

First design of a superconducting qubit for the QUB-IT experiment

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Abstract

Quantum sensing is a rapidly growing field of research which is already improving sensitivity in fundamental physics experiments. The ability to control quantum devices to measure physical quantities received a major boost from superconducting qubits and the improved capacity in engineering and fabricating this type of devices. The goal of the QUB-IT project is to realize an itinerant single-photon counter exploiting Quantum Non Demolition (QND) measurements and entangled qubits, in order to surpass current devices in terms of efficiency and low dark-count rates. Such a detector has direct applications in Axion dark-matter experiments (such as QUAX[1]), which require the photon to travel along a transmission line before being measured. In this contribution we present the design and simulation of the first superconducting device consisting of a transmon qubit coupled to a resonator using the Qiskit-Metal software developed by IBM. Exploiting the Energy Participation Ratio (EPR) simulation we were able to extract the circuit Hamiltonian parameters, such as resonant frequencies, anharmonicity and qubit-resonator couplings.

1. Design

The design and simulation phase is fundamental in order to address the best circuit parameters for the superconducting qubit device before moving to manufacturing stage. The aim of our first design is to build a superconducting qubit that can be controlled and read through a resonator coupled to a feedline. For this chip we considered a substrate consisting of $0.3 \mu\text{m}$ of silicon oxide on top of $600 \mu\text{m}$ of silicon.

The design of our circuit was developed exploiting Qiskit-Metal [2] toolkit and it is shown in Fig. 1. The circuit consists of an Xmon-type qubit capacitively coupled to a quarter wave readout resonator. Each electrode of the Xmon cross is $30 \mu\text{m}$ wide and $360 \mu\text{m}$ long. The gap between the cross and the ground plane is $20 \mu\text{m}$ wide. The readout resonator is 5.76mm long, with $10 \mu\text{m}$ trace width and $6 \mu\text{m}$ gap, matching a characteristic impedance $Z_0 = 50 \Omega$. The coupling element is a $130 \mu\text{m}$ long claw, with $5 \mu\text{m}$ gap to the ground plane. The resonator is capacitively coupled to the feedline by a $400 \mu\text{m}$ long coupling leg. The lumped element circuit equivalent to our design is shown in Fig. 2.

2. Simulations

The simulations are performed exploiting Ansys Q3D and Ansys HFSS¹. The former is used to extract the capacitance

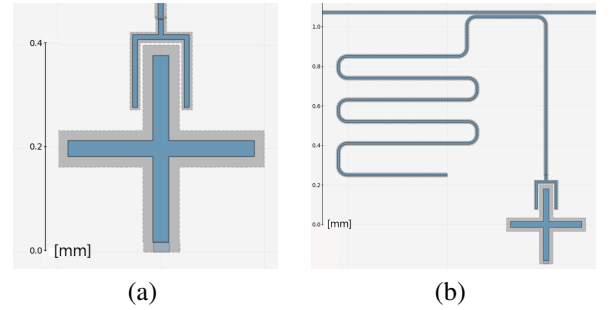


Figure 1: Design rendered in Qiskit-Metal GUI. (a) Zoom on the Xmon qubit: this type of qubit consists of a Josephson Junction shunted by a cross-shaped capacitance. (b) Xmon qubit capacitively coupled to a quarter wave resonator for readout. The readout resonator is also capacitively coupled to the feedline.

values for circuit elements. The simulated capacitances are $C_s = 98.19 \text{fF}$, for the qubit shunt capacitance, $C_g = 4.40 \text{fF}$ and $C_k = 8.62 \text{fF}$ for the qubit-resonator and resonator-feedline coupling capacitances respectively. The lumped element equivalent inductance and capacitance for a quarter wave resonator can be calculated as:

$$C_r = \frac{\pi}{4\omega_r Z_0} \approx 499 \text{fF} \quad (1)$$

$$L_r = \frac{1}{C_r \omega_r^2} \approx 2.03 \text{nH} \quad (2)$$

from [3].

The chosen value for the Josephson junction inductance is

¹ANSYS Electronics Desktop 2021 R2

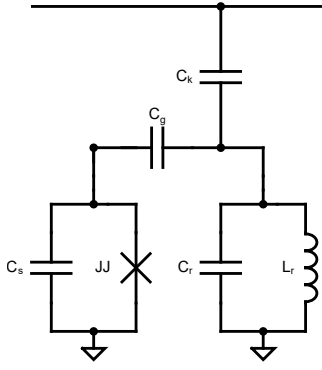


Figure 2: Lumped element circuit equivalent of our design. The resonator is represented as an LC circuit (L_r , C_r), while the qubit is a Josephson Junction shunted by a capacitance (C_s). C_g is the qubit-resonator coupling capacitance and C_k is the resonator-feedline coupling capacitance.

$L_j = 11$ nH, matching a critical current of $I_c = 29.92$ nA. With these circuit parameters we expect a Josephson energy $E_j = 14.86$ GHz and a capacitive energy $E_c = 188.80$ MHz, resulting in a ratio $E_j/E_c \approx 79$ in the transmon regime. The qubit and readout resonator resonant frequencies are $\omega_{01}/2\pi = 4.55$ GHz and $\omega_r/2\pi = 5.01$ GHz respectively, leading to a detuning of $\Delta_0/2\pi \approx 457$ MHz. The qubit-resonator coupling strength can be calculated as ([4]):

$$g_{n,n+1} = \sqrt{n+1} \frac{2\beta e V_{rms}}{\hbar} \left(\frac{E_j}{32E_c} \right)^{\frac{1}{4}} \quad (3)$$

with $\beta = C_g/(C_g + C_s)$, $V_{rms} = \sqrt{\hbar\omega_r/2C_r}$ and e elementary charge, leading to $g_{01}/2\pi = 47.38$ MHz. We can then calculate the total dispersive shift as ([4]):

$$\chi = \chi_{01} - \frac{\chi_{12}}{2} \quad (4)$$

where $\chi_{ij} = g_{ij}^2/(\omega_{ij} - \omega_r)$. The total dispersive shift value is $\chi/2\pi = -1.44$ MHz, being larger than the resonator resonance width $\kappa/2\pi = 1.12$ MHz allows the qubit state readout. Fig. 3 shows the expected transmission on the feedline as a function of frequency for the qubit in the ground or excited state.

An estimate of the qubit relaxation time can be calculated as follows ([5]):

$$T_1 = \frac{\Delta_0^2}{g_{01}^2} \frac{Q}{\omega_r} \approx 13 \mu\text{s} \quad (5)$$

where $Q \approx 4432$ (calculated as in [6]) is the resonator quality factor.

Ansys HFSS is used to perform the eigenmode simulation in order to compute the resonant frequencies of the circuit and exploit the Energy Participation Ratio (EPR) simulation [7, 8]. From the EPR analysis we can extract the qubit and resonator frequencies, anharmonicities and the total dispersive shift. The simulated qubit and resonator frequencies are $\omega_{01}^{EPR}/2\pi = 4.43$ GHz and $\omega_r^{EPR}/2\pi = 5.17$ GHz respectively. These values match the expected frequencies within 2.6% and 3.2% respectively. The qubit anharmonicity extracted from the

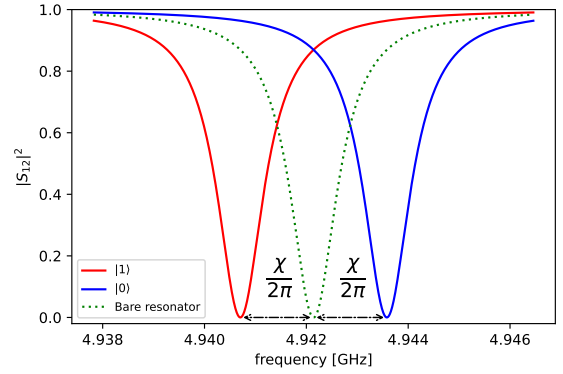


Figure 3: Feedline transmission as a function of frequency when the qubit is in the ground (blue) or excited state (red).

EPR simulation is $\alpha^{EPR} = -193.43$ MHz and matches the expected E_c within 2.5%. The simulated value for the total dispersive shift is $\chi^{EPR}/2\pi = -1.37$ MHz, within 4.9% the expected value.

3. Conclusions

We were able to simulate one possible design for the first chip fabrication, comparing the results with the expected circuit features. The simulations agree with the calculated values within a few percents. It should be noted that longer and more accurate simulations could further reduce these gaps.

Before moving to the manufacturing stage, a similar design with inductive resonator-feedline coupling will be evaluated, as well as different qubit and Josephson junction parameters. Higher values for the anharmonicity and longer qubit relaxation time will be pursued by accurately tuning couplings and frequencies. Further parameter tuning is ongoing to optimize the qubit readout. A simulation-data comparison will be performed as soon as the first chip is produced in order to validate the design procedure.

References

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