Cavity Quantum Electrodynamics, Simulation for circuit fabrication

science deep tech and innovation
4ª OI2I OFICINA DE INSTRUMENTAÇÃO E INOVAÇÃO

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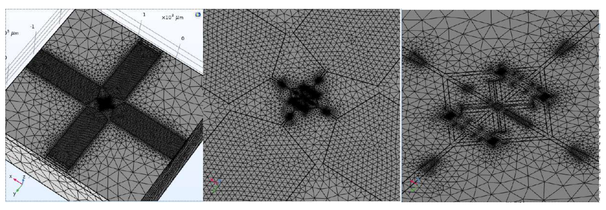
Simulations enable fabrication to cost less, progress faster, and gain complexity. Using a combination of both open source and proprietary software such as ANSYS, COMSOL, and Python libraries such as Qiskik Metal, it is possible to explore and design prototypes for cQED experiments. The Qiskit Metal Python Library is especially useful as it takes advantage of different means of extracting the quantum properties of the model through classical simulations.

Finite element method

- Computational Method to solve differential equations.
- Relies on mesh fragmentation of model.



$$H = H_0\, e^{i\omega t - k\vec{r}} \qquad E = E_0\, e^{i\omega t - k\vec{r}}$$

$$\vec{J} = \sigma\vec{E} \qquad \vec{B} = \mu\vec{H} \qquad \vec{D} = \epsilon\vec{E}$$

$$+i\omega\vec{D} = \nabla\times\vec{H}, \quad \text{(Faraday's Law)} \qquad -i\omega\vec{B} = \nabla\times\vec{E}, \quad \text{(Ampère's Law)}$$

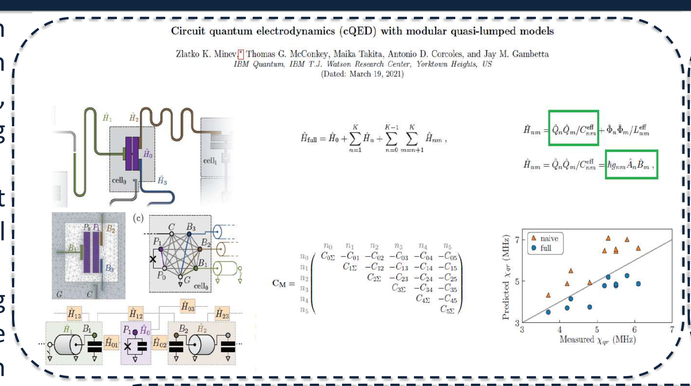
$$\vec{E} + i\omega\epsilon\vec{E} = \nabla\times\vec{I} \qquad \vec{H} = \frac{\nabla\times\vec{I}}{-i\omega\mu}$$

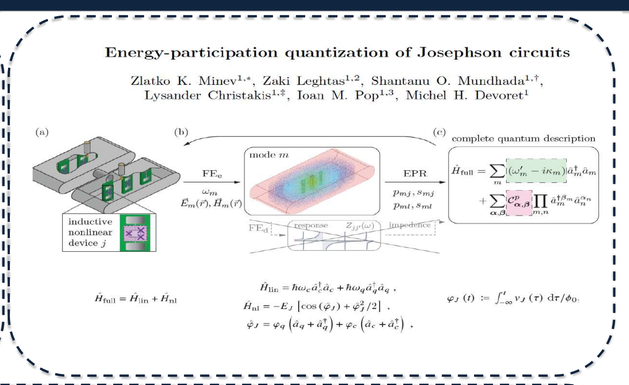
$$\vec{\nabla}\times\mu_r^{-1}(\vec{\nabla}\times\vec{E}) - k_0^2(\epsilon_r - \frac{i\sigma}{\omega\epsilon_0})\vec{E} = \vec{0}$$

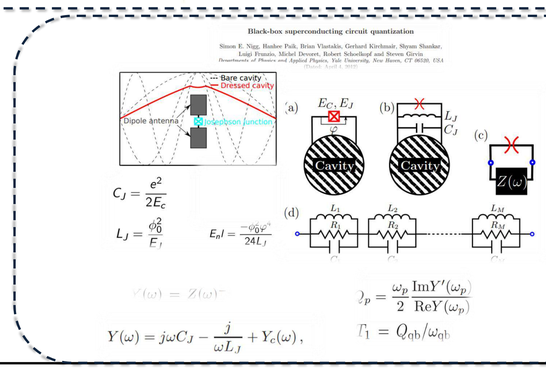
Quantization

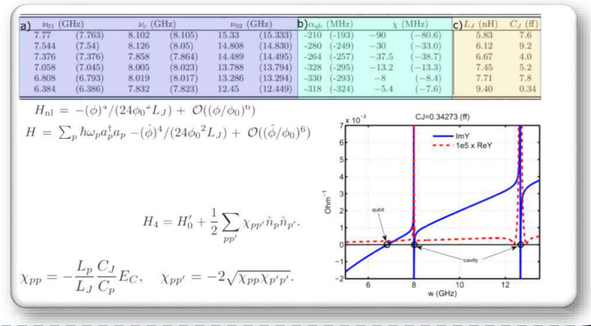
- These are the 3 different known methods for simulating quantum properties of microwave cavities, qubits(artificial superconducting atoms) and interactions.
- They all share the basic concept of a quantization of a classical simulation.
- They can be implemented using qiskit Metal and Ansys as a finite element solver or manually on COMSOL Multyphisics.

1. Quasi lumped models calculate quantization based on capacitance matrices.
2. Energy participation quantization calculates energy levels based on energy stored in junction.
3. Impedance analysis uses transmission and reflection of the waveguide.



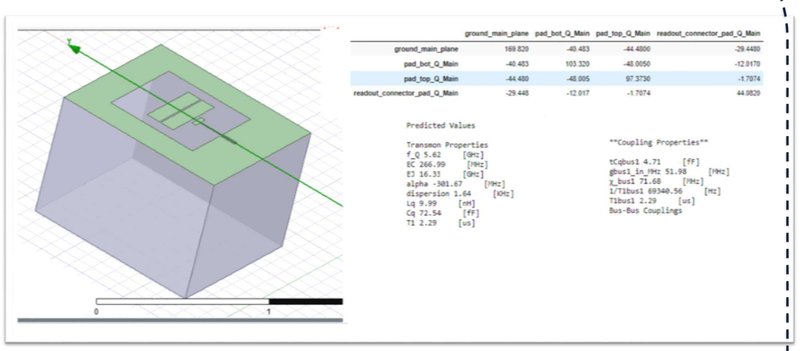






Simulation Results

Lumped element analysis



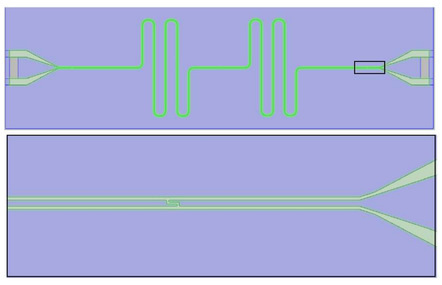
	ground_main_plane	pad_bot_Q_Main	pad_top_Q_Main	readout_connector_pad_Q_Main
ground_main_plane	169.820	-40.483	-44.4800	-29.4480
pad_bot_Q_Main	-40.483	103.329	-48.0050	-12.0170
pad_top_Q_Main	-44.480	-48.005	97.3730	-1.7074
readout_connector_pad_Q_Main	-29.448	-12.017	-1.7074	44.0820

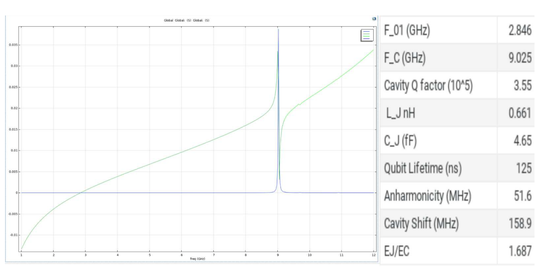
Predicted Values

Transmon Properties
f_Q 5.62 [GHz]
EC 266.99 [MHz]
EJ 16.33 [GHz]
alpha -301.67 [MHz]
dispersion 1.64 [KHz]
Lq 9.99 [nH]
Cq 72.54 [fF]
T1 2.29 [us]

Coupling Properties
tCqbus1 4.71 [ff]
gbus1_in_MHz 51.98 [MHz]
χ_bus1 71.68 [MHz]
1/Tlbus1 69340.56 [Hz]
Tlbus1 2.29 [us]
Bus-Bus Couplings

Impedance analyses - qubit is modeled as an inductor

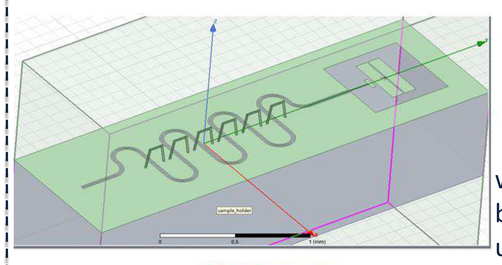


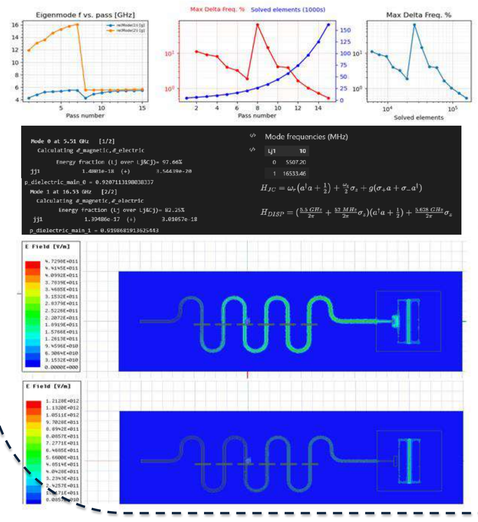


F_01 (GHz)	2.846
F_C (GHz)	9.025
Cavity Q factor (10^5)	3.55
L_J nH	0.661
C_J (fF)	4.65
Qubit Lifetime (ns)	125
Anharmonicity (MHz)	51.6
Cavity Shift (MHz)	158.9
EJ/EC	1.687

- Our results show how individual components can be simulated and useful experimental information extracted.

Energy Participation Ratio analysis

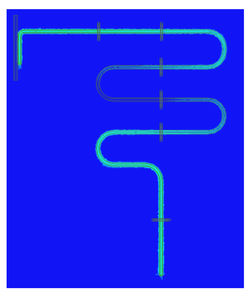




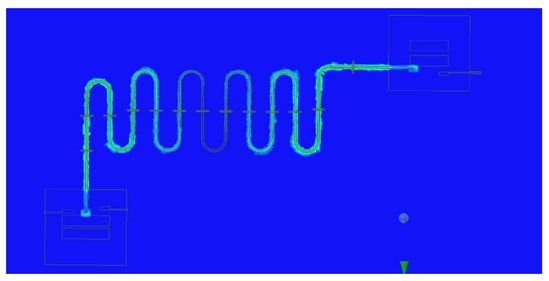
The simulation workflow usually starts by tunning the qubit, by using lumped element simulation, capacitances between the qubits and its enviroment are calculated, all inductances are negligible on most circuits and the only inductance taken into account is the Josephson Inductance.

- It is possible to simulate both quarter and half wave cavities.

Hanger capacitive coupler - quarter wave waveguide at 6.86 GHz mode 0.

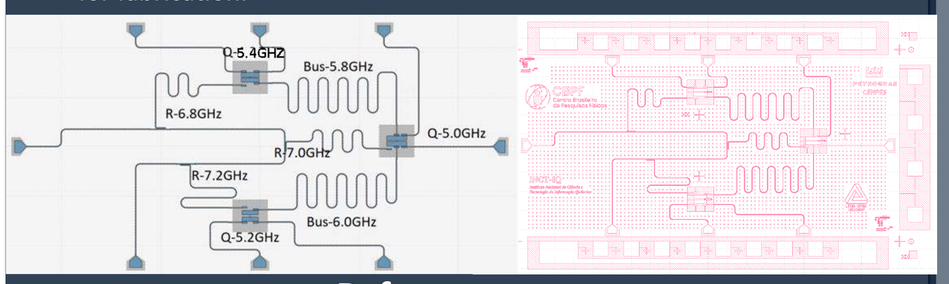


Half wave coupler connecting two qubits – 6.05GHz mode 0



Conclusion

- By taking individual components we are able to export a gds extension file, which can be directly used for photo and e-beam lithography. On the left the circuit layout and on the right the mask for fabrication.



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