QubIT WP1

15/11/2021

Quantum Simulation Module (QSM - NIST)

https://github.com/Borealis126/QSM

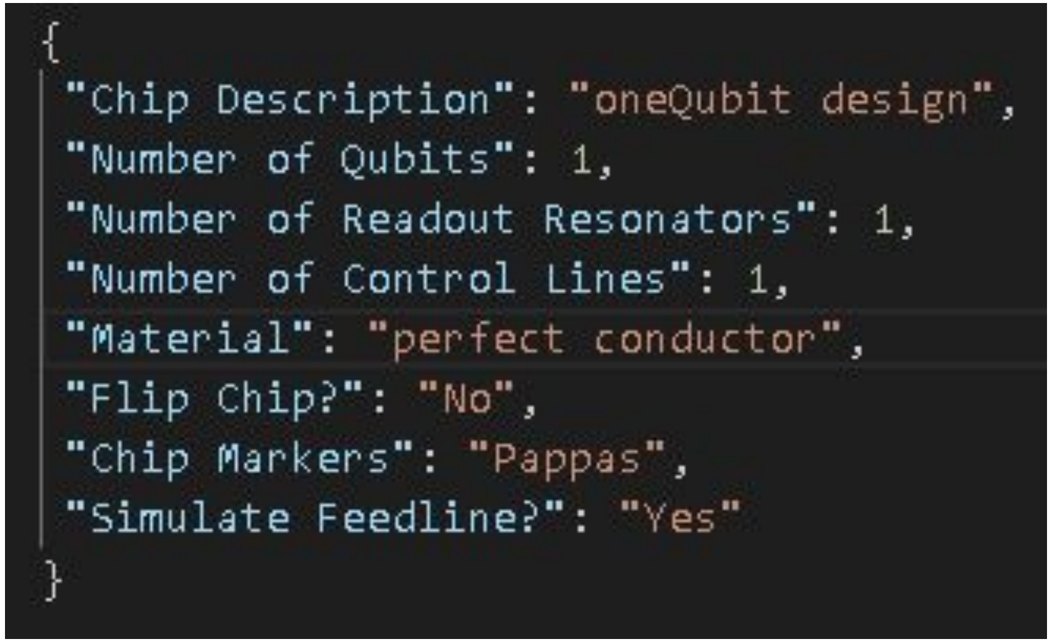
Chip design

- Chip design and component parameters (inductances) defined using .json files
- Qubit
  - Floating/Grounded
  - Single/Double JJ
  - Only rectangular pads at the moment
- Resonator
  - CPW transmission line
- Transmission lines
  - Feedline
  - Launchpads
  - Qubit-Qubit coupling

Workflow - Layout phase

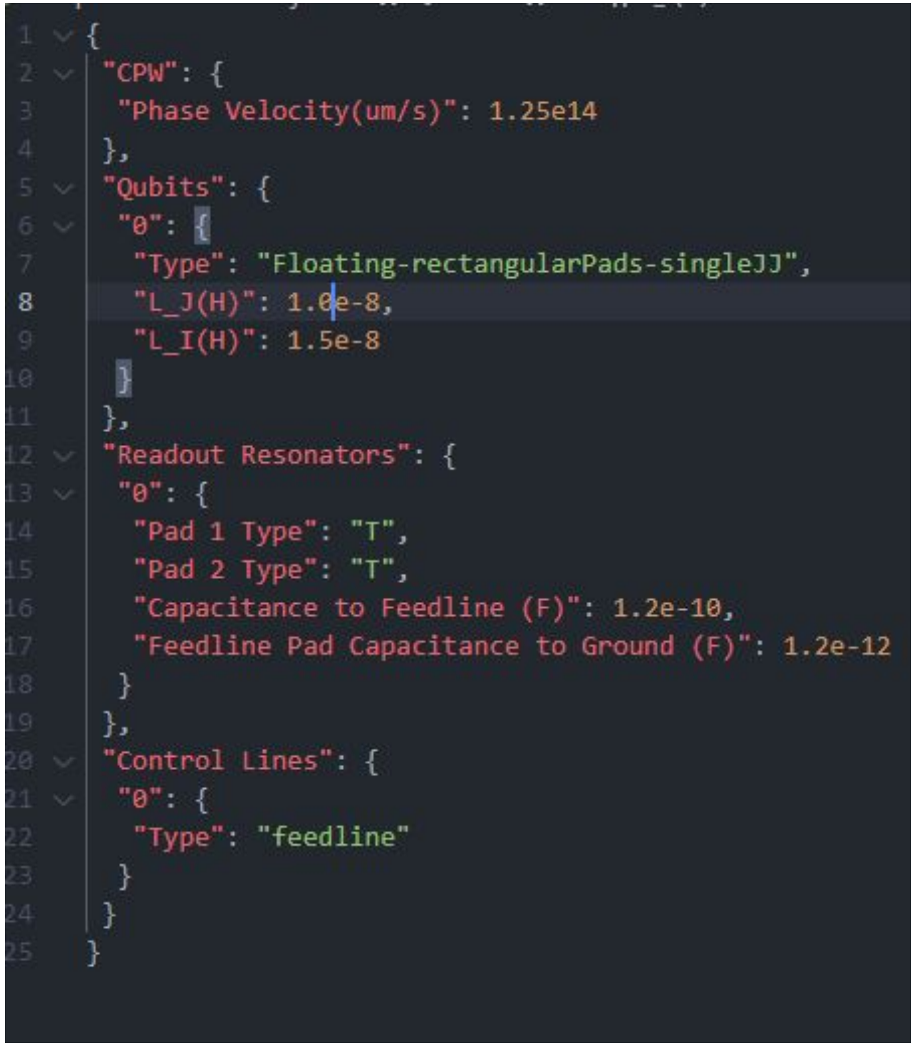
- *systemParameters.json* → main chip information
  - Number of qubits
  - Number of control lines
  - Material
- *componentParameters.json:*
  - CPW phase velocity
  - Qubits type and inductances
  - Resonators and control lines definition
- *componentGeometries.json:*
  - Position and dimensions of all the components

systemParameters.json



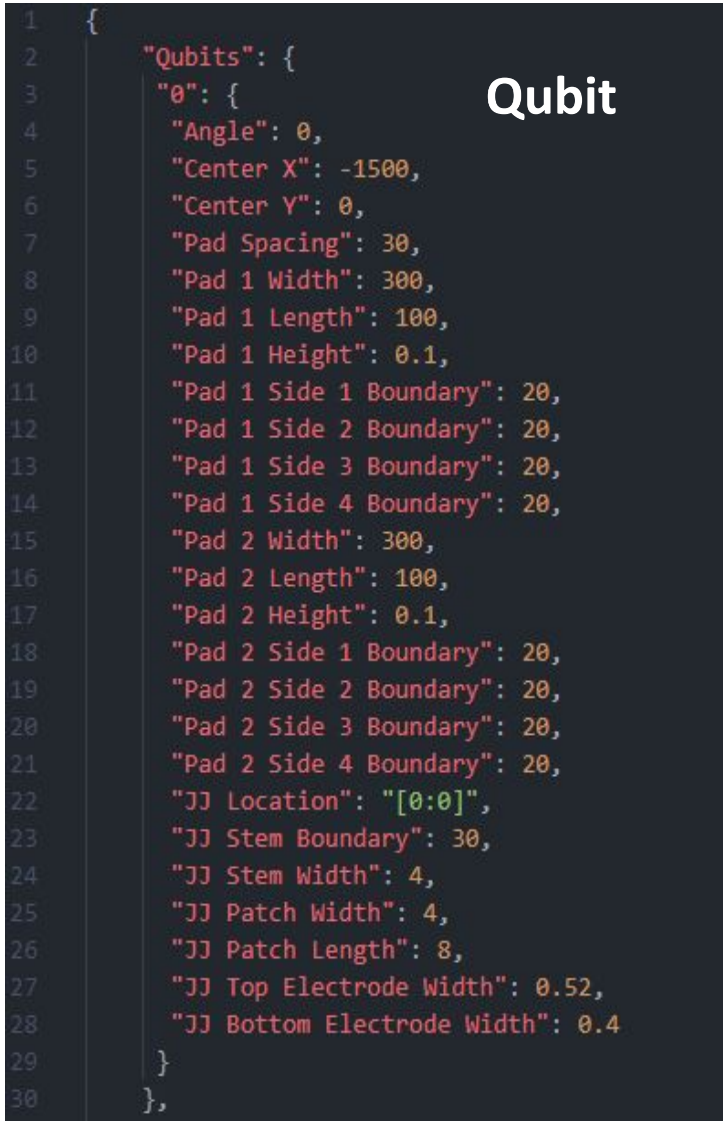
```
{
  "Chip Description": "oneQubit design",
  "Number of Qubits": 1,
  "Number of Readout Resonators": 1,
  "Number of Control Lines": 1,
  "Material": "perfect conductor",
  "Flip Chip?": "No",
  "Chip Markers": "Pappas",
  "Simulate Feedline?": "Yes"
}
```

componentParameters.json



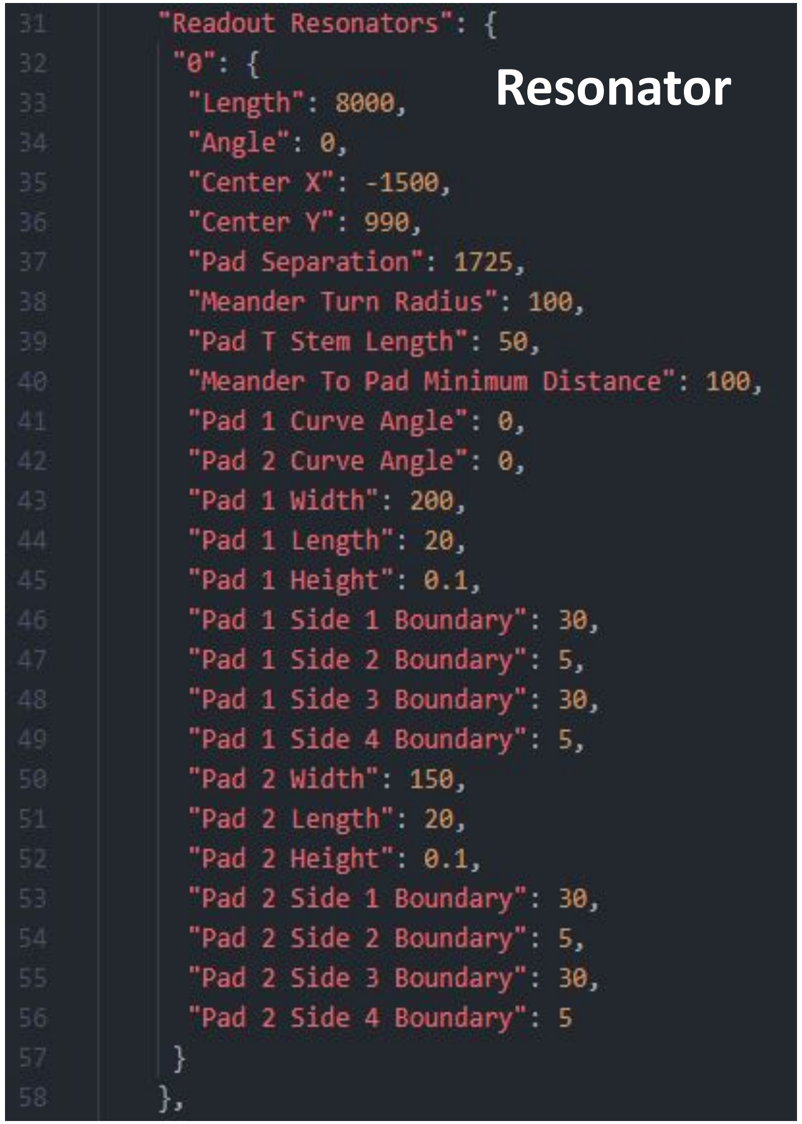
```
{
 "CPW": {
  "Phase Velocity(um/s)": 1.25e14
 },
 "Qubits": {
  "0": {
   "Type": "Floating-rectangularPads-singleJJ",
   "L_J(H)": 1.0e-8,
   "L_I(H)": 1.5e-8
  }
 },
 "Readout Resonators": {
  "0": {
   "Pad 1 Type": "T",
   "Pad 2 Type": "T",
   "Capacitance to Feedline (F)": 1.2e-10,
   "Feedline Pad Capacitance to Ground (F)": 1.2e-12
  }
 },
 "Control Lines": {
  "0": {
   "Type": "feedline"
  }
 }
}
```

componentGeometries.json



Qubit

```
{
    "Qubits": {
     "0": {
      "Angle": 0,
      "Center X": -1500,
      "Center Y": 0,
      "Pad Spacing": 30,
      "Pad 1 Width": 300,
      "Pad 1 Length": 100,
      "Pad 1 Height": 0.1,
      "Pad 1 Side 1 Boundary": 20,
      "Pad 1 Side 2 Boundary": 20,
      "Pad 1 Side 3 Boundary": 20,
      "Pad 1 Side 4 Boundary": 20,
      "Pad 2 Width": 300,
      "Pad 2 Length": 100,
      "Pad 2 Height": 0.1,
      "Pad 2 Side 1 Boundary": 20,
      "Pad 2 Side 2 Boundary": 20,
      "Pad 2 Side 3 Boundary": 20,
      "Pad 2 Side 4 Boundary": 20,
      "JJ Location": "[0:0]",
      "JJ Stem Boundary": 30,
      "JJ Stem Width": 4,
      "JJ Patch Width": 4,
      "JJ Patch Length": 8,
      "JJ Top Electrode Width": 0.52,
      "JJ Bottom Electrode Width": 0.4
     }
    },
```



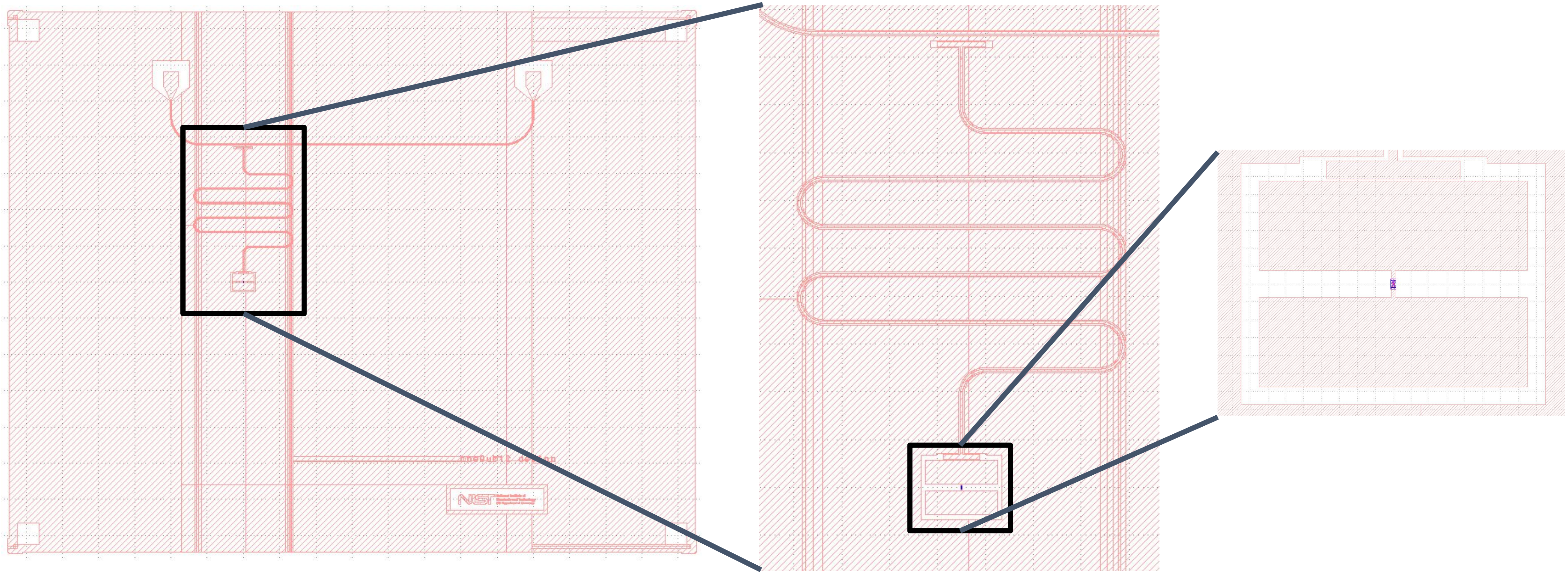
Resonator

```
    "Readout Resonators": {
     "0": {
      "Length": 8000,
      "Angle": 0,
      "Center X": -1500,
      "Center Y": 990,
      "Pad Separation": 1725,
      "Meander Turn Radius": 100,
      "Pad T Stem Length": 50,
      "Meander To Pad Minimum Distance": 100,
      "Pad 1 Curve Angle": 0,
      "Pad 2 Curve Angle": 0,
      "Pad 1 Width": 200,
      "Pad 1 Length": 20,
      "Pad 1 Height": 0.1,
      "Pad 1 Side 1 Boundary": 30,
      "Pad 1 Side 2 Boundary": 5,
      "Pad 1 Side 3 Boundary": 30,
      "Pad 1 Side 4 Boundary": 5,
      "Pad 2 Width": 150,
      "Pad 2 Length": 20,
      "Pad 2 Height": 0.1,
      "Pad 2 Side 1 Boundary": 30,
      "Pad 2 Side 2 Boundary": 5,
      "Pad 2 Side 3 Boundary": 30,
      "Pad 2 Side 4 Boundary": 5
     }
    },
```

Control lines

```
    "Control Lines": {
     "0": {
      "Start X": -2500,
      "Start Y": 2500,
      "Start Angle": -1.57,
      "Section Code": "(S:200)(R:1.57:400)(S:4200)(R:1.57:400)(S:200)"
     }
    },
    "CPW": {
     "Width": 10,
     "Gap": 6,
     "Trench": 0.1,
     "Height": 0.1
    },
    "Ground(s)": {
     "0": {
      "Height": 0.1,
      "Mesh Boundary": 40,
      "Mesh Spacing": 50,
      "Mesh Size": 5
     }
    },
    "Substrate(s)": {
     "0": {
      "Material": "silicon",
      "Thickness": 500,
      "Width": 9500,
      "Length": 7500
     }
    },
```

Result of the layout phase → GDS file



Workflow - Simulations and analysis

1) Capacitance matrix extracted with Ansys Q3D

$$\begin{pmatrix} C_{1,1} & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & C_{i,i} & -C_{i,j} & \cdots \\ \cdots & \cdots & -C_{j,i} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & C_{n,n} \end{pmatrix}$$

$$C_{i,i} = C_{i,g} + \sum_{i \neq j}^{N} C_{i,j}$$

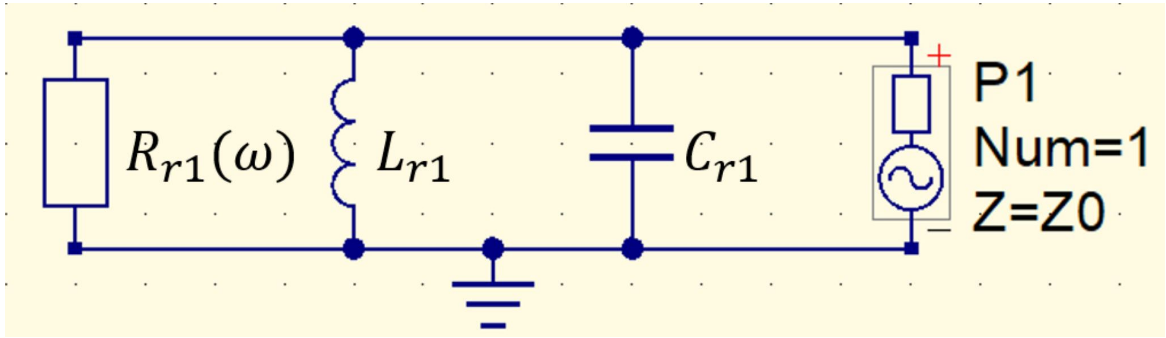
$$C_{i,j} < \ 0 \, , \, i \neq j$$

$$i, j = \ resonators \, and \, qubits \, pads$$

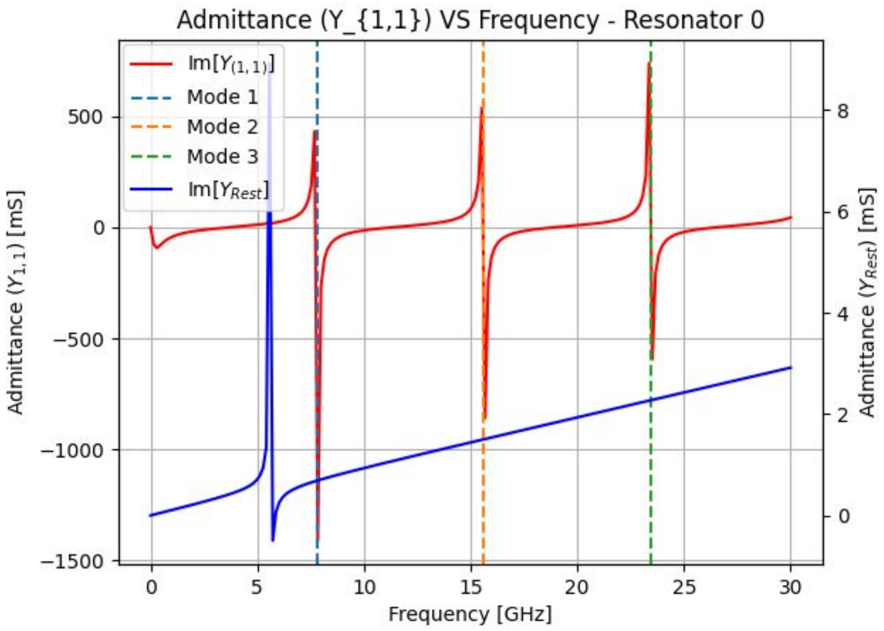
	Q0Pad1	Q0Pad2	R0Pad1	R0Pad2
Q0Pad1	0.09411	-0.01927	0	-0.01935
Q0Pad2	-0.01927	0.08391	0	-0.00039
R0Pad1	0	0	0.05146	0
R0Pad2	-0.01935	-0.00039	0	0.04416

Workflow - Simulations and analysis

2) Predict resonator frequency using admittance



$$\omega_n = n \times \frac{\pi v_p}{d}$$ for λ/2 resonator



Directly probing each readout resonator

$$Y_{1,1}(\omega) = \frac{1}{j\omega L_r} + j\omega C_r + \frac{1}{R_r(\omega)}$$

Workflow - Simulations and analysis

3) E_C and E_J for qubits

$$\frac{E_J}{E_C} \approx 45$$

$$E_C^{(Q)} = \frac{e^2}{2\left[C_{i,i}^{-1}\right]^{-1}}$$

$C_{i,i}^{-1}$ i^{th} diagonal element of the inverted capacitance matrix

$$E_J^{(Q)} = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{1}{L_J}$$

with $\Phi_0 = \frac{\hbar\pi}{e}$, magnetic flux quantum

L_J defined in componentParameters.json

Workflow - Quantization

4) Quantization

$$\omega_q \approx 6.48\,GHz$$

$$\Phi = \sqrt{\frac{\hbar Z}{2}}\left(a^\dagger + a\right) \qquad Q = j\sqrt{\frac{\hbar}{2Z}}\left(a^\dagger - a\right)$$

$$H = \frac{1}{2}Q^T C^{-1} Q - \sum_{i}^{N_{qubits}}\left[E_j^{(i)}\cos\left(\frac{\Phi_i}{\Phi_0}\right)\right] + \sum_{i}^{N_{resonators}}\left[\frac{\Phi_i^2}{2L_i}\right]$$

Calculations

Anharmonicity

$$\alpha = (E_2 - E_1) - (E_1 - E_0) \approx \; -390\,MHz$$

$$\text{with}\,E_q \;\rightarrow q = qubit\;state$$

Dispersive shift

$$\chi = (E_{1,1} - E_{1,0}) \; - \; (E_{0,1} - E_{0,0}) \approx \; -1.79\,MHz$$

$$\text{with}\;E_{q,r} \;\rightarrow q = qubit\;state;\; r \;=\; resonator\;state$$

Qubit-Qubit coupling

$$ZZ_{coupling} = \; E_{1,1} - E_{0,1} - E_{1,0}$$

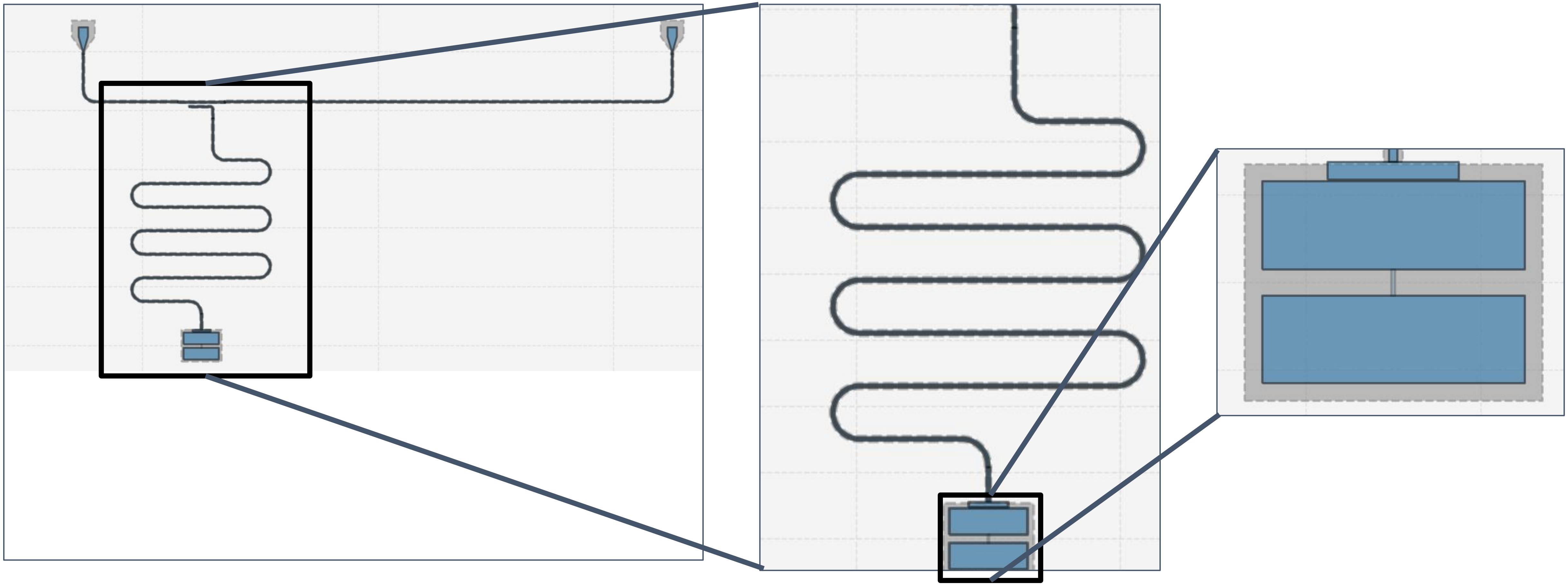
$$\text{with}\,E_{q1,q2}$$

Qiskit Metal
(IBM)

Chip design

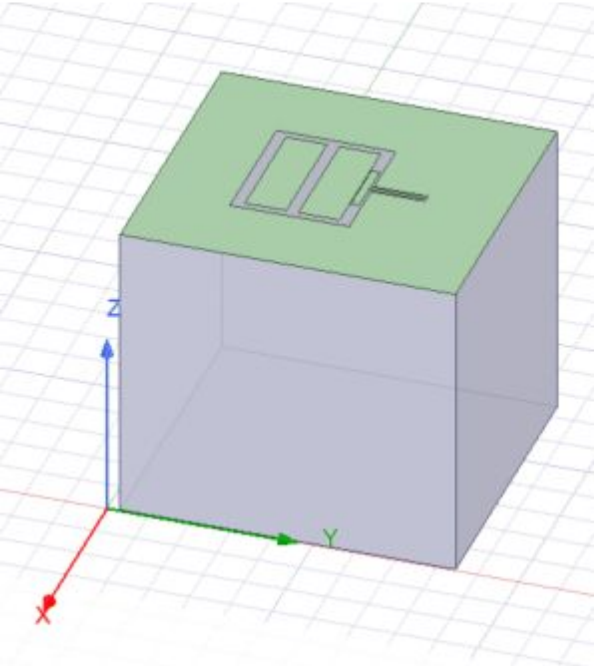
- Each component is an object with dedicated design options and pins
- Qubits
  - Simple transmon
  - Interdigitated transmon
  - Xmon
  - Concentric transmon
- Resonator
  - CPW transmission line
- Transmission lines
  - Semi-automatic management → Path finder from pin to pin

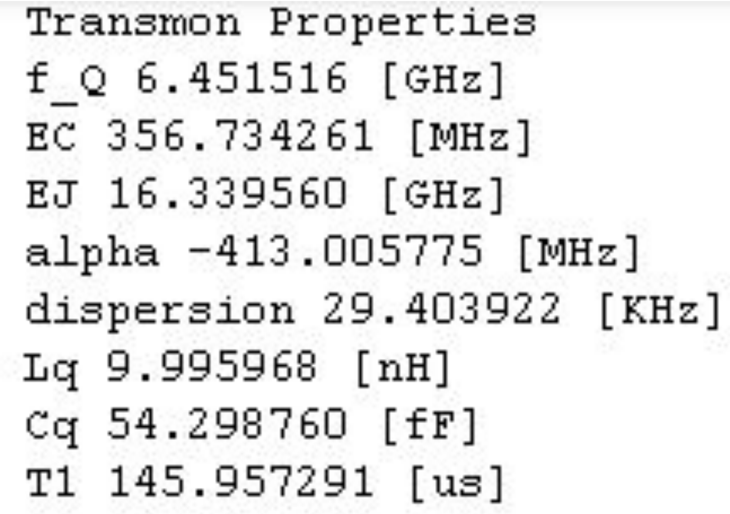
Result of the layout phase



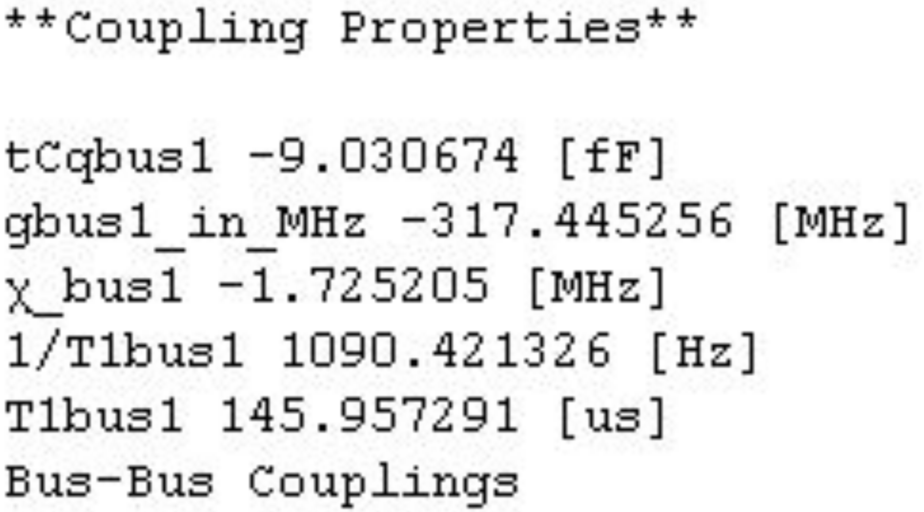
Analysis - Lumped element analysis

- Capacitance matrix → lumped oscillator model (LOM) simulation





```
Transmon Properties
f_Q 6.451516 [GHz]
EC 356.734261 [MHz]
EJ 16.339560 [GHz]
alpha -413.005775 [MHz]
dispersion 29.403922 [KHz]
Lq 9.995968 [nH]
Cq 54.298760 [fF]
T1 145.957291 [us]
```



```
**Coupling Properties**

tCqbus1 -9.030674 [fF]
gbus1_in_MHz -317.445256 [MHz]
χ_bus1 -1.725205 [MHz]
1/T1bus1 1090.421326 [Hz]
T1bus1 145.957291 [us]
Bus-Bus Couplings
```

Analysis - Finite Element Analysis and Energy Participation Ratio (EPR)

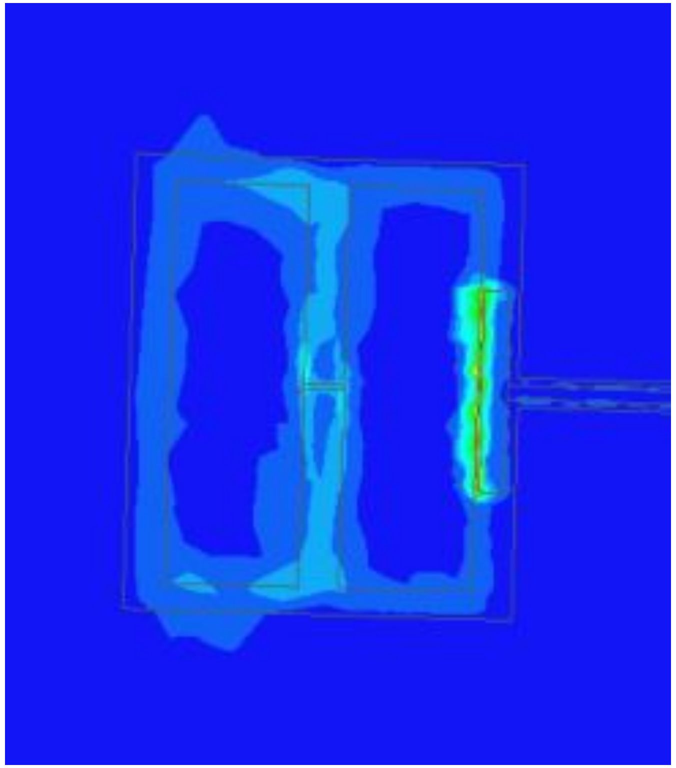
Participation ratio $p_m := \frac{\text{Inductive energy stored in the junction}}{\text{Total inductive energy of mode } m}$

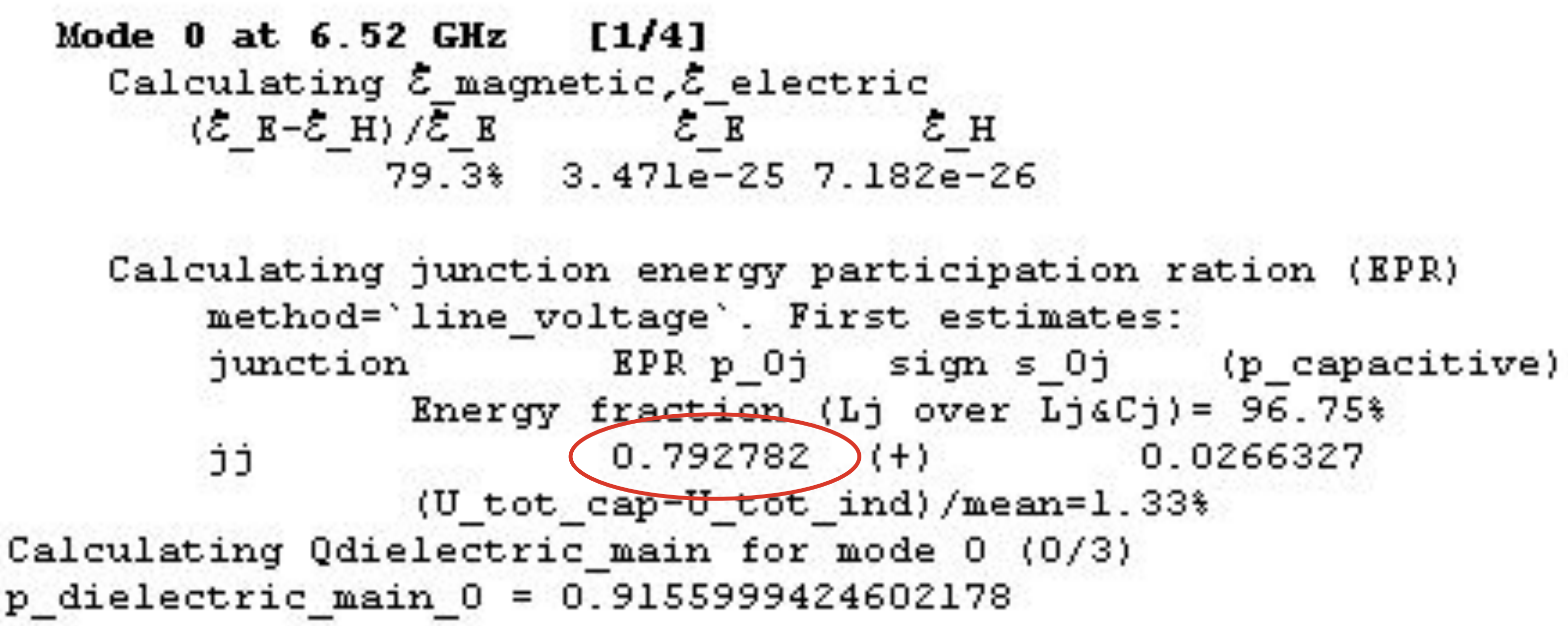
$$\frac{\phi_{mj}^2}{\hbar} = p_{mj}\frac{\omega_m}{E_J} \quad \text{j=junction and m=mode}$$

$$\alpha_m = p_m^2\frac{\hbar\omega_m^2}{8E_J} \qquad \chi_{qc} = p_q p_c\frac{\hbar\omega_q\omega_c}{4E_J}$$

https://www.nature.com/articles/s41534-021-00461-8

Analysis - Finite Element Analysis and Energy Participation Ratio (EPR)



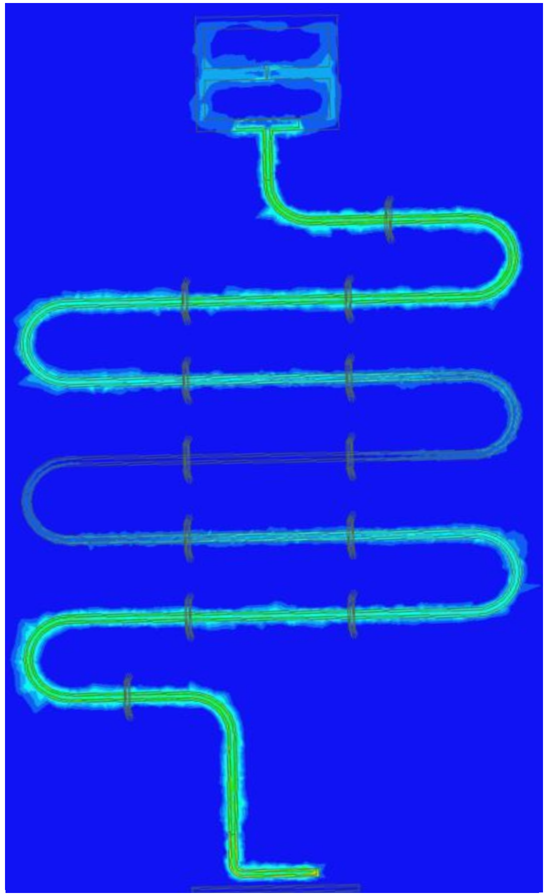


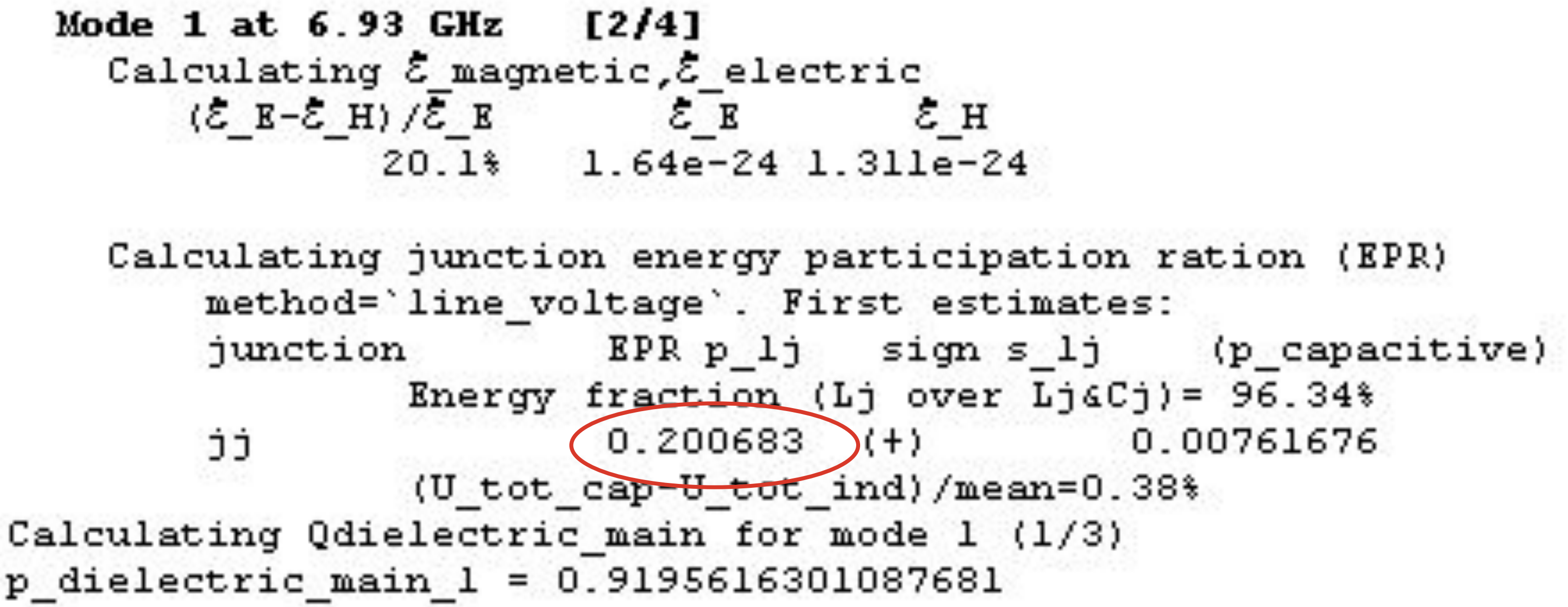
```
  Mode 0 at 6.52 GHz   [1/4]
    Calculating ℰ_magnetic,ℰ_electric
       (ℰ_E-ℰ_H)/ℰ_E      ℰ_E       ℰ_H
               79.3%  3.471e-25 7.182e-26

    Calculating junction energy participation ration (EPR)
        method=`line_voltage`. First estimates:
        junction        EPR p_0j   sign s_0j    (p_capacitive)
                Energy fraction (Lj over Lj&Cj)= 96.75%
        jj              0.792782  (+)        0.0266327
                (U_tot_cap-U_tot_ind)/mean=1.33%
Calculating Qdielectric_main for mode 0 (0/3)
p_dielectric_main_0 = 0.915599424602178
```

https://www.nature.com/articles/s41534-021-00461-8

Analysis - Finite Element Analysis and Energy Participation Ratio (EPR)



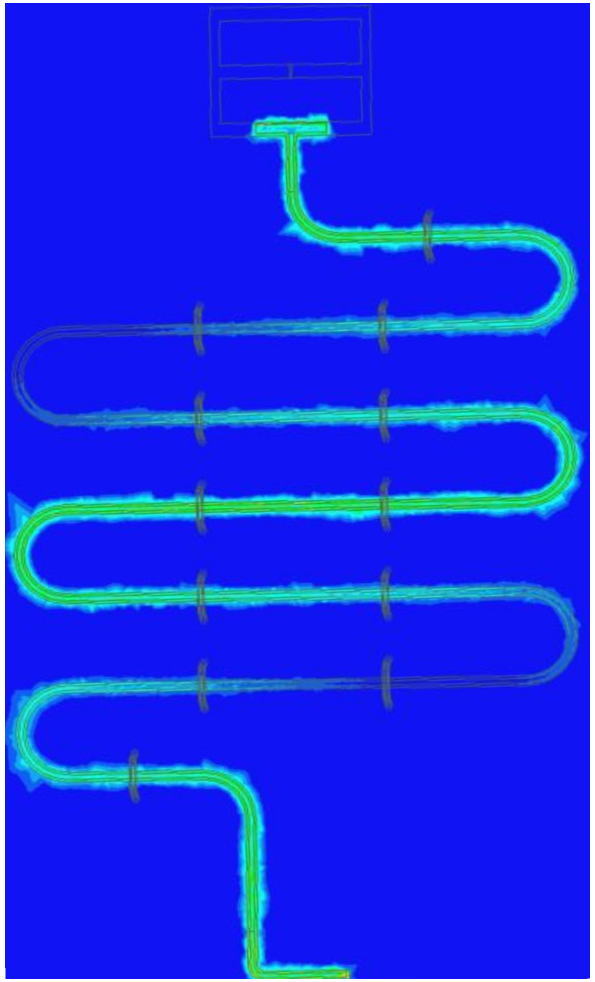


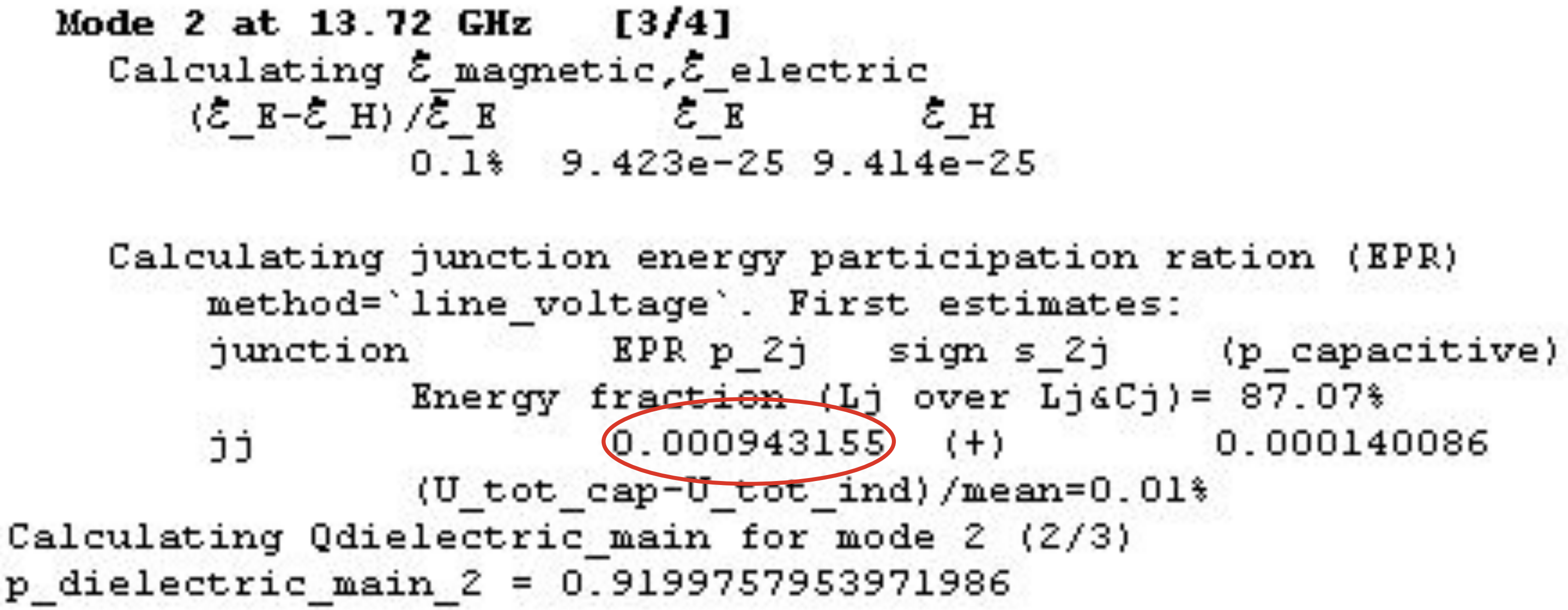
```
Mode 1 at 6.93 GHz   [2/4]
  Calculating ℰ_magnetic,ℰ_electric
     (ℰ_E-ℰ_H)/ℰ_E        ℰ_E        ℰ_H
           20.1%   1.64e-24 1.311e-24

  Calculating junction energy participation ration (EPR)
      method=`line_voltage`. First estimates:
      junction          EPR p_lj   sign s_lj    (p_capacitive)
              Energy fraction (Lj over Lj&Cj)= 96.34%
      jj                0.200683  (+)          0.00761676
              (U_tot_cap-U_tot_ind)/mean=0.38%
Calculating Qdielectric_main for mode 1 (1/3)
p_dielectric_main_1 = 0.9195616301087681
```

https://www.nature.com/articles/s41534-021-00461-8

Analysis - Finite Element Analysis and Energy Participation Ratio (EPR)



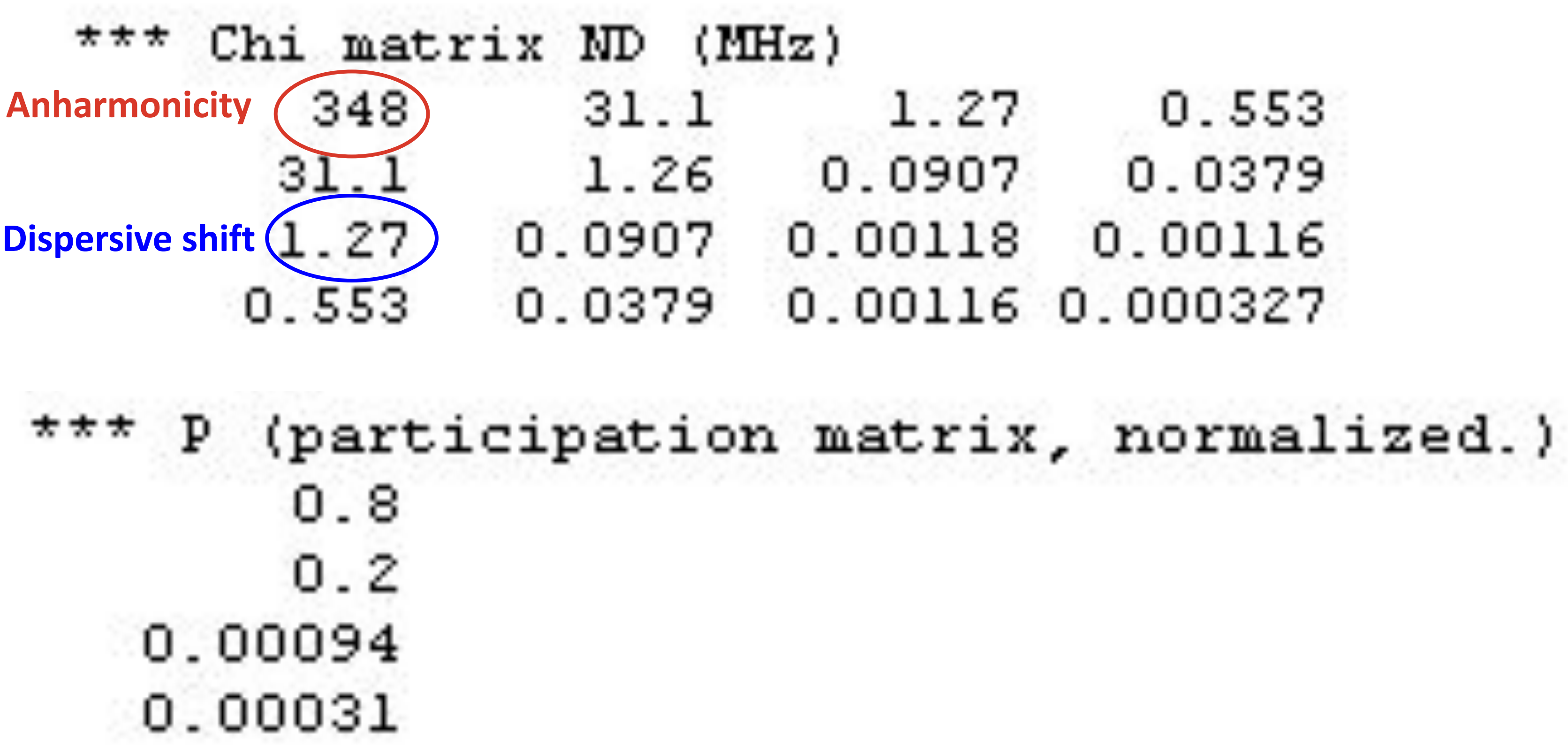


```
 Mode 2 at 13.72 GHz   [3/4]
   Calculating ℰ_magnetic,ℰ_electric
       (ℰ_E-ℰ_H)/ℰ_E       ℰ_E       ℰ_H
               0.1%  9.423e-25 9.414e-25

   Calculating junction energy participation ration (EPR)
       method=`line_voltage`. First estimates:
       junction        EPR p_2j   sign s_2j    (p_capacitive)
               Energy fraction (Lj over Lj&Cj)= 87.07%
       jj              0.000943155  (+)        0.000140086
               (U_tot_cap-U_tot_ind)/mean=0.01%
Calculating Qdielectric_main for mode 2 (2/3)
p_dielectric_main_2 = 0.9199757953971986
```

https://www.nature.com/articles/s41534-021-00461-8

Analysis - Finite Element Analysis and Energy Participation Ratio (EPR)



```
  *** Chi matrix ND (MHz)
       348       31.1      1.27     0.553
      31.1       1.26    0.0907    0.0379
      1.27     0.0907   0.00118   0.00116
     0.553     0.0379   0.00116  0.000327

*** P (participation matrix, normalized.)
       0.8
       0.2
   0.00094
   0.00031
```

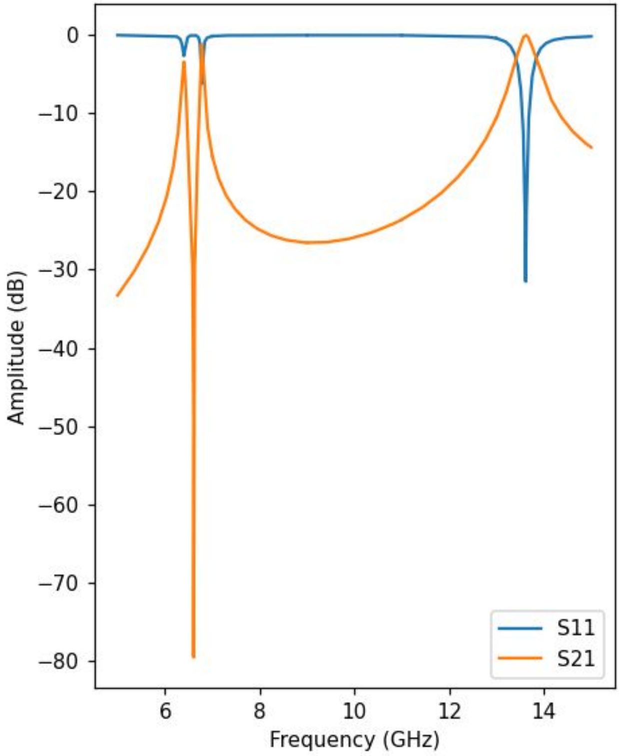
Anharmonicity

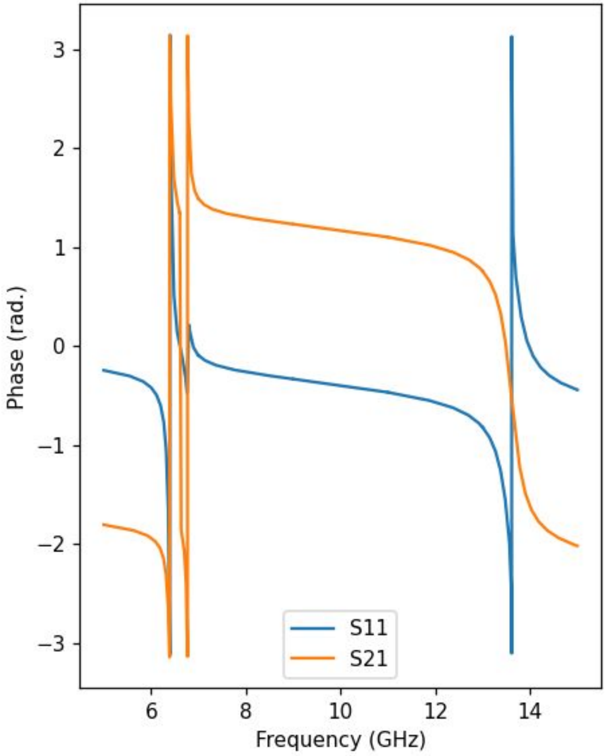
Dispersive shift

https://www.nature.com/articles/s41534-021-00461-8

Analysis - Impedance, Scattering and Admittance

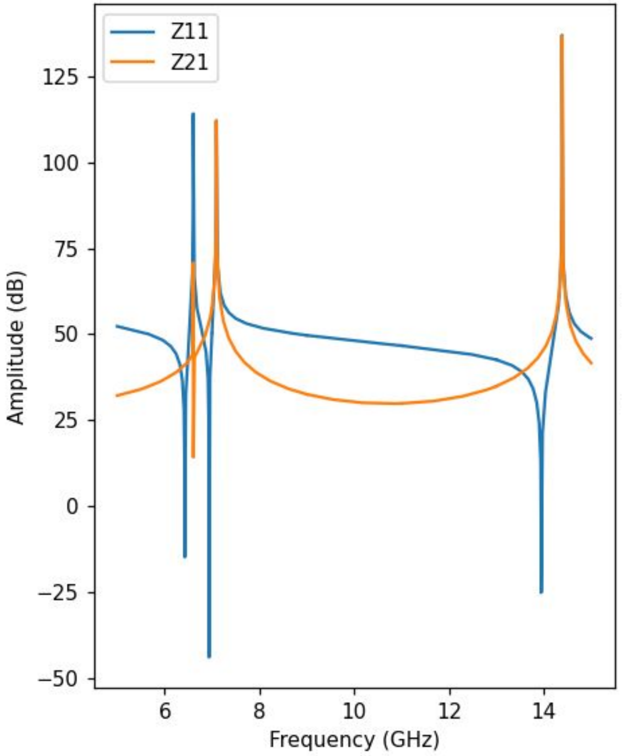
- Circuit analysis

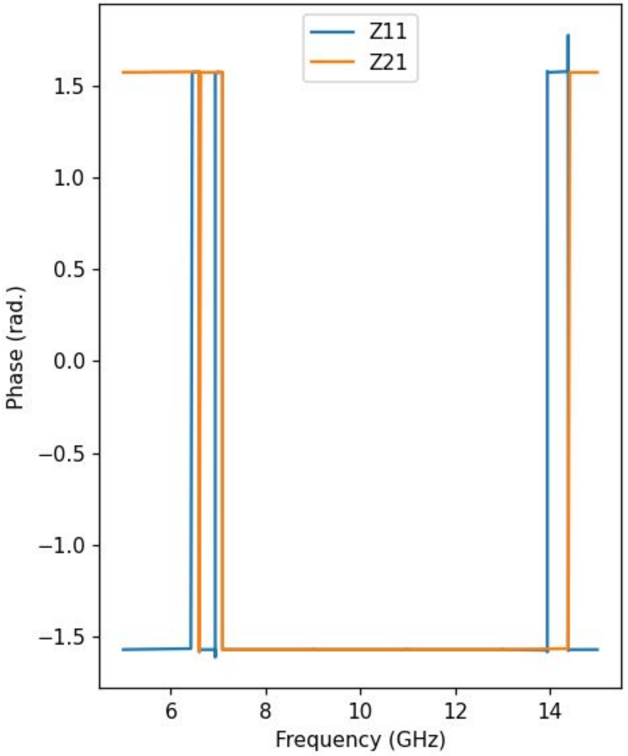




Analysis - Impedance, Scattering and Admittance

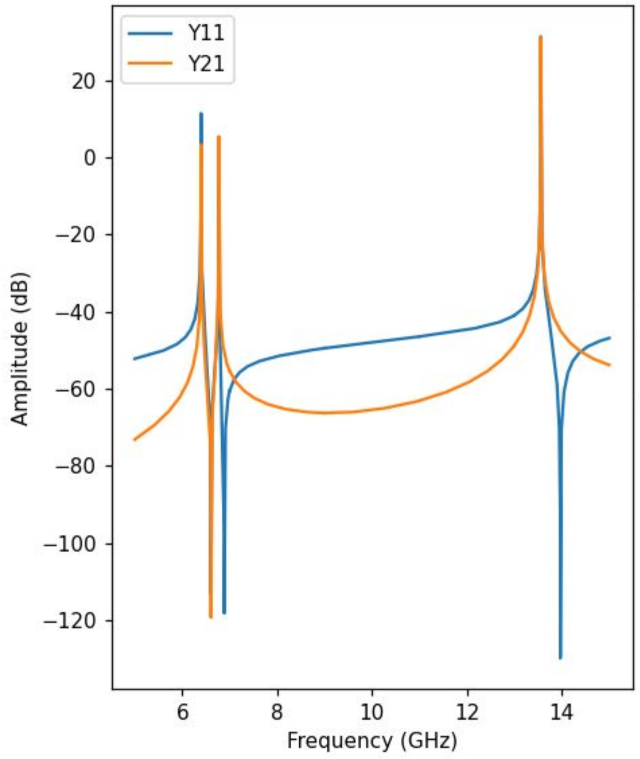
- Circuit analysis

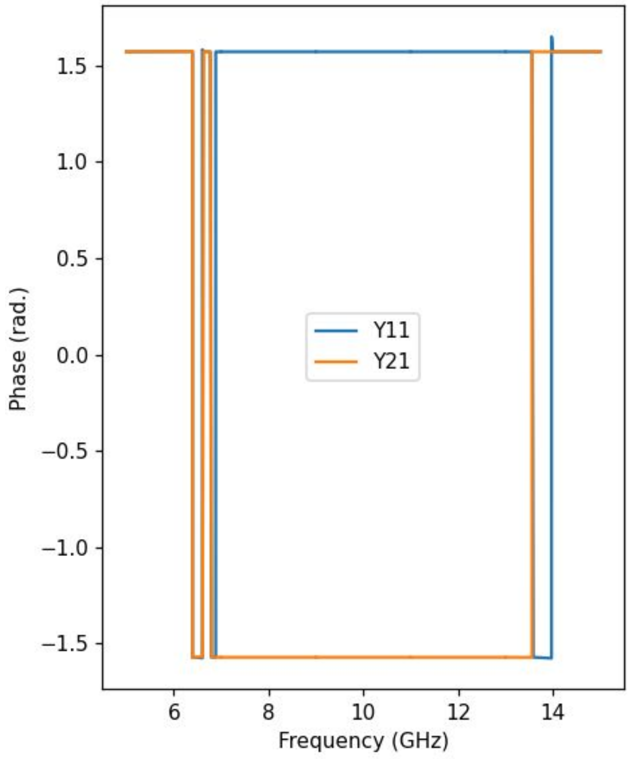




Analysis - Impedance, Scattering and Admittance

- Circuit analysis

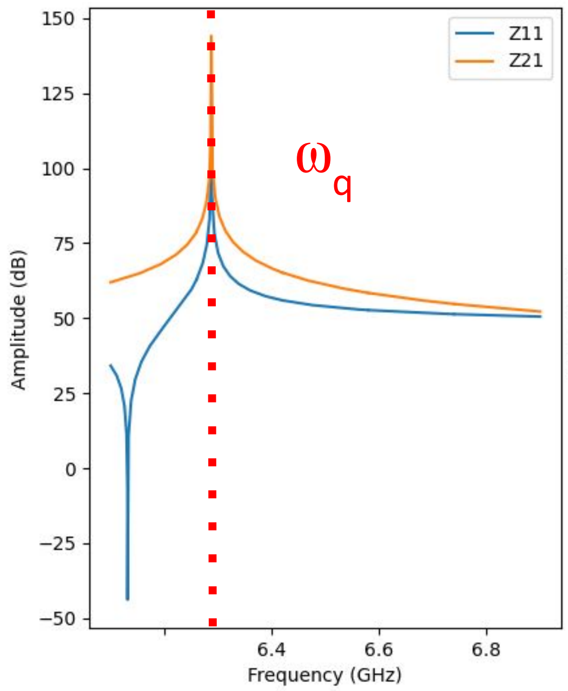


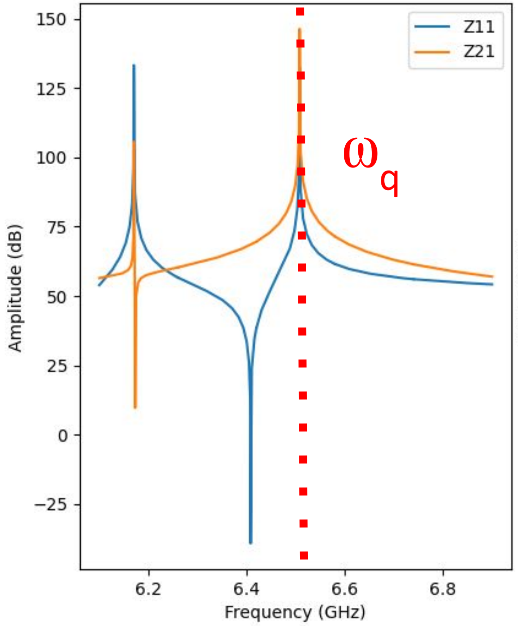


Comparison QSM-Qiskit

Parameters	QSM	Qiskit-Metal	
		LOM	EPR
ω_q [GHz]	6.48	6.45	6.52
α [MHz]	-390	-413	-348
χ [MHz]	-1.79	-1.73	-1.27
E_C [MHz]	359.77	356.73	/
E_J [GHz]	16.35	16.34	/
E_J/E_C	45.44	45.80	/
T_1	To be implemented	146	/
Computational cost	Low	Low	High
User defined parameters	L_i, L_j	L_j, C_j, readoutFrequency	L_j,C_j

Qubit only





Qubit + Resonator

Conclusions and next steps

- QSM is still far from Qiskit-Metal in terms of possibilities
- On the other hand, for QSM it's easy to add custom simulations and calculations
- QSM also aims to be totally open-source (e.g. using FasterCap https://www.fastfieldsolvers.com/fastercap.htm)
- Qiskit-Metal offers more options for the design and also custom qubits
- Next step: simulation of other designs (e.g. trying to recreate the design shown https://www.nature.com/articles/nphys1710.pdf)