Coplanar waveguide resonators

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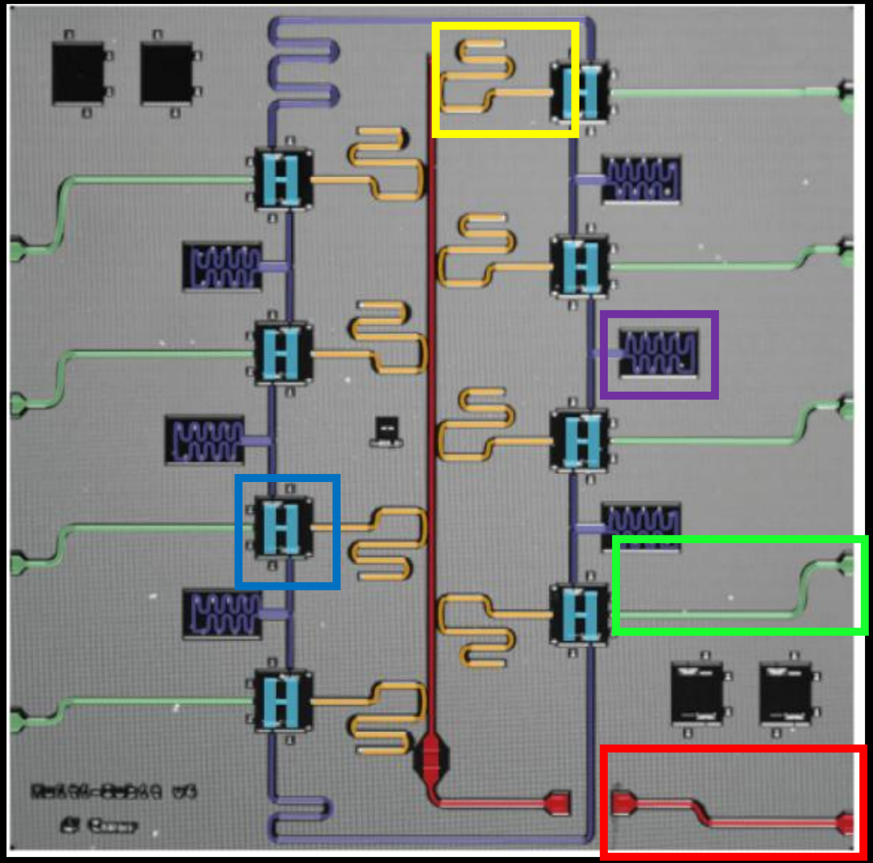
Outline and outcomes

- Superconducting Quantum circuits
- Resonator’s noise sources
- Design parameters to consider
- Input-output coupling
- Worked examples
- Full design workflow
- Use cases

Superconducting quantum circuit



Main components:

1.Resonator CPWr.

2. Qubit (nonlinear inductor).

Complementary:

3. Coupler for entanglement CPWr.

4. Drive line CPWr.

5. Readout line CPWr.

- Resonators are used in quantum circuits for:
    - Entanglement (qbit-qbit coupling).
    - Readout filtering and readout channel.
    - Control and drive of qubit states.
- Therefore, better resonators means less noise in the circuit.

What is resonator's loss or noise?

$$Q = \frac{Energy\ stored}{Energy\ lost\ per\ cycle}$$

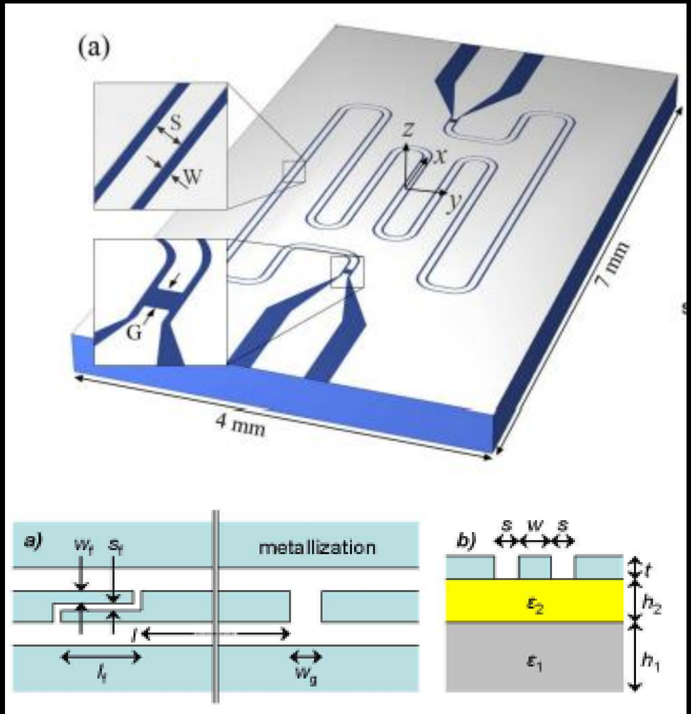
Internal losses (Qi):
Physical loss sources causes the stored energy in the resonator to dissipate. This is measured assuming the resonator is in complete isolation from all other circuit components.

- Fabrication defects
- Metal contamination
- Substrate loss tangent

External losses (Qe):
Simulated loss is determined by capacitive or inductive coupling between the circuit components using a simulation software.

- Crosstalk between circuit elements.
- Strong coupling between drive lines or readout line.

Design parameters in resonators



- Frequency: $f = \frac{c}{\sqrt{\varepsilon_{eff}}}\frac{1}{2l}$ or $f = \frac{c}{\sqrt{\varepsilon_{eff}}}\frac{1}{4l}$
- Characteristic impedance: $Z_o = \sqrt{L_l/C_l}$
- External quality factor (Qe)
- Capacitance and coupling.

- HFSS
- CST
- COMSOL

Where:

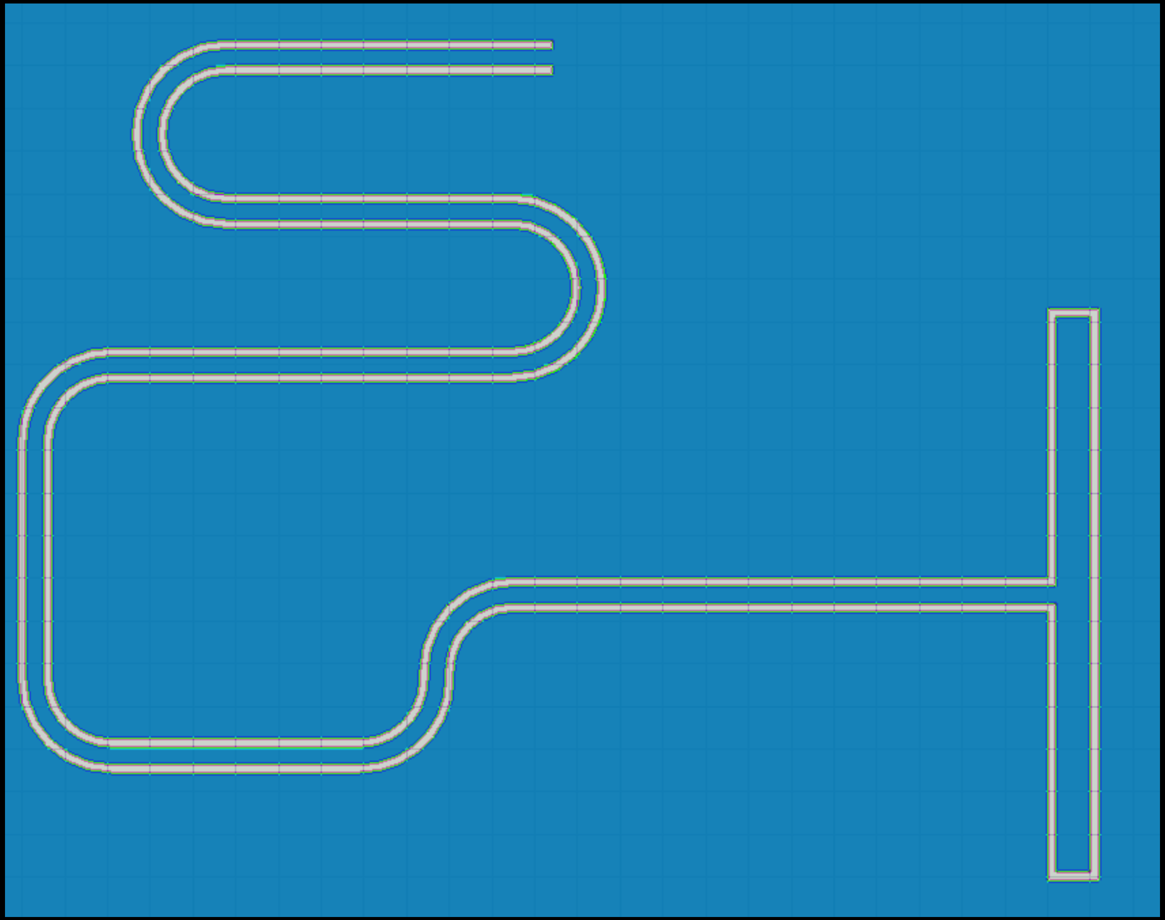
L_l=$\frac{\mu_0}{4}\frac{K(k'_0)}{K(k_0)}$ and C_l= $4\varepsilon_0\varepsilon_{eff}\frac{K(k_0)}{K(k'_0)}$

k_0=$\frac{w}{w+2s}$ and $k'_0 = \sqrt{1-{k_0}^2}$

Typically W:S is 2:1 (w=20 μm and s=10 μm):

$k_0 = 0.5$ and k'_0=0.866 $\longrightarrow$ L_l= 402 nH/m and C_l = 145 pF/m $\longrightarrow$ Z_o= 52.65 Ω

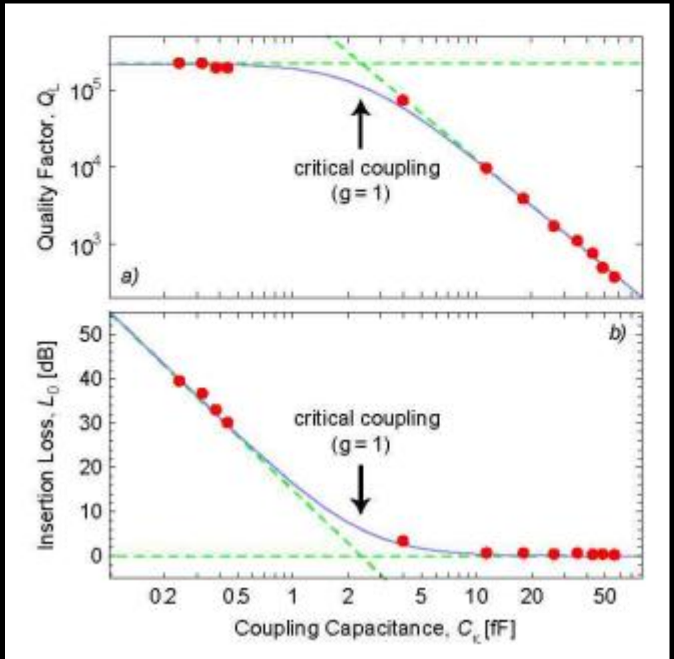
Example of a resonator design

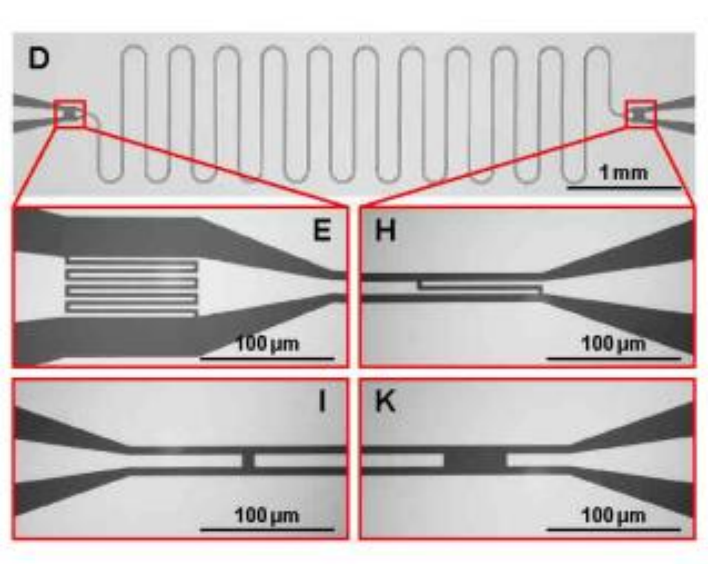


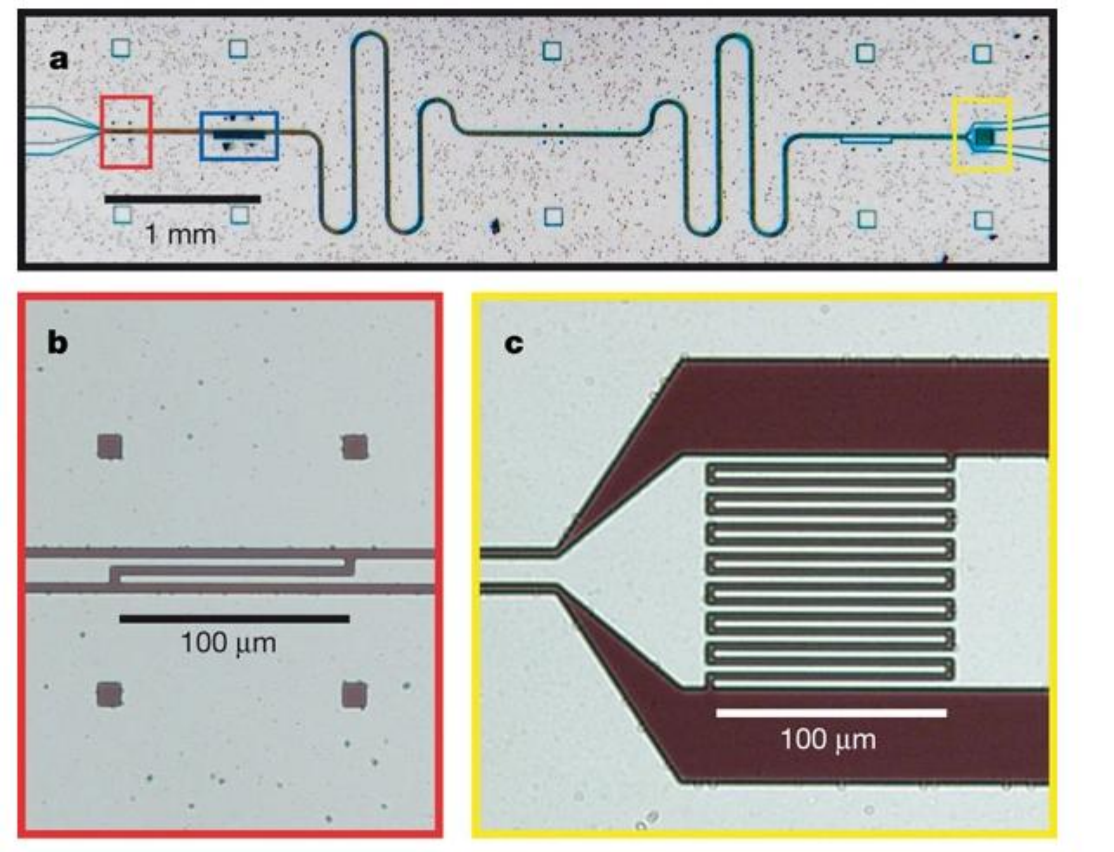
- Middle conductor to gap is 2:1
- Total length corresponds to 6 GHz

- Blue is the metal (Perfect E) and white is silicon.

Input-output coupling

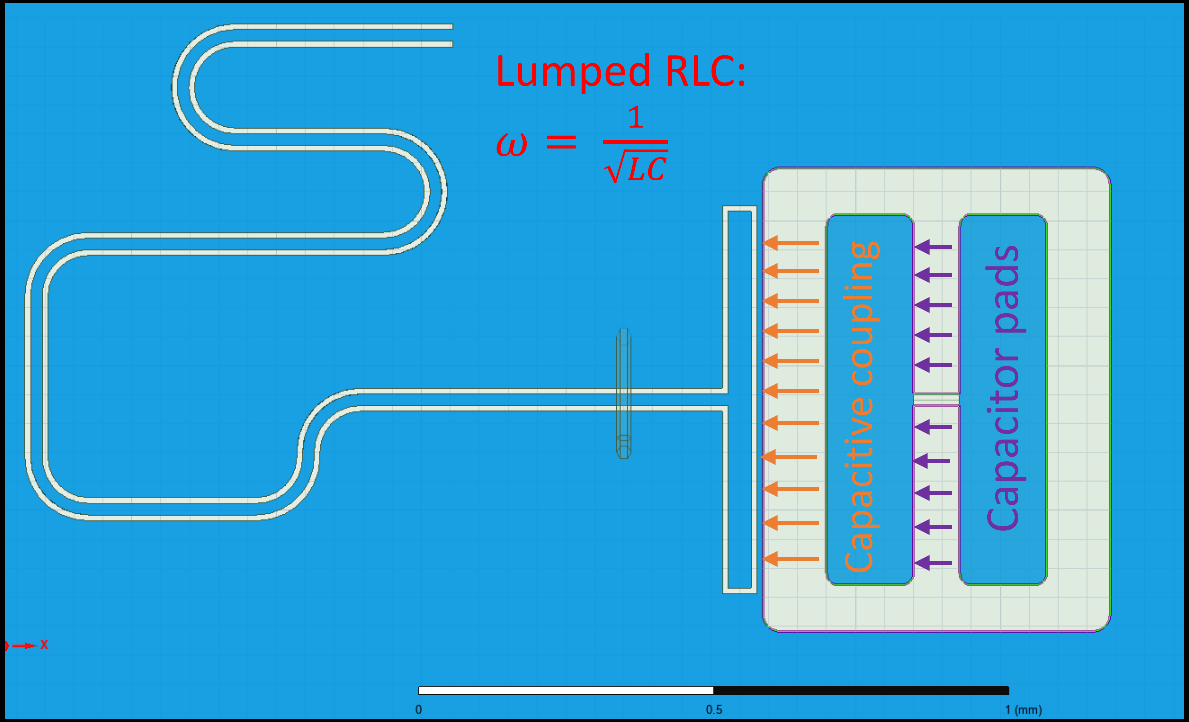






More on capacitive coupling

- Capacitive coupling is also important in terms of connecting different circuit elements.

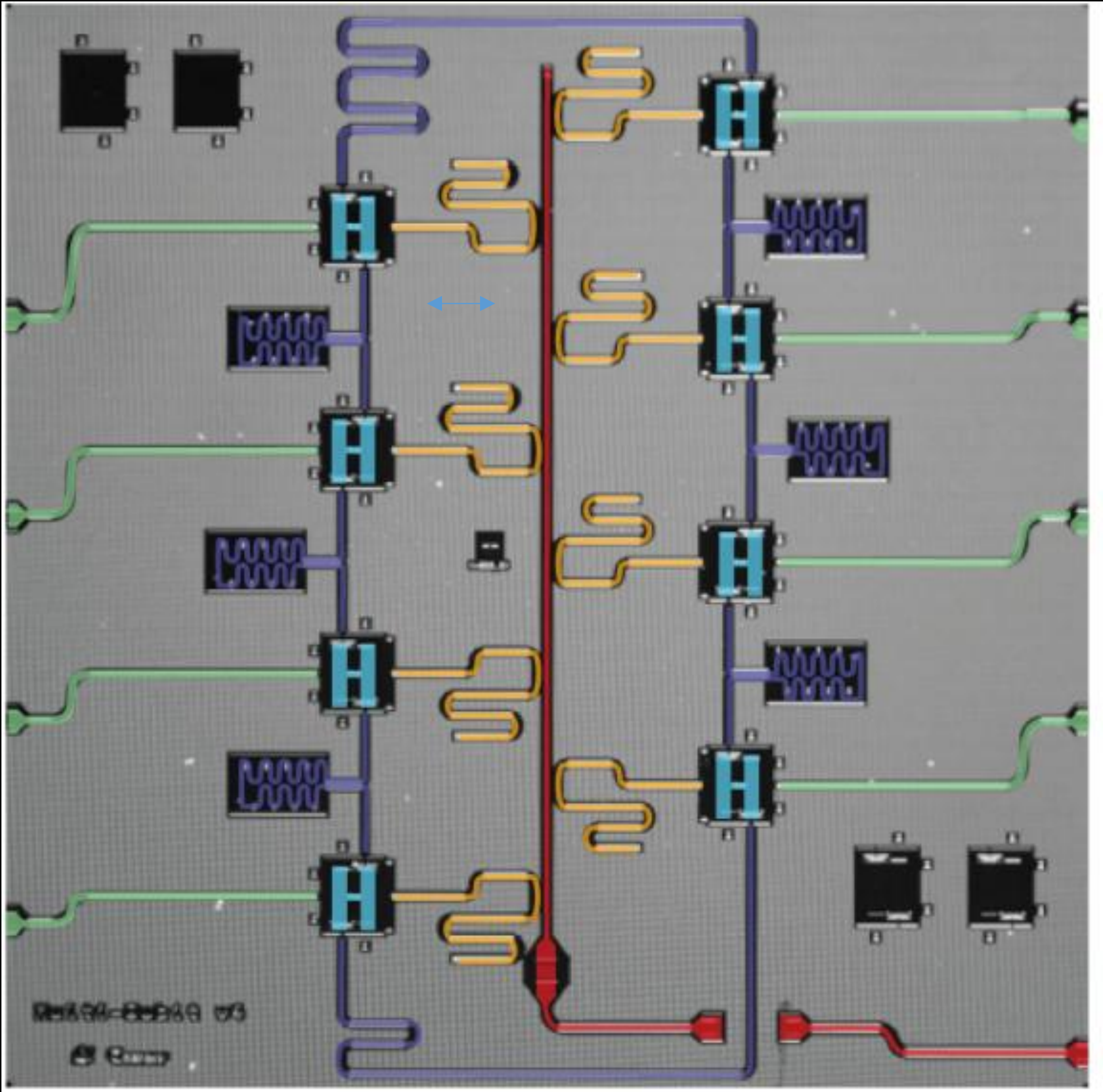


All capacitances are computed with Maxwell 3D including:

- Capacitor pads
- Qubit-resonator coupling
- Resonator-readout coupling
- Qubit-qubit coupling

Additionally:
The coupling strength can be estimated from the external quality factor of each component on HFSS.

Complete design workflow



Full design steps:

- Draw coplanar structures for all resonators and readout lines:
  - Adjust the frequencies based on length
  - Adjust the impedance matching (2:1)
  - Adjust the external Q
- Qubit pads:
  - Optimize the capacitance with Maxwell 3D to get the qubit frequency
  - Reach the desired coupling by optimizing Qe and capacitance.
  - Apply lumped RLC ~12 nH box to simulate the frequency classically.
    - For accurate frequency and anharmonicity use PyEPR instead.

Discussion:use cases

- Algorithm specific design
- High kinetic inductance
- Compact fields and resonators
- Remote entanglement

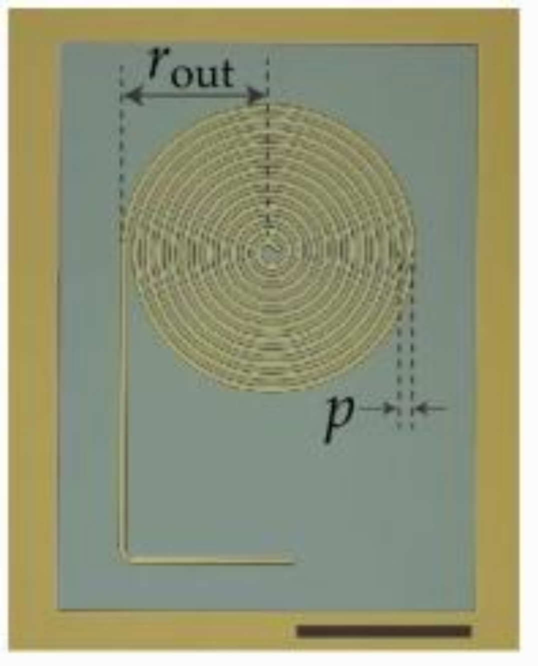
- All of the above are based on the design principles we discussed.

Thanks

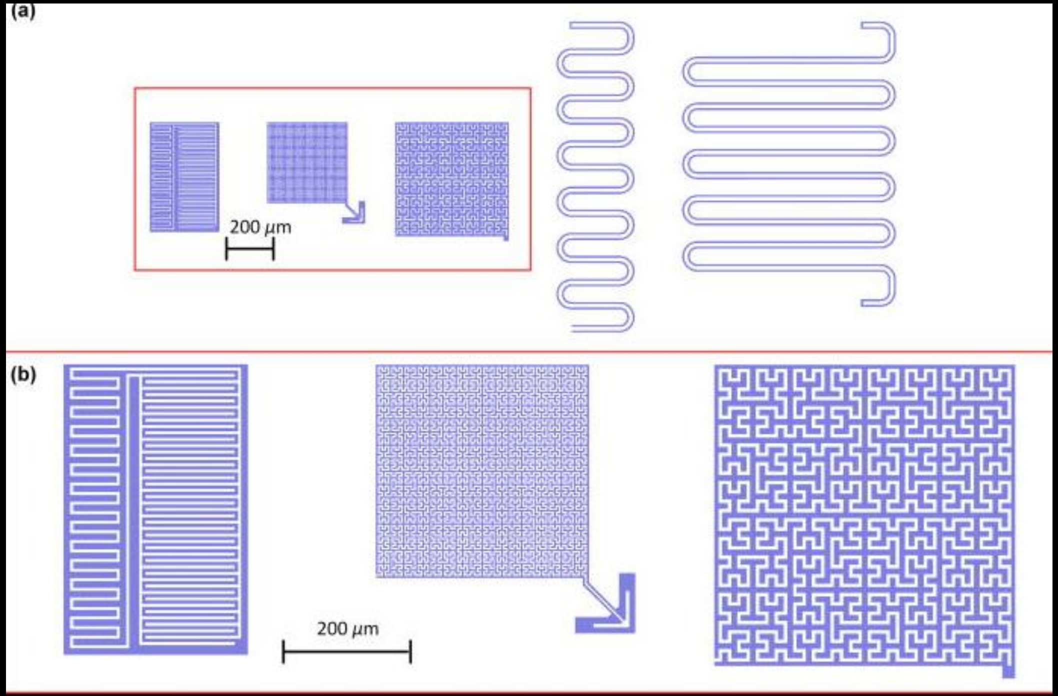
Questions?

Design geometry and field intensity can also change Qi

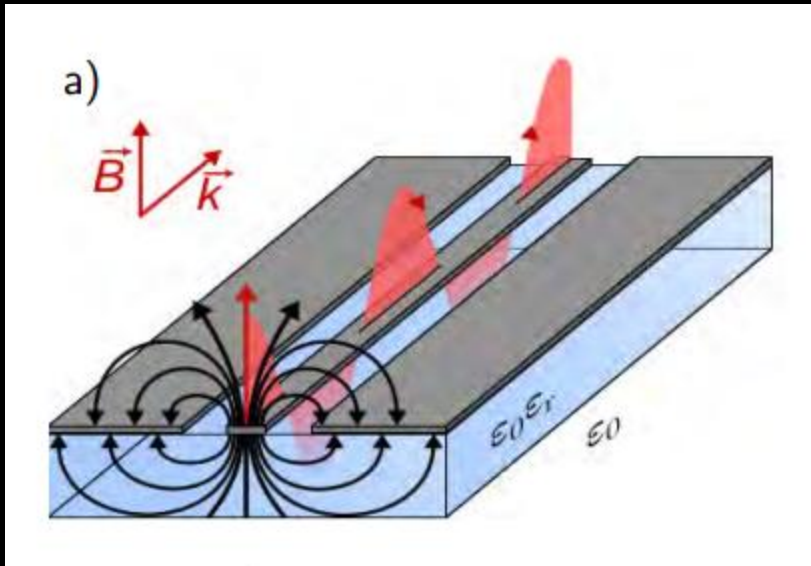
Spiral geometry (10M Qi)



Spiral geometry (100K Qi)

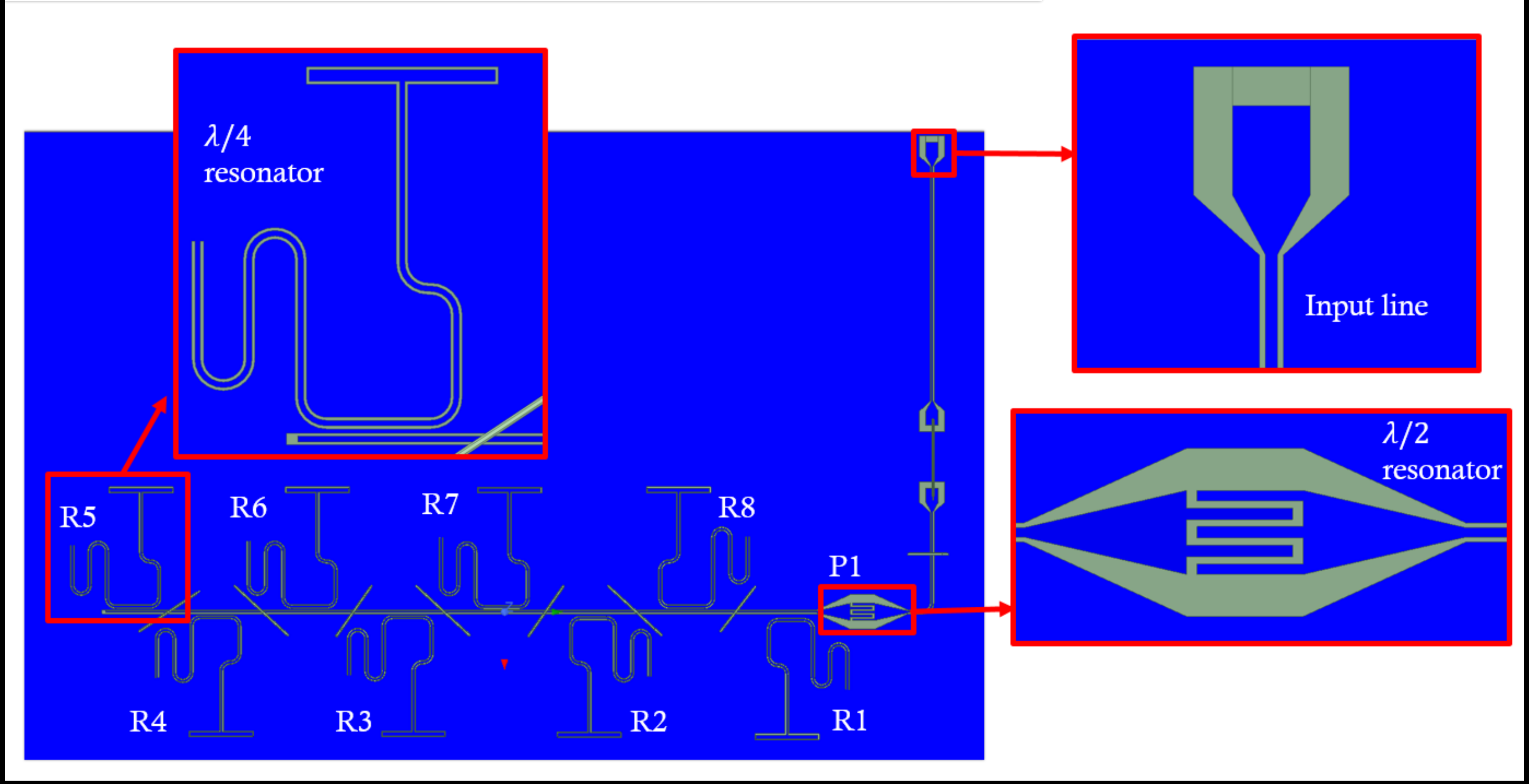


CPW geometry (2-6M Qi)



Example on how to design resonators on HFSS

Mode 2	6.22718 +j 0.000912640	3411.63
Mode 3	6.30231 +j 0.000716784	4396.24
Mode 4	6.37433 +j 0.00120086	2654.07
Mode 5	6.44766 +j 0.000801508	4022.21
Mode 6	6.52060 +j 0.00114187	2855.22
Mode 7	6.59587 +j 0.00273451	1206.04
Mode 8	6.66570 +j 0.00195929	1701.05
Mode 9	6.74680 +j 0.000807601	4177.06
Mode 10	6.85900 +j 0.275826	12.4436



- Blue is the metal of the CPW.
- Green is the substrate.
- The finger capacitors determines the coupling to the measurement instruments.