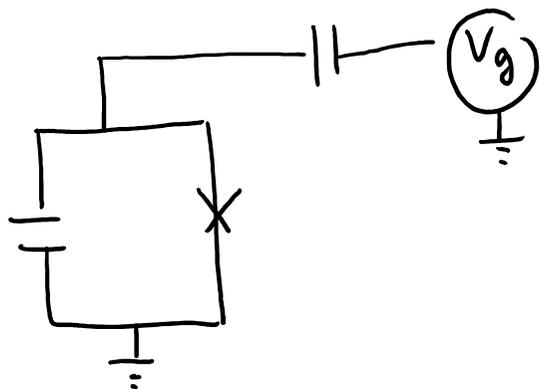
Because $\tilde{E}(\Phi_{\text{ext}}) \sim 2E_J \cos(\Phi_{\text{ext}} \pi/\phi_0)$ is tuneable, we have

$$(g + \tilde{g}(\Phi_{\text{ext}})) (a_1^\dagger a_2 + a_2^\dagger a_1)$$

where the total coupling may be dynamically tuned and even cancelled.

Charge qubit decoherence

viernes, 19 de febrero de 2016 8:22



$$H = 4E_c (n - n_g)^2 - E_J \cos\left(\phi - \frac{2\pi}{\Phi_0} \int V_g dt\right)$$

We know that decoherence in the charge qubit is dominated by fluctuations in V_g^{real} , which

contains $V_g^{\text{real}} = V_g + \text{voltage induced by trapped charges} + \text{spurious fields from antennae...} + \text{etc}$

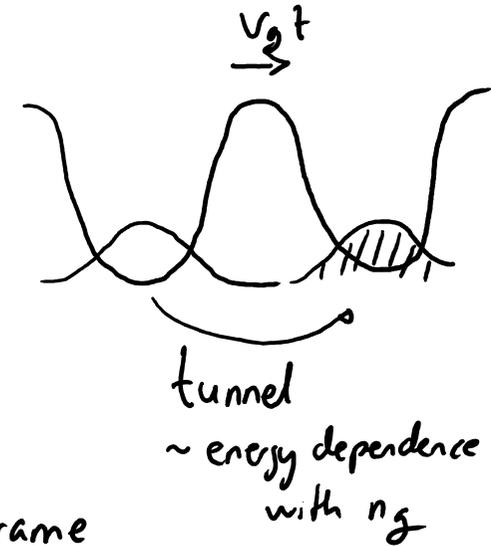
This is confirmed by working at the symmetry point $n_g = 1/2$ where $\frac{\partial E_{\pm}}{\partial n_g} \approx 0$ and dephasing is minimal

Transmon idea

viernes, 19 de febrero de 2016 8:26

The charge qubit Hamiltonian in the phase representation

$$H \sim 4E_c (-i\partial_\varphi - n_g)^2 - E_J \cos(\varphi)$$
$$\sim (-4E_c \partial_\varphi^2) - 4E_c n_g (-i\partial_\varphi) - E_J \cos(\varphi)$$



Intuitively, this Hamiltonian is like evolving on a "rotating" frame

$$\varphi \rightarrow \varphi - v t \quad v \propto 4E_c n_g$$

$$H(t) \sim (-4E_c \partial_\varphi^2) - E_J \cos(\varphi - v_g t)$$

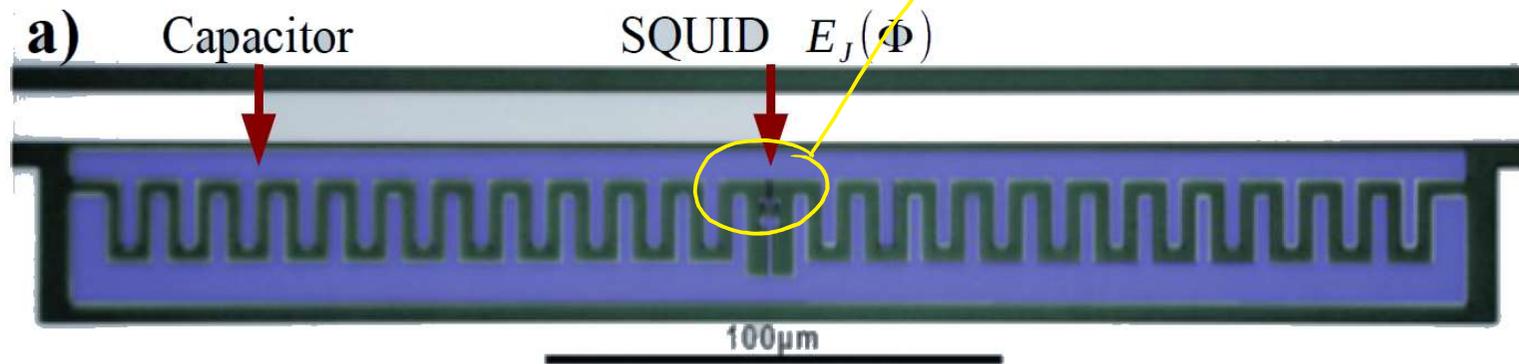
For the energy to depend on " v_g ", the system must be able to tunnel to neighboring wells. This amplitude is exponentially suppressed in E_J/E_c

Koch, Jens, Yu, Terri, Gambetta, Jay, Houck, A., Schuster, D., Majer, J., Blais, Alexandre, Devoret, M., Girvin, S., and Schoelkopf, R. 2007. Charge-insensitive qubit design derived from the Cooper pair box. Physical Review A, 76(4).

Design

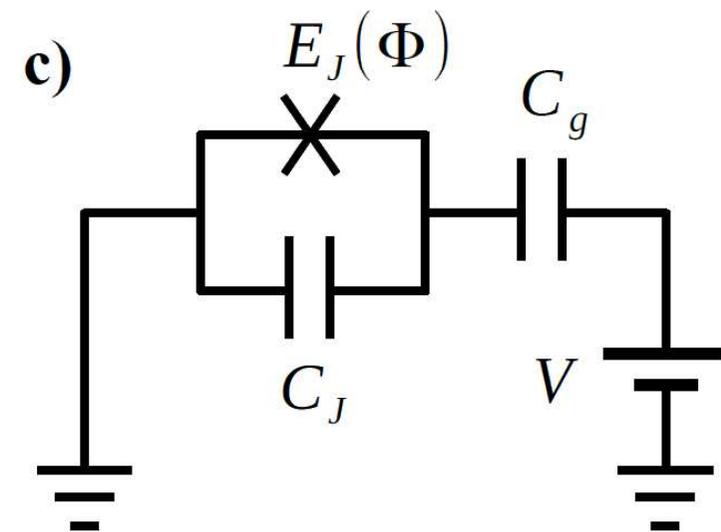
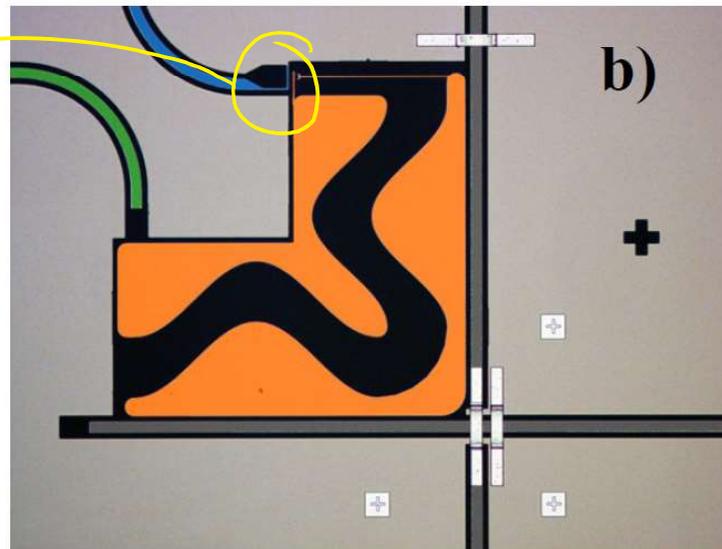
lunes, 22 de febrero de 2016 19:37

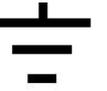
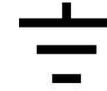
Compare the size of the capacitor with the charge qubit design



tunable junction
or SQUID

tunable junction
or SQUID

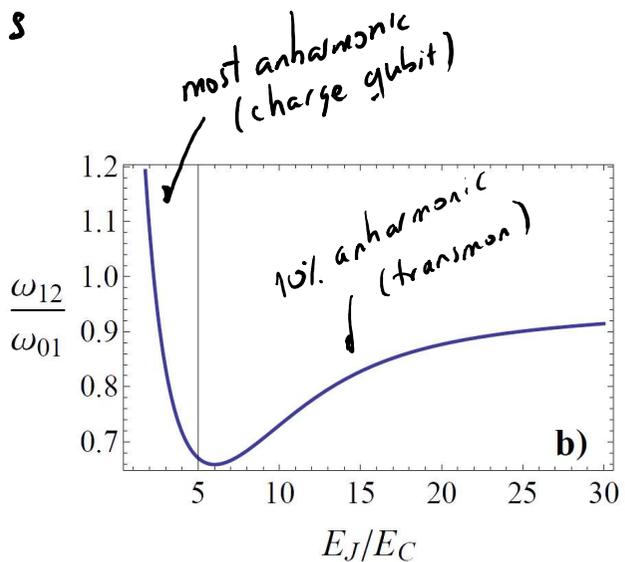
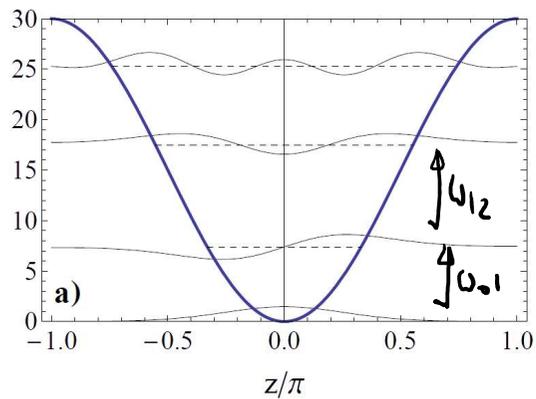




Charge qubit $E_J/E_C \sim 0.1-1$, transmon $E_J/E_C \sim 50-100$

Transmon energy levels

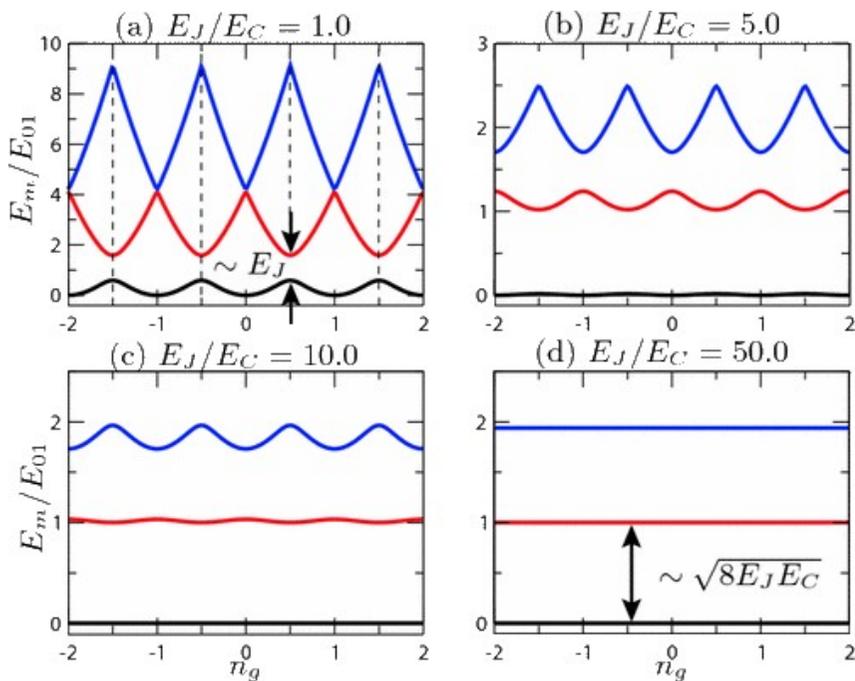
viernes, 19 de febrero de 2016 8:08



Eigen energies

$$[-4E_C \partial_\varphi^2 - E_J \cos(\varphi)]\psi = \epsilon_n \psi$$

a) Use harmonic oscillator and approximate and approximate



$$4E_C \sim \frac{\hbar^2}{2m} \rightarrow \omega \sim \frac{1}{\hbar} \sqrt{8E_J E_C}$$

$$E_J \sim m\omega^2$$

b) Solve exactly using Mathieu equation (Mathematica)

Dephasing model

lunes, 22 de febrero de 2016 21:08

We have $H \sim \left[\frac{\Delta}{2} + \frac{1}{2} \frac{\partial E}{\partial \lambda} \cdot \lambda \right] \sigma^z$ where " λ " is some "bath" operator or noise source that enters our model linearly. Coherence is destroyed by this

$$\rho_{01} = \langle \sigma^-(t) \rangle \sim \langle \exp \left(-i \int_0^t dz \frac{\partial E}{\partial \lambda} \cdot \lambda(z) \right) \rangle \cdot \rho_{01}(0) e^{-i\omega_0 t}$$

For a Gaussian noise model with zero average,

$$\rho_{01}(t) = e^{-i\omega_0 t} \exp \left[-\frac{1}{2} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S_{\lambda}(\omega) \left| \frac{\sin(\omega t)}{\omega/2} \right|^2 \right]$$

$$S_{\lambda}(\omega) \sim \left| \frac{\partial E}{\partial \lambda} \right|^2 \int_{-\infty}^{\infty} dz \langle \lambda^{\dagger}(0) \lambda(z) \rangle e^{-i\omega z}$$

Slow vs. fast noise

lunes, 22 de febrero de 2016 21:35

- Under ordinary conditions we can assume a short memory time

$$\exp \left[-\frac{1}{2} S_1(0) \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \left| \frac{\sin(\omega t)}{\omega/2} \right|^2 \right] \sim \exp \left[-|t|/T_2 \right]$$

where dephasing comes from contributions at small frequency.

- In solid state systems we find $1/f$ or "slow" noise where $S(\omega) \sim \frac{2\pi A^2}{|\omega|^\mu}$

This means that correlation times diverge and we never reach a truly exponential regime

$$\exp \left[-\frac{1}{2} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{2\pi A^2}{|\omega|^\mu} \cdot \frac{\sin(\omega t)^2}{(\omega/2)^2} \right] \sim e^{-|t|^{\mu+1}/T_2^{\mu+1}}$$

$$\omega = \nu/t, \quad d\omega = d\nu/t$$

Comparison

viernes, 19 de febrero de 2016 8:42

Transmon

$$n_g = 0$$

$$\text{Dephasing 1st order} \propto \left| \frac{\partial E_{01}}{\partial n_g} \right|$$

$$\left| \frac{\partial E_{01}}{\partial n_g} \right| \sim \pi \epsilon_1 \sin(2\pi n_g)$$

$$\epsilon_1 \sim \dots \left(\frac{E_J}{2E_C} \right)^{5/4} e^{-\sqrt{8E_J/E_C}}$$

$$\frac{E_J}{E_C} \sim 20, 50, 100$$

$$\left| \frac{\partial E_{01}}{\partial n} \right| \sim (0.07, 0.00015, 10^{-7}) \times E_C$$

Charge qubit (symmetry point)

$$n_g = 1/2$$

$$\text{Dephasing 2nd order} \frac{\partial^2 E_{01}}{\partial n_g^2}$$

$$\left| \frac{\partial^2 E_{01}}{\partial n_g^2} \right| \sim \frac{(8E_C)^2}{E_J}$$

! very large curvature!

$$E_J/E_C \sim 1, 0.1 \dots$$

$$\left| \dots \right| \sim 64E_C, 640E_C \dots$$

Some numbers

viernes, 19 de febrero de 2016 8:50

Effect of voltage on energy levels →

Effect of fluctuations on the SQUID

Critical current in junctions is fluctuating due to the presence of trapped charges near or in the junction, which affect the tunneling amplitude

Noise source	1 / f amplitude	Transmon $E_J / E_C = 85T_2$ (ns)	CPB $E_J / E_C = 1$ T_2 (ns)
Charge	$A = 10^{-4} - 10^{-3} e$ [51]	400 000	1 000^a
Flux	$A = 10^{-6} - 10^{-5} \Phi_0$ [52,54]	3 600 000 ^a	1 000 000 ^a
Critical current	$A = 10^{-7} - 10^{-6} I_0$ [53]	35 000	17 000

dominant

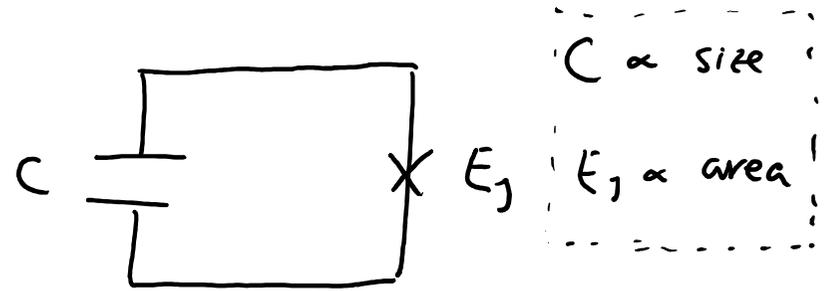
dominant

Koch, Jens, Yu, Terri, Gambetta, Jay, Houck, A., Schuster, D., Majer, J., Blais, Alexandre, Devoret, M., Girvin, S., and Schoelkopf, R. 2007. Charge-insensitive qubit design derived from the Cooper pair box. Physical Review A, 76(4).

3D transmons

martes, 23 de febrero de 2016 9:35

- * Working in the dispersive regime, we do not really need to tune the gap, provided this is at a suitable value w.r.t. cavity
- * In transmons $\Delta \propto \sqrt{E_J}$ is not very sensitive to fabrication errors in the junctions.
 - ↳ 5% reproducibility errors are possible
- * The size of the transmon may be increased by enlarging the capacitors and adjusting (E_J)
 - ↳ larger electric dipoles
- * They can also be fabricated on separate sample holders, with no control antennas



$$\omega \sim \sqrt{E_C E_J} \sim \sqrt{\frac{E_J}{C}}$$

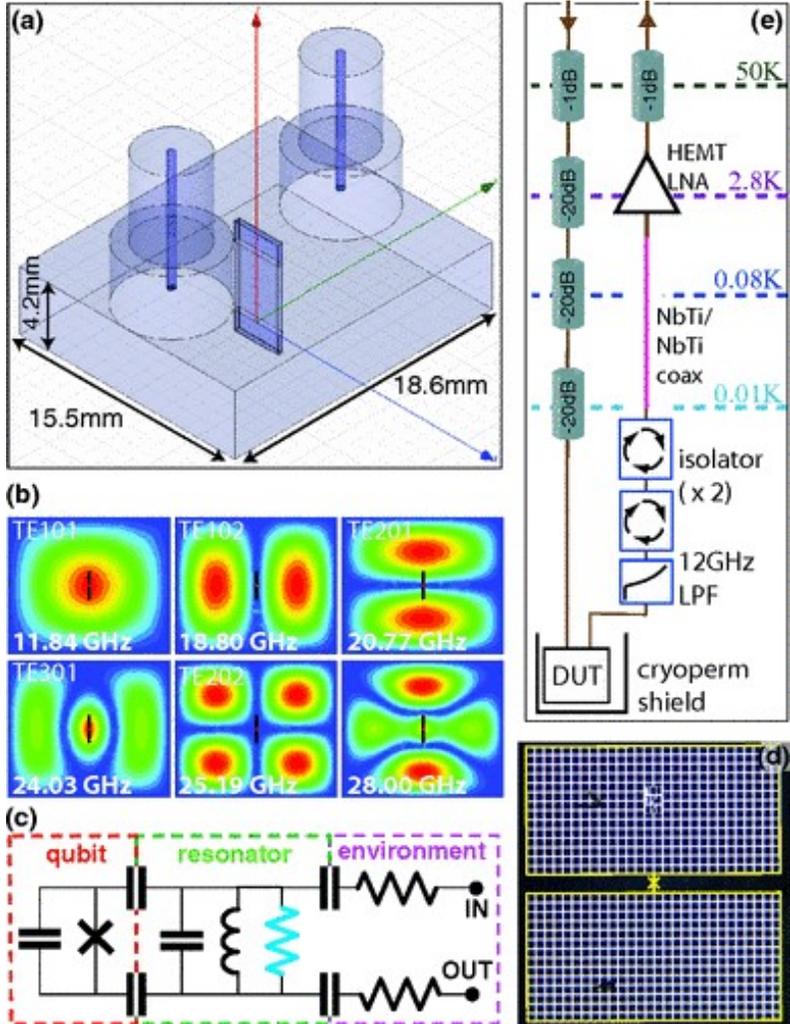
Increase $C \Rightarrow$ increase E_J
 \sim
 increase junction area

$$g \sim \sqrt[4]{2} \sim \sqrt[4]{\frac{1}{C E_J}} \quad \text{does not change much}$$

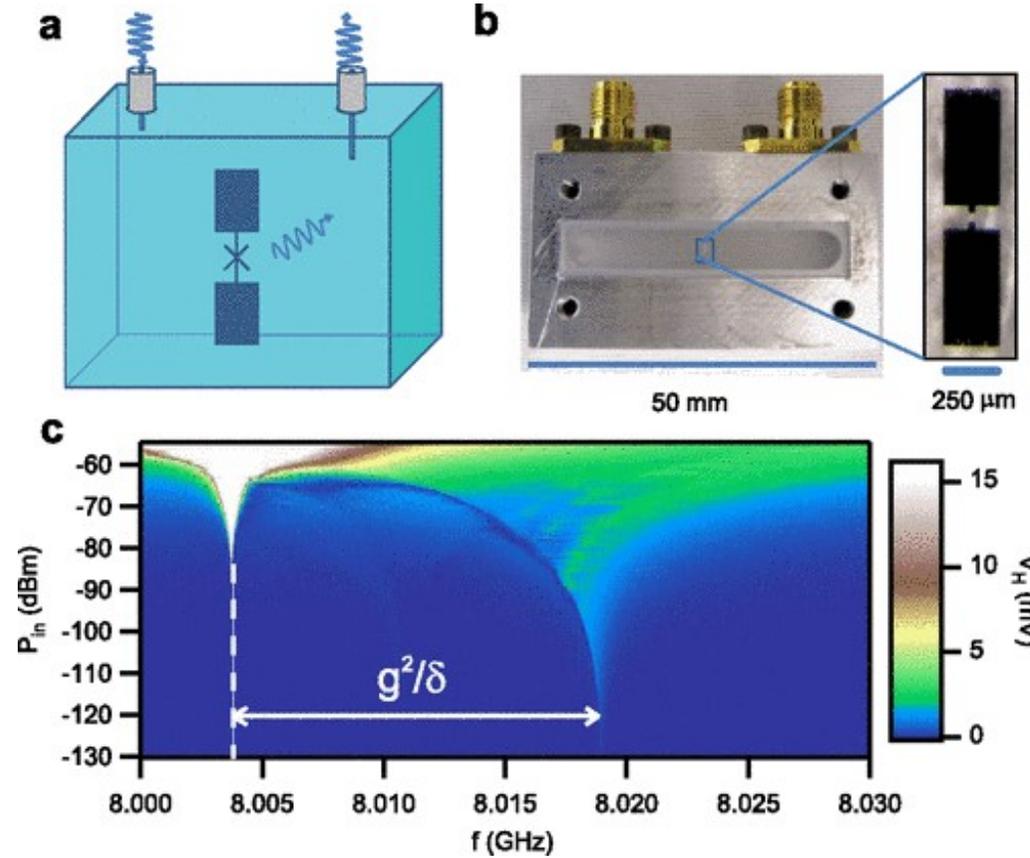
$l \sim \text{size} \sim$ can be increased an order of magnitude
 $d \sim g \cdot l \Rightarrow$ larger electric dipole!

3D Transmons (2)

martes, 23 de febrero de 2016 9:45



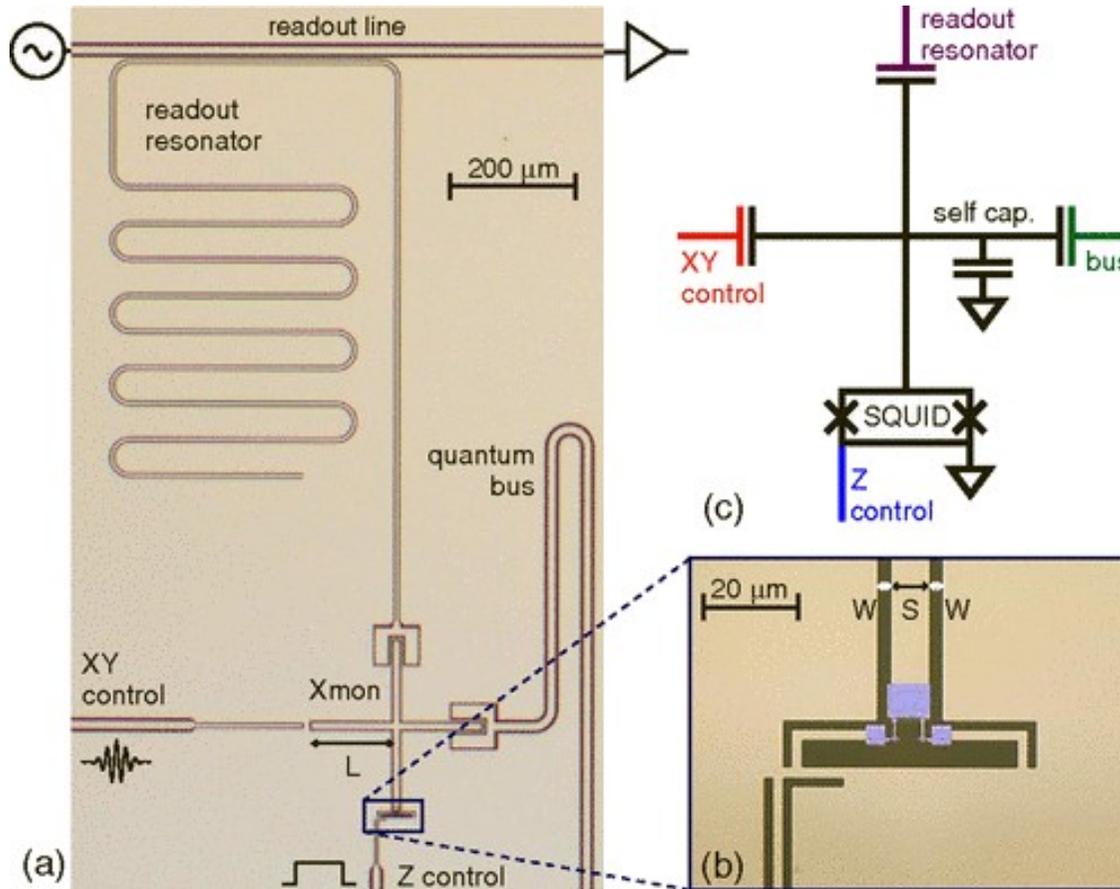
Chad Rigetti, et al
Phys. Rev. B 86, 100506(R) (2012)



Hanhee Paik et al,
Phys. Rev. Lett. 107, 240501 (2011)

X-mon

martes, 23 de febrero de 2016 10:36



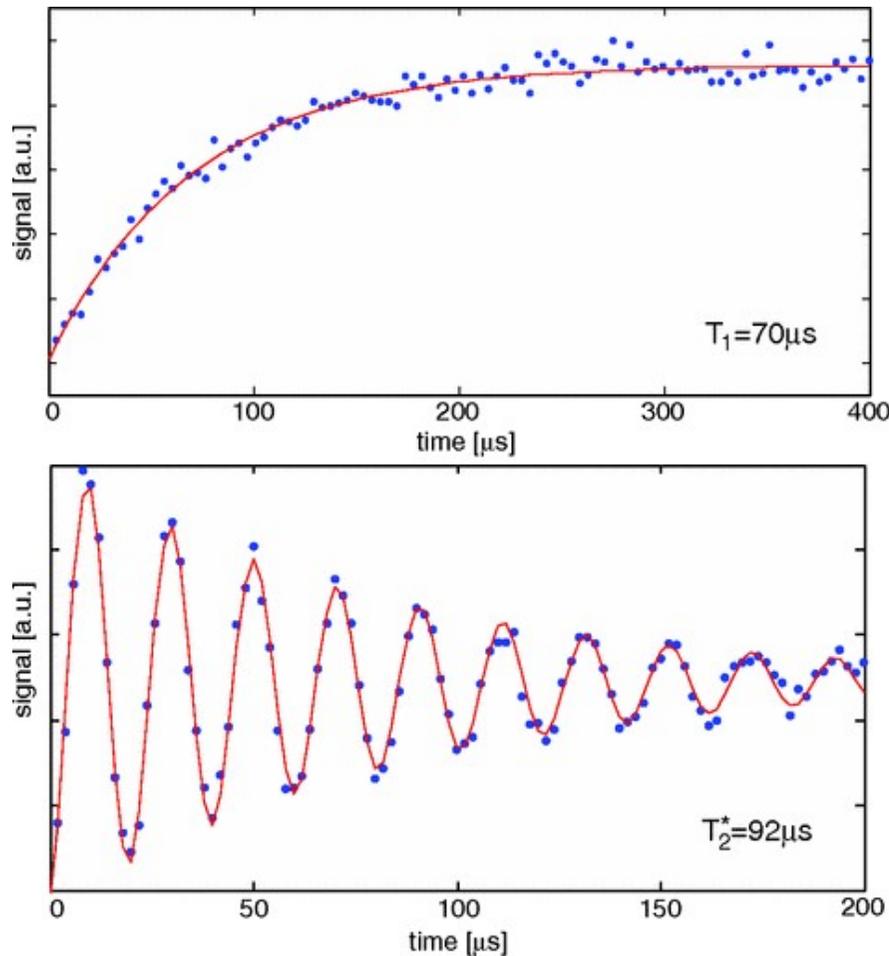
- * A customized transmon with minimal radiative losses
- * 2D design that allows for simple arrangements and qubit-qubit coupling
- * Individual addressing via readout resonator
- * Two controls
 - capacitive $\sim \Omega(t) \sigma^x$
 - SQUID $\sim \Delta(t) \sigma^z$

R. Barends et al
Phys. Rev. Lett. 111, 080502 (2013)

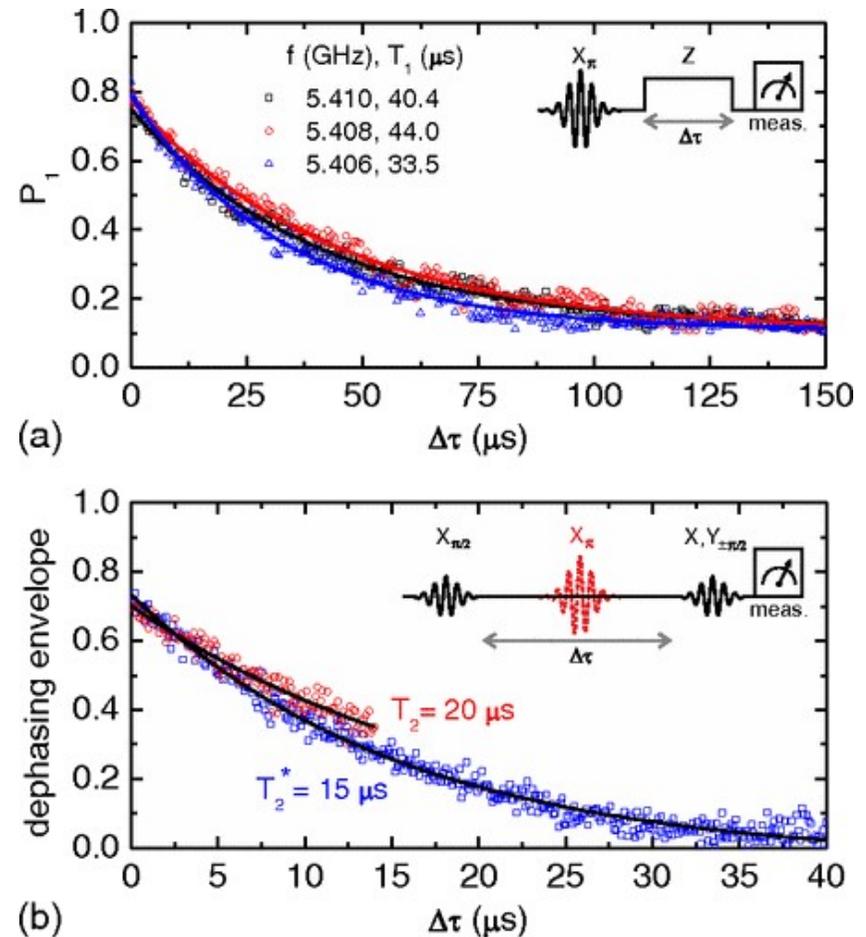
Sample lifetimes

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Coherence times for 3D transmons are good (0.1ms) but also planar qubits are improving



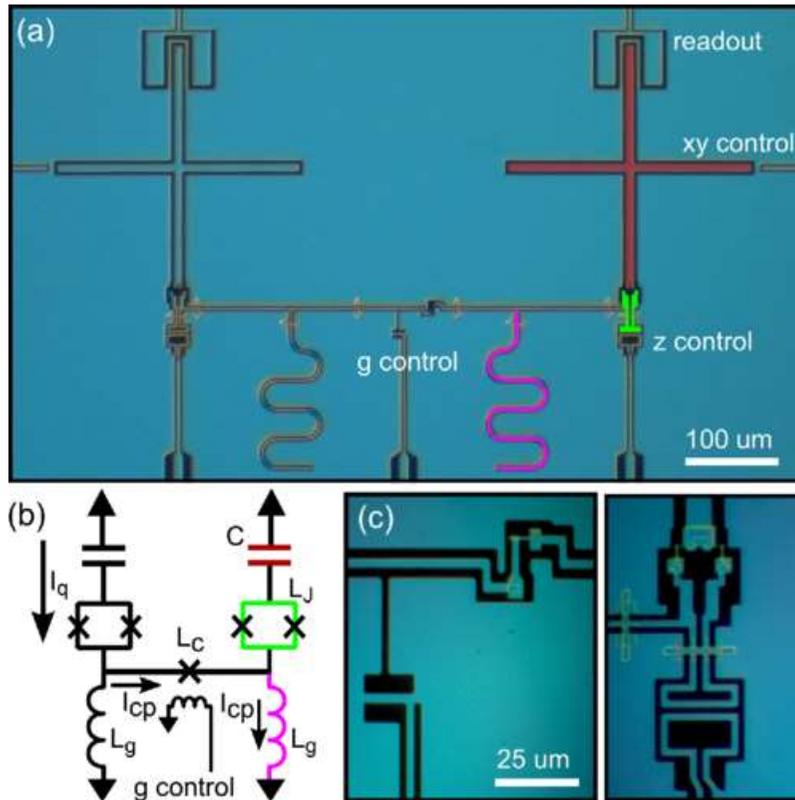
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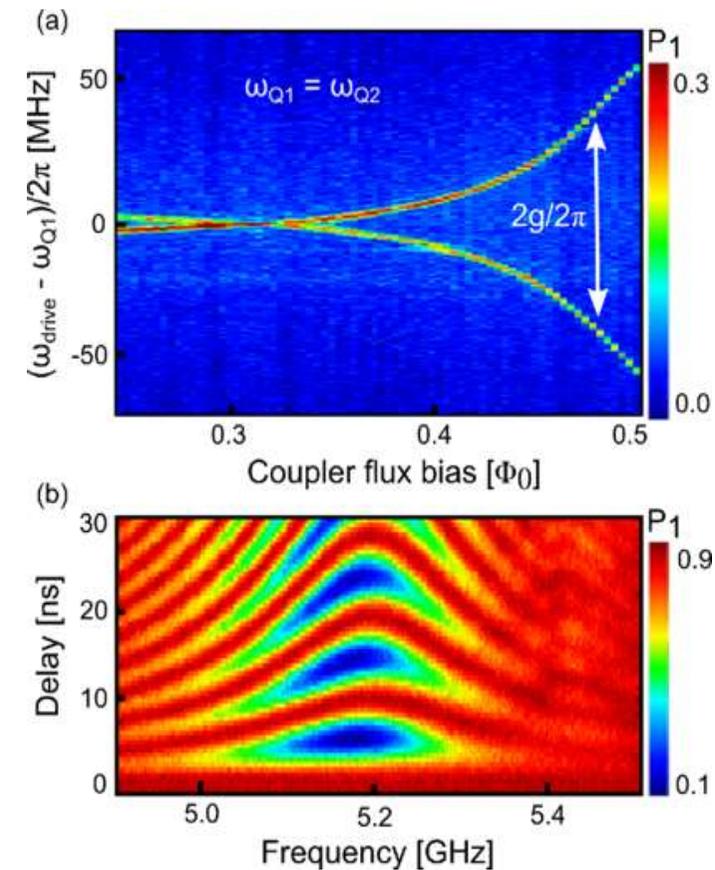
R. Barends et al
 Phys. Rev. Lett. 111, 080502 (2013)

G-mon

martes, 23 de febrero de 2016 10:41



A device that allows tuning the coupling between X-mons using bias currents



Yu Chen et al
Phys. Rev. Lett. 113, 220502 (2014)