

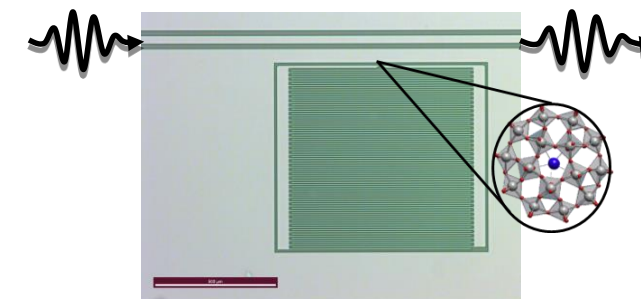


Lumped element on-chip resonators for molecular spin qubits control and read-out

Marina Calero de Ory

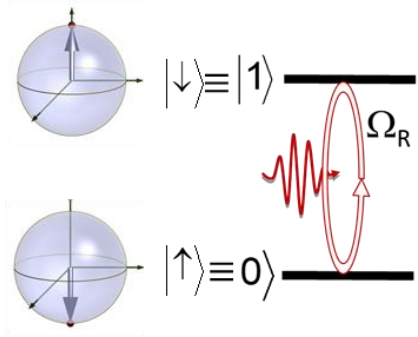
mcalero@cab.inta-csic.es

8th October 2021

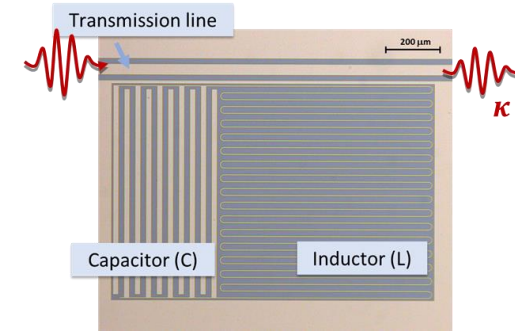


Outline

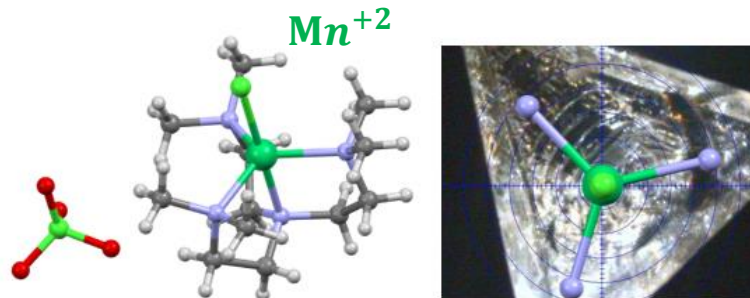
1. Introduction of molecular spin quantum processors



2. Superconducting lumped element resonators for quantum processors



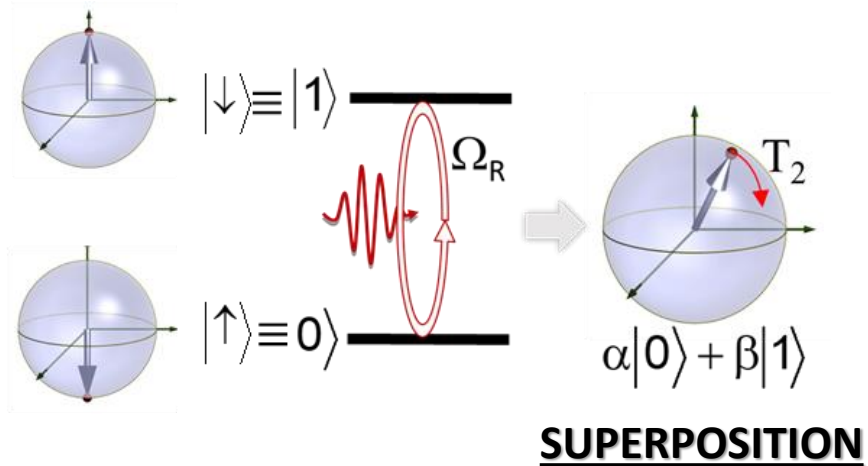
3. Hybrid devices for magnetic / electric spin control



Molecular spins as qudits!

Quantum computing

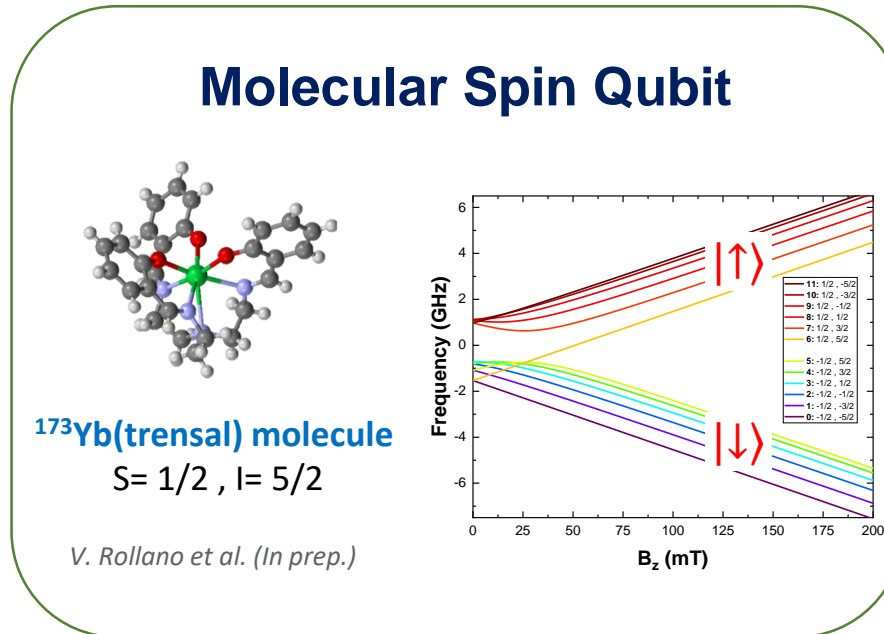
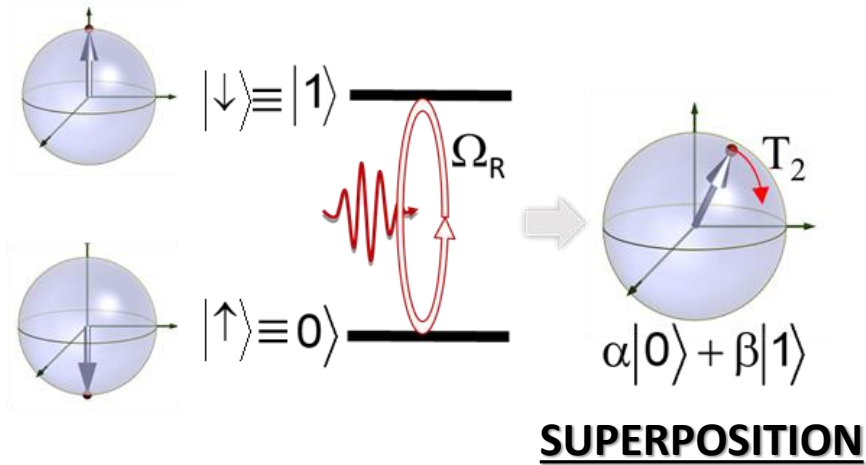
- Basic unit of information: Bit \rightarrow **Qubit**



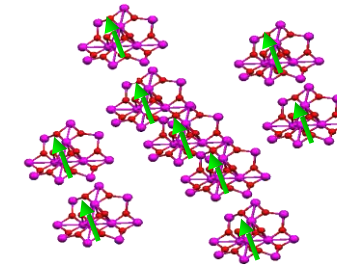
Molecular spins as qudits!

Quantum computing

- Basic unit of information: Bit \rightarrow **Qubit**



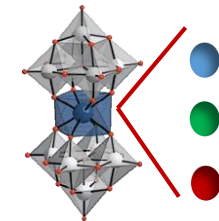
Reproducibility



Identical
microscopic
qubits

Nature chemistry 11 (4), 301-309 (2019)

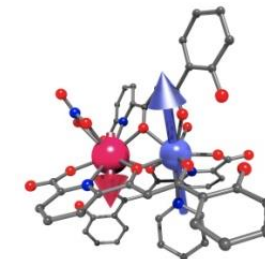
Tunability



Fine tuning of
qubit properties

Phys. Rev. Lett. 108, 247213 (2012)

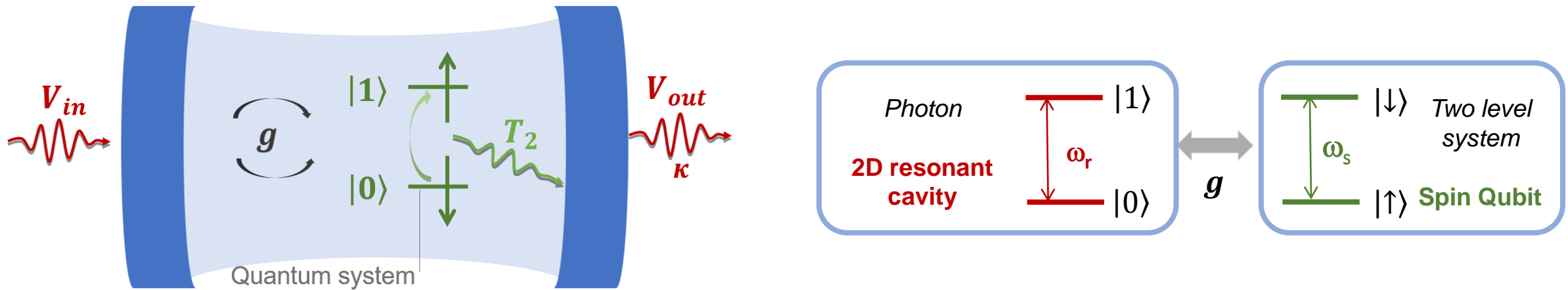
Scalability



Error
correction

*Á Gómez-León et al.
arXiv (2021)*

Quantum electrodynamics on a chip



Spin qubit coupled (g) to a superconducting resonator:

Strong coupling regime:

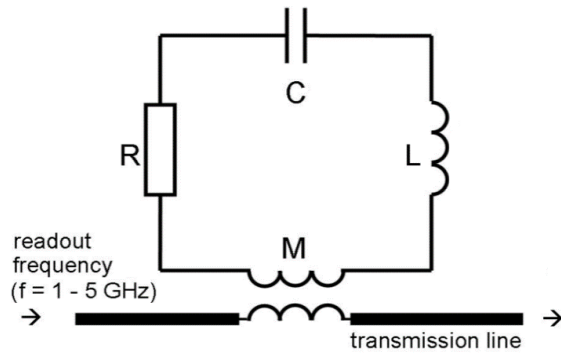
$$g \gg 1/T_{\kappa}, 1/T_2$$



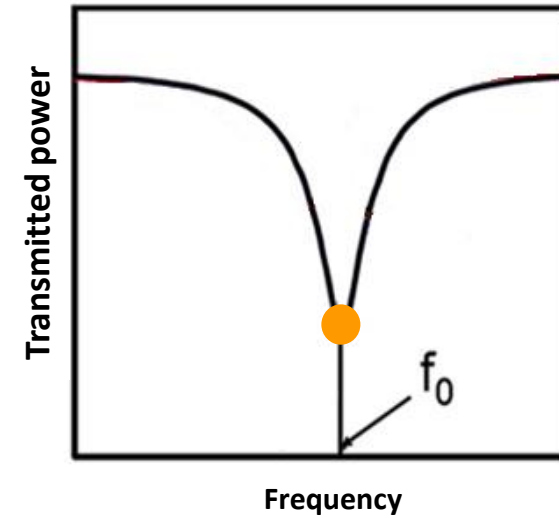
Non demolition read-out
Two qubits entangling gates

Superconducting lumped element resonators (LERs)

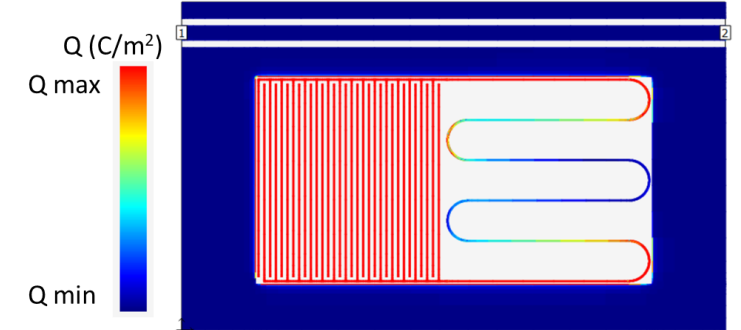
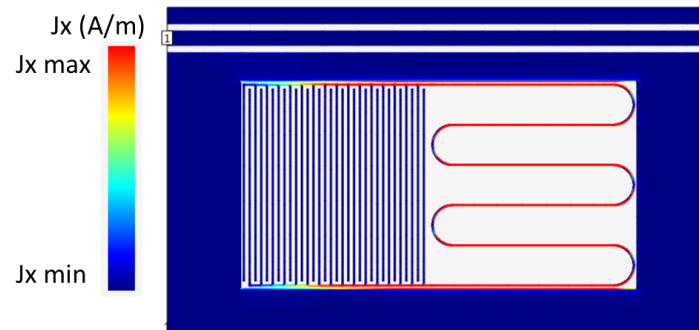
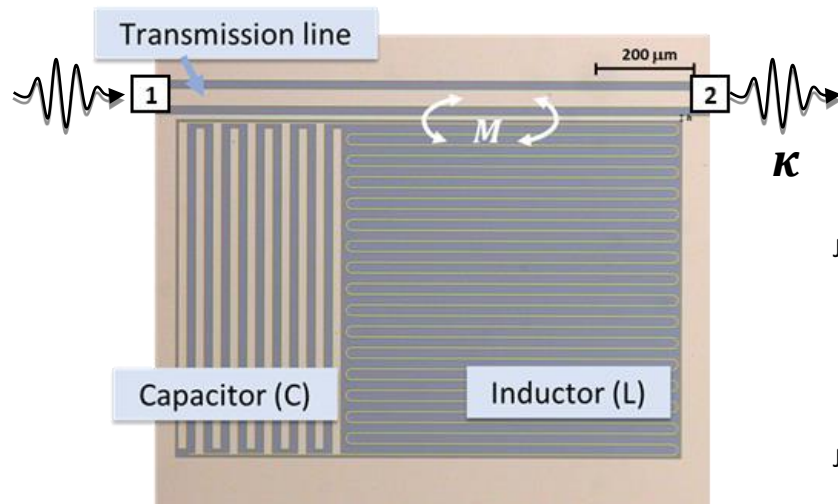
Superconducting LC resonator



S_{21} : Transmitted AC signal

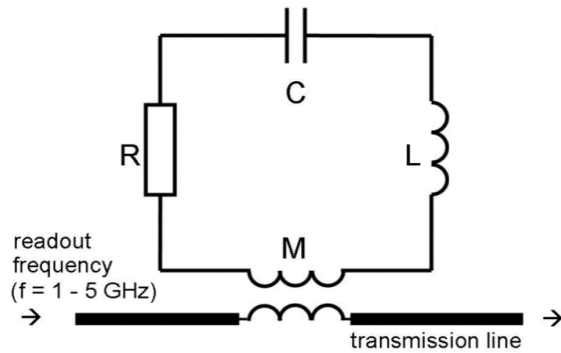


$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

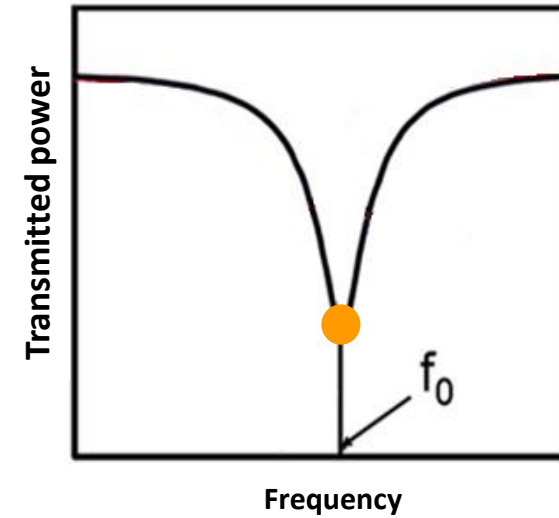


Superconducting lumped element resonators (LERs)

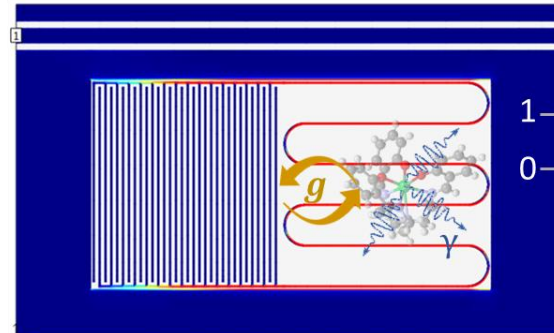
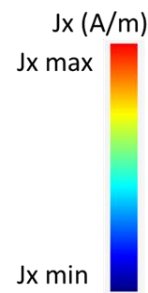
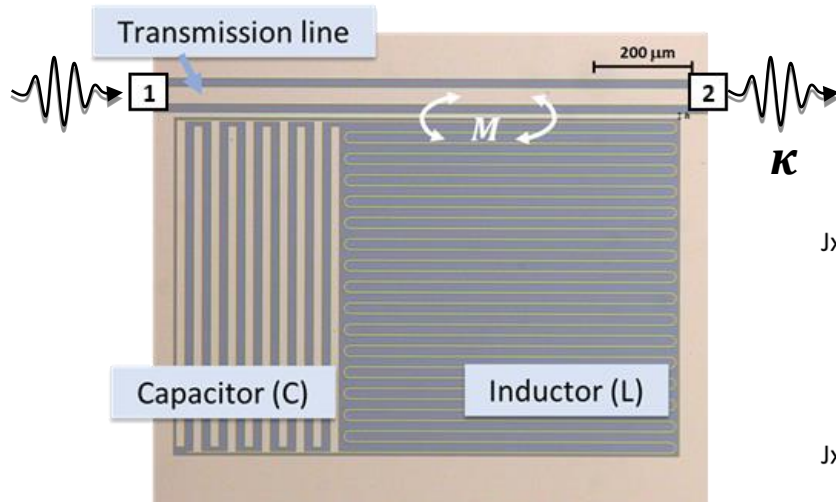
Superconducting LC resonator



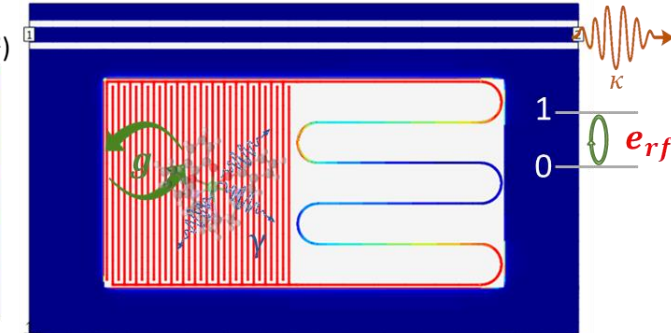
S_{21} : Transmitted AC signal



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$



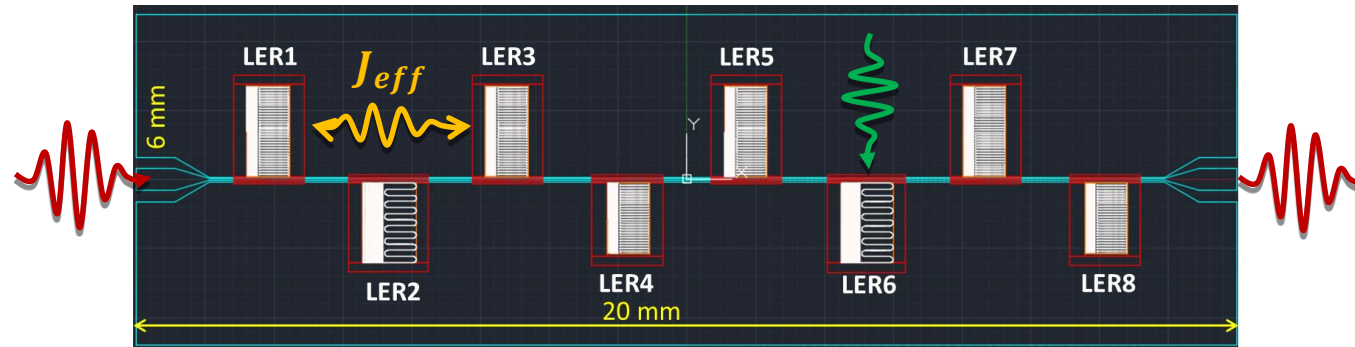
Magnetic Coupling



Electric Coupling

LERs for molecular spin quantum processor

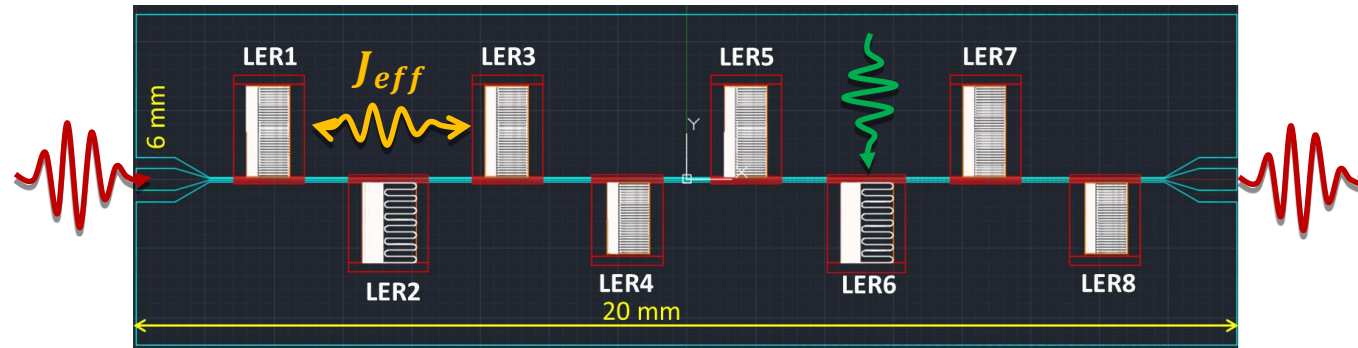
Quantum electrodynamics on a chip



- ✓ Multiple read-out with a single transmission line.
- ✓ High power pulses to implement gates.
- ✓ Photon-mediated interactions between different qubits.

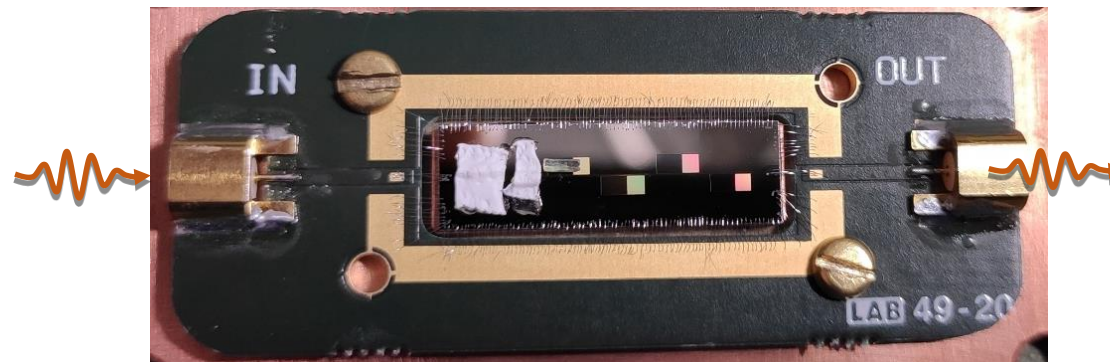
LERs for molecular spin quantum processor

Quantum electrodynamics on a chip



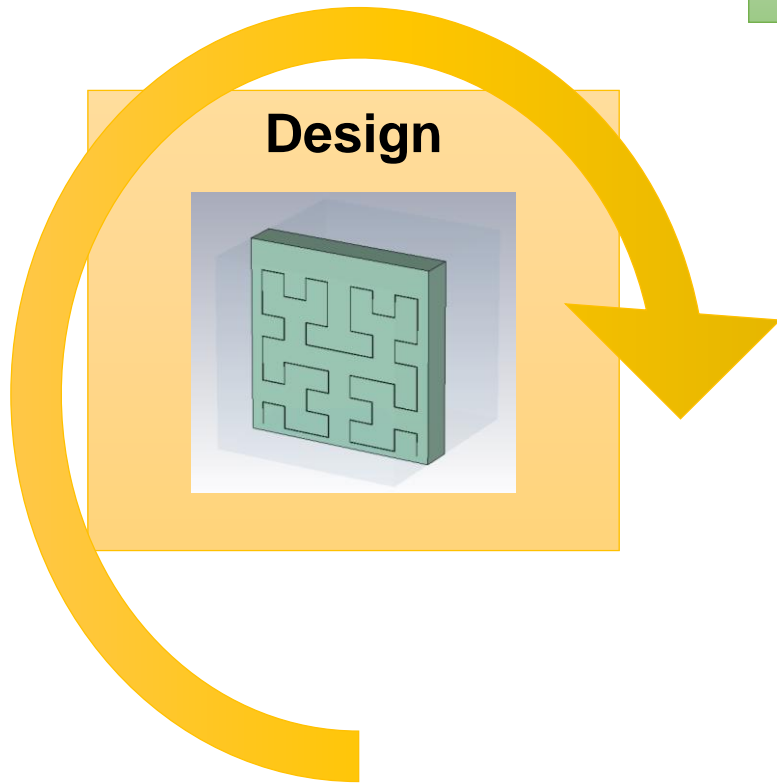
- ✓ Multiple read-out with a single transmission line.
- ✓ High power pulses to implement gates.
- ✓ Photon-mediated interactions between different qubits.

Fabricated and characterized chip



LERs for molecular spin quantum processor

How are LERs made?



LERs for molecular spin quantum processor

LER Parameters

Resonance frequency f_r

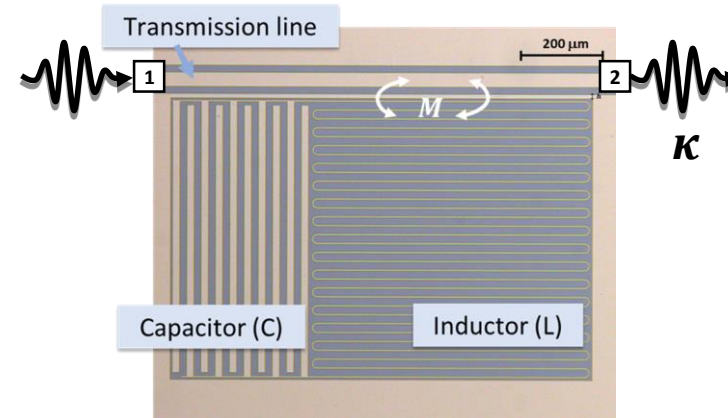
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Quality factor Q

$$Q = 2\pi f_r \frac{\text{Average energy stored}}{\text{Energy loss/second}} = \frac{\pi f_r}{\kappa}$$

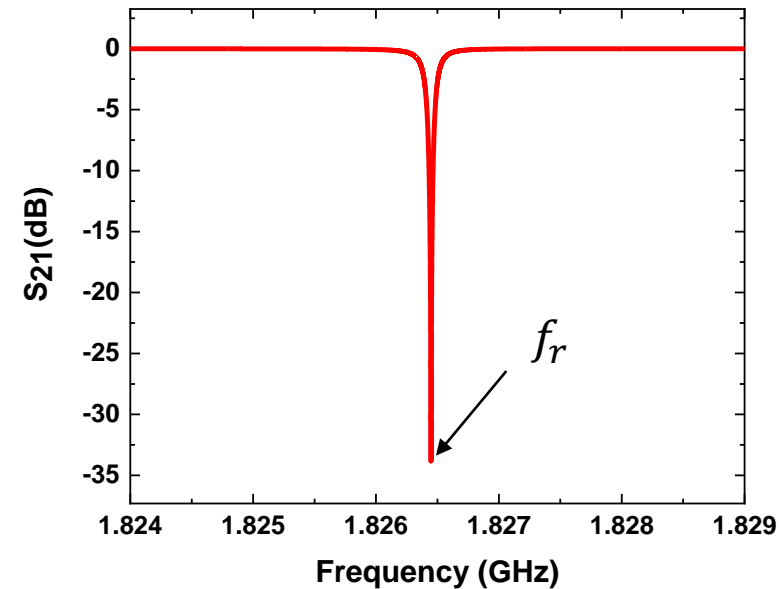
κ : Photon decay rate (rad/s)

Microwave electromagnetic
simulations



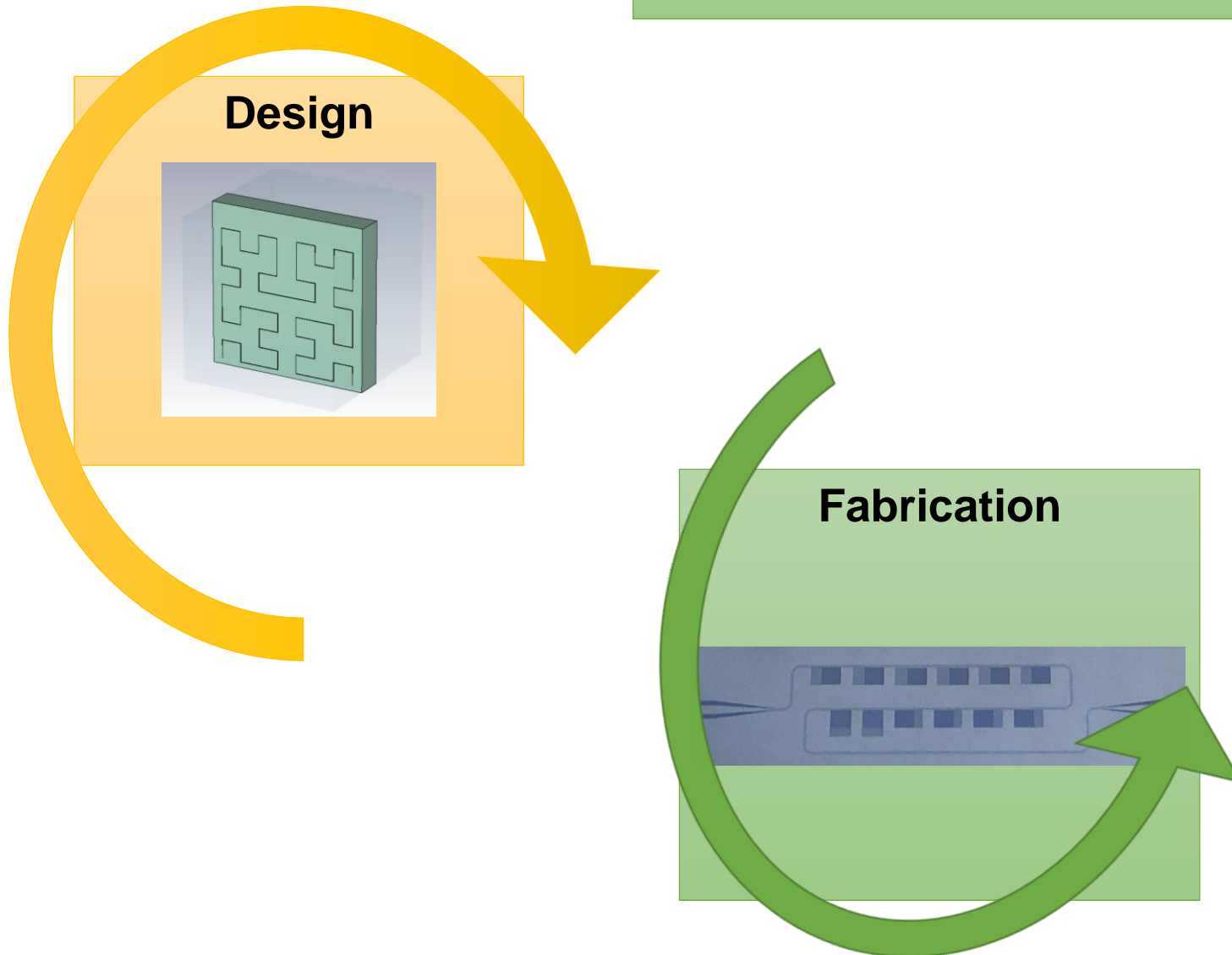
S_{21} : Transmitted AC signal

Simulated transmitted AC signal



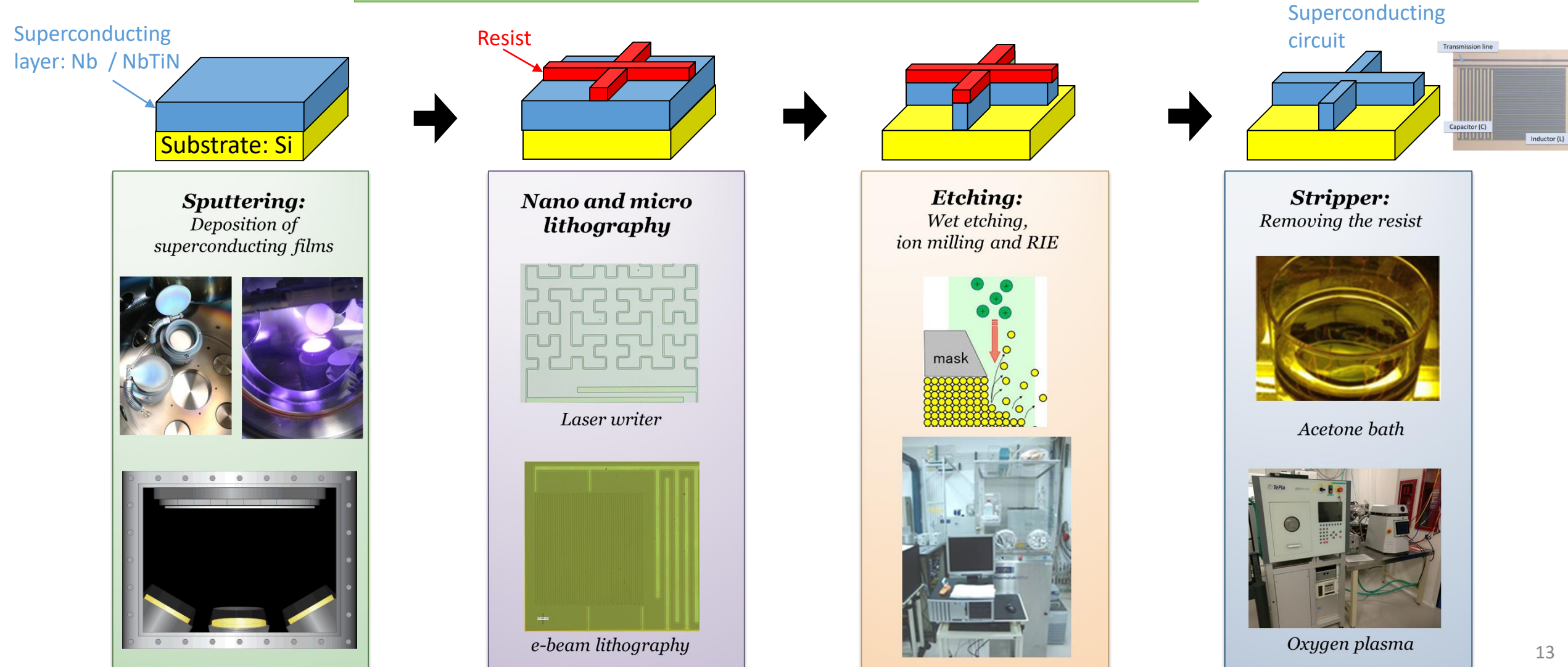
LERs for molecular spin quantum processor

How are LERs made?



LERs for molecular spin quantum processor

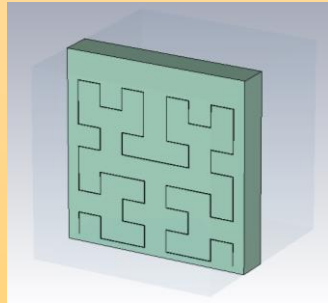
LERs nanofabrication in a Clean Room



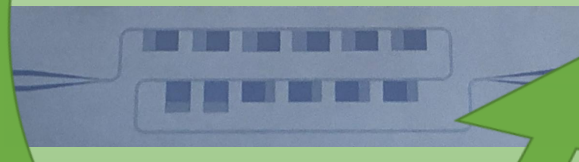
LERs for molecular spin quantum processor

How are LERs made?

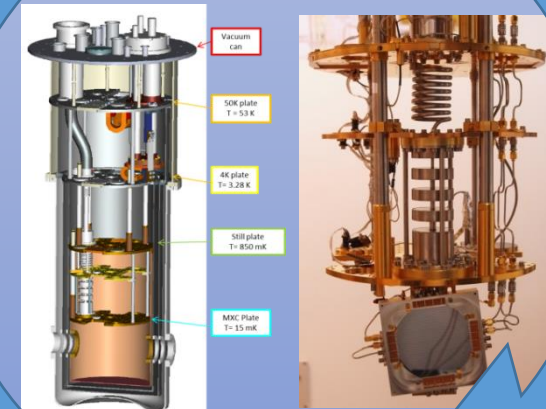
Design



Fabrication



Characterization



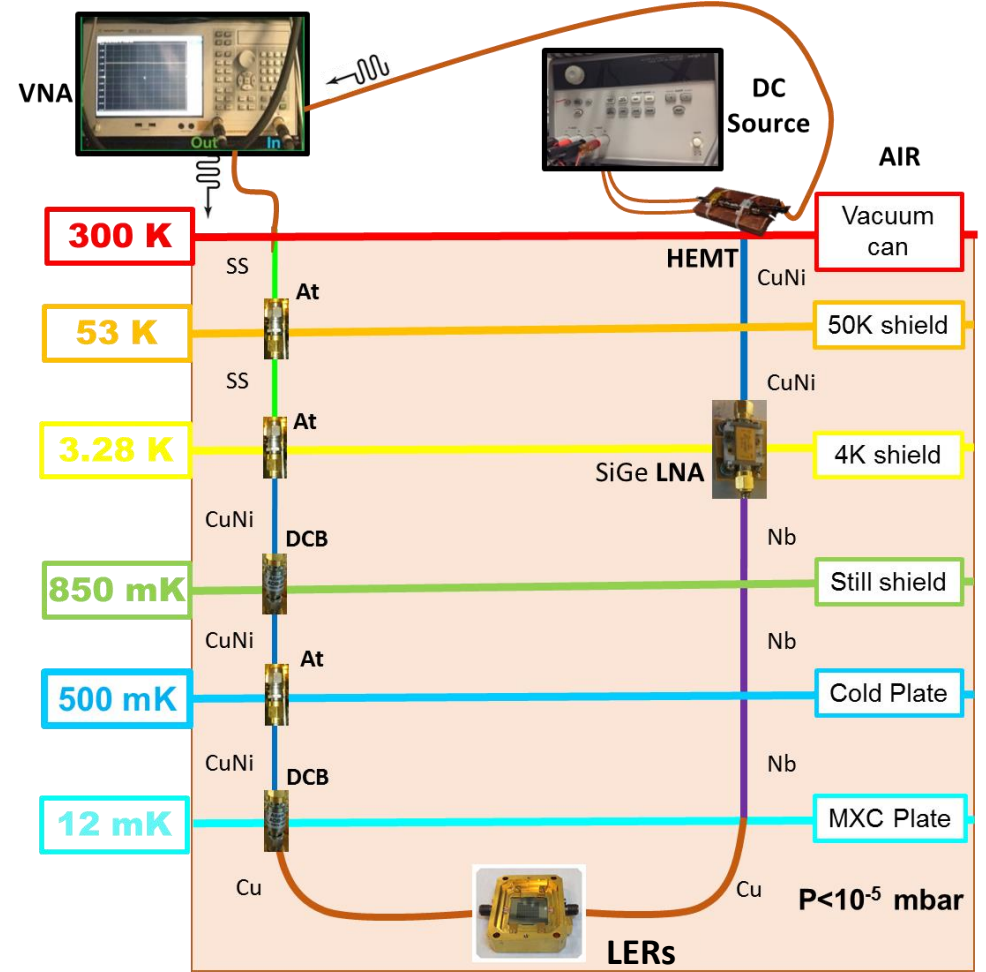
LERs for molecular spin quantum processor

Cryogenic characterization

He³/He⁴ Dilution Refrigerator

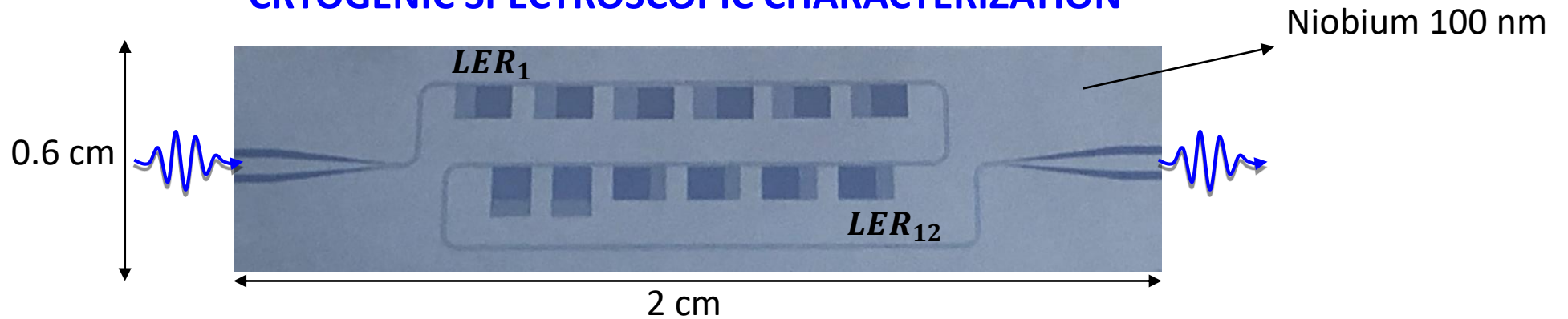


Electrical characterization harness set-up

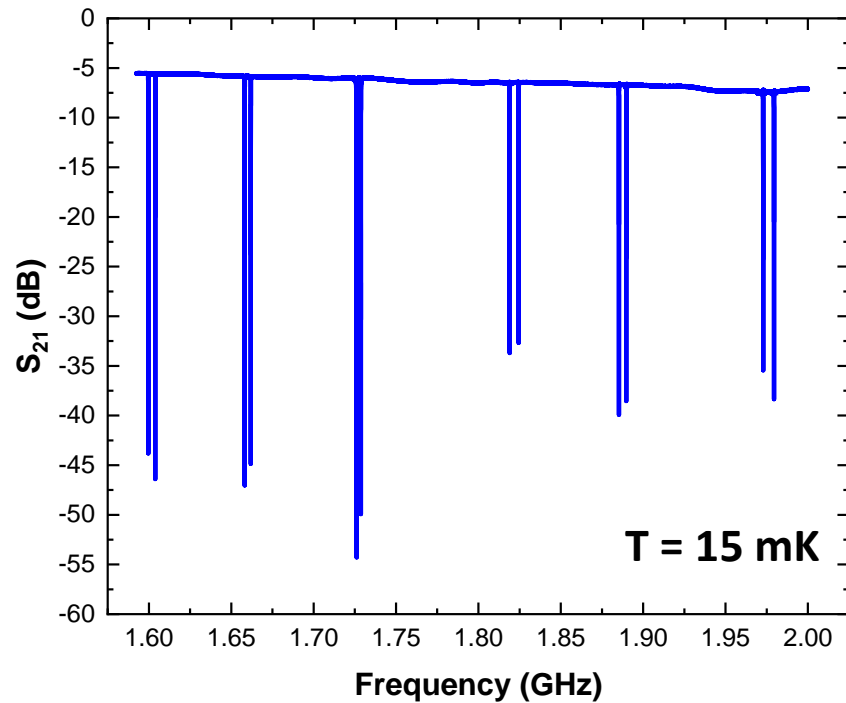


LERs for molecular spin quantum processor

CRYOGENIC SPECTROSCOPIC CHARACTERIZATION

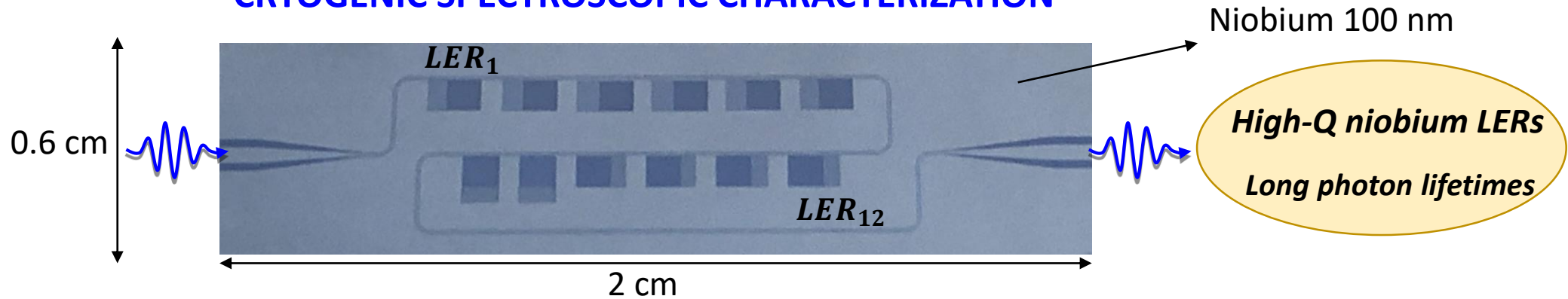


Transmission measurement

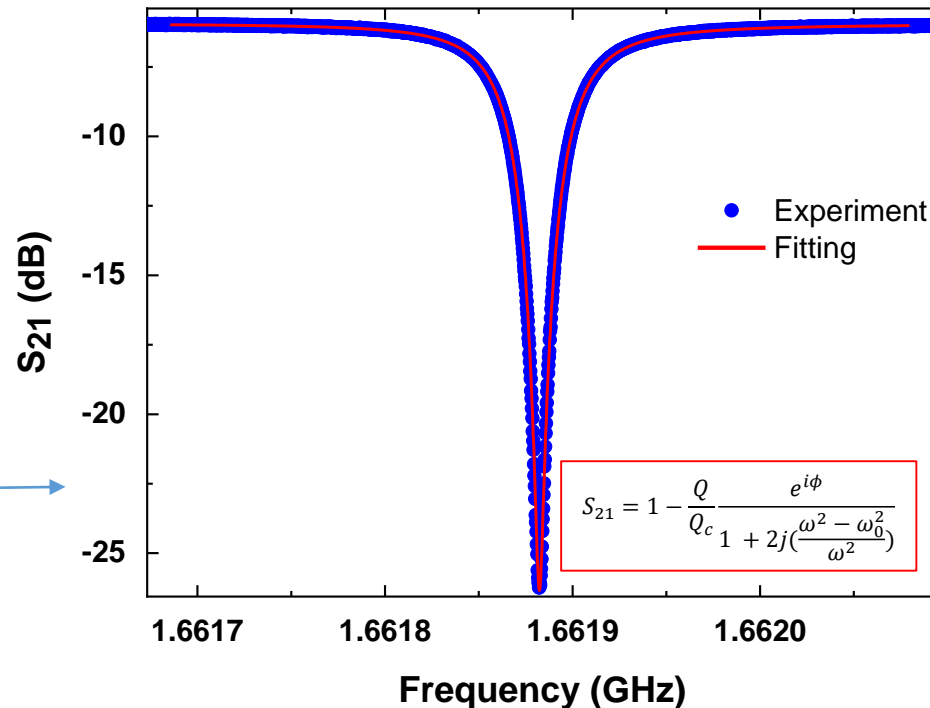
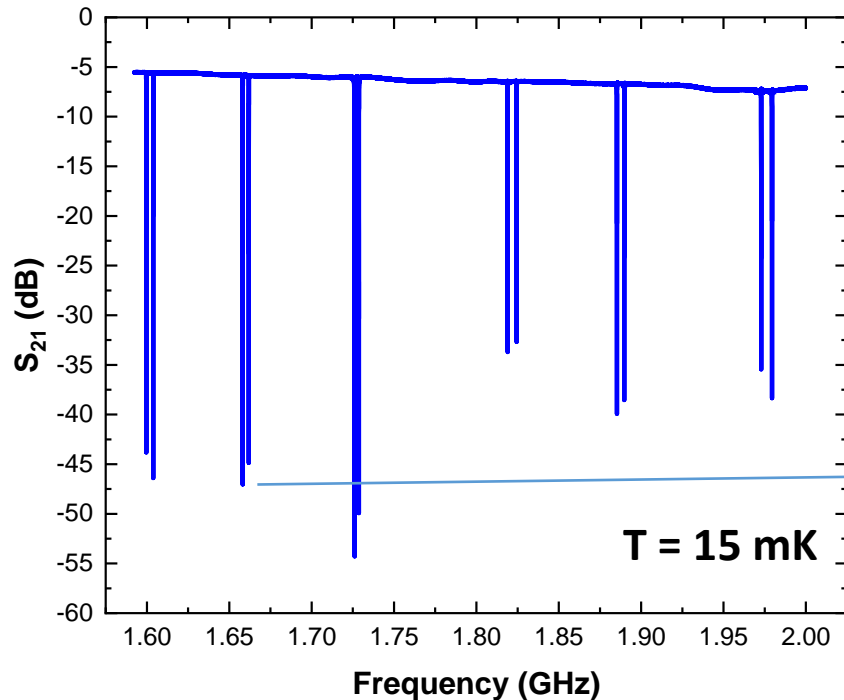


LERs for molecular spin quantum processor

CRYOGENIC SPECTROSCOPIC CHARACTERIZATION



Transmission measurement



Resonance frequency:

$$f_0 = 1.6618 \text{ GHz}$$

Quality factor:

$$Q = \frac{f_0}{\delta f} \approx 10^5$$

Photon decay rate:

$$\frac{\kappa}{2\pi} = \frac{f_0}{Q} \approx 4.18 \times 10^{-5} \text{ GHz}$$

Photon lifetime:

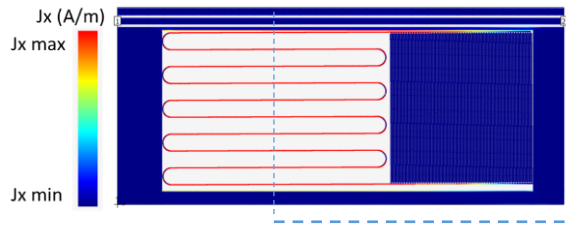
$$T_\kappa = \frac{1}{\kappa} \approx 0.2 \text{ ms}$$

LERs for molecular spin quantum processor

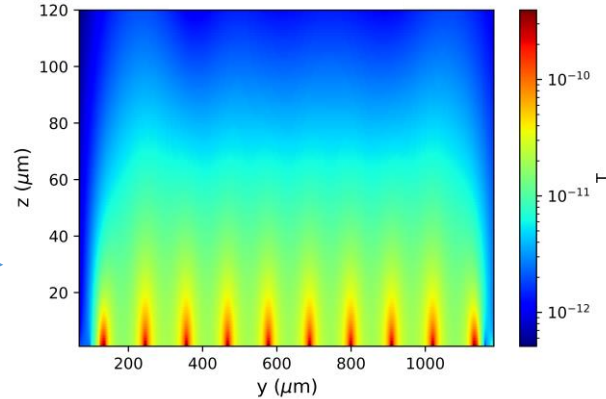
LERs for magnetic coupling with spin ensembles

Increase the magnetic mode volume V_m

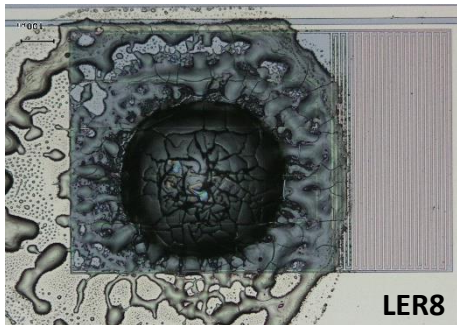
SIMULATED CURRENT @ f_0



MAGNETIC FIELD PROFILE

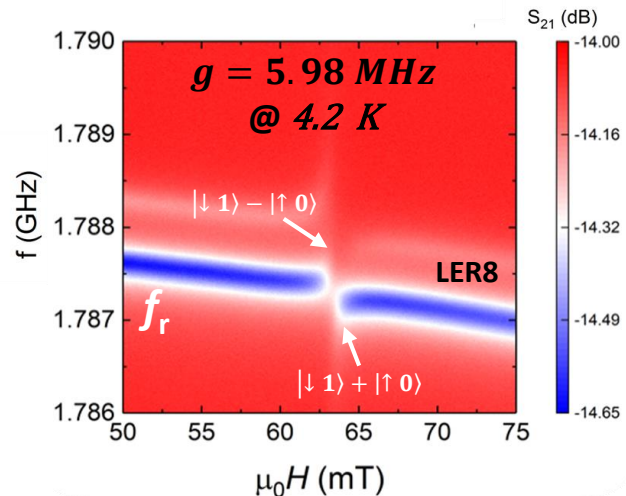


Free radical: PTM $S=1/2$



$N \sim 10^{10} - 10^{13}$ spins

MAGNETOSCOPIC CHARACTERIZATION

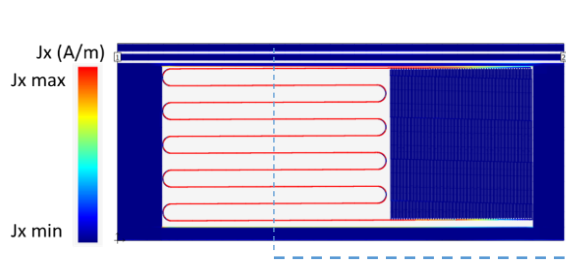


LERs for molecular spin quantum processor

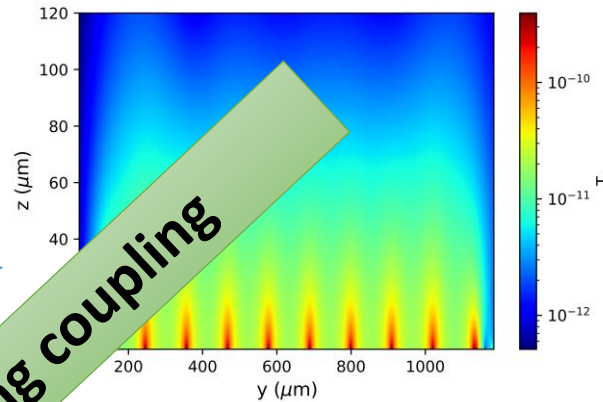
LERs for magnetic coupling with spin ensembles

Increase the magnetic mode volume V_m

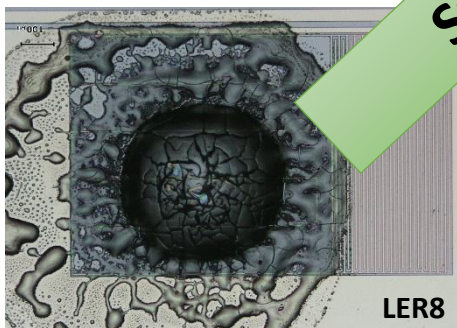
SIMULATED CURRENT @ f_0



MAGNETIC FIELD PROFILE



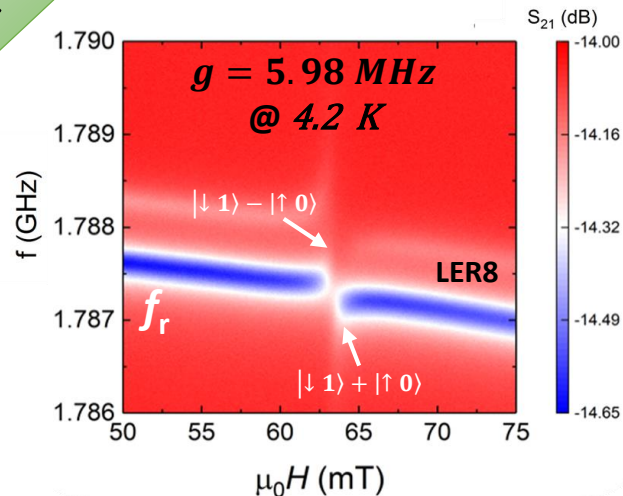
Free radical: PTM $S=1/2$



$N \sim 10^{10} - 10^{13}$ spins

Strong coupling

MAGNETOSCOPIC CHARACTERIZATION

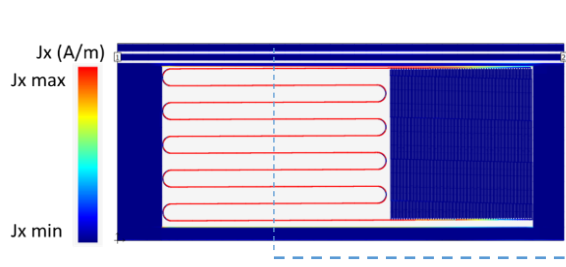


LERs for molecular spin quantum processor

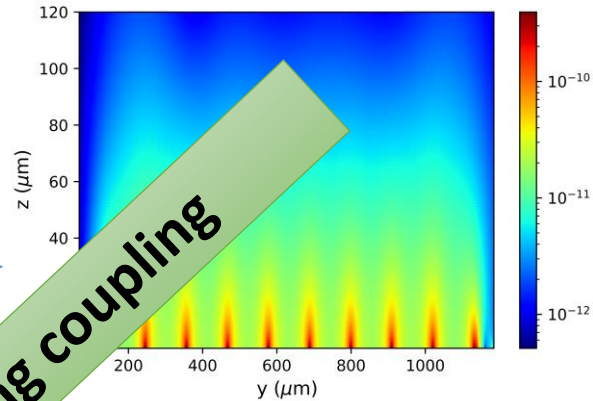
LERs for magnetic coupling with spin ensembles

Increase the magnetic mode volume V_m

SIMULATED CURRENT @ f_0

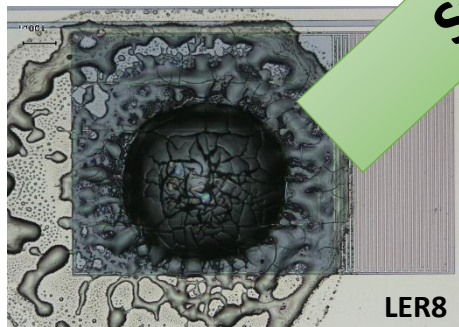


MAGNETIC FIELD PROFILE



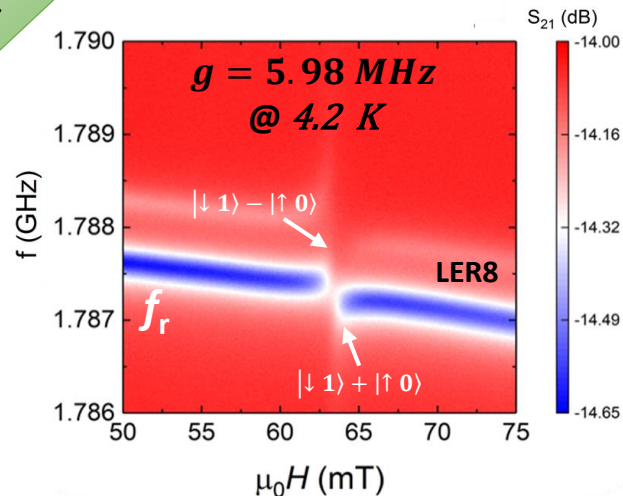
Strong coupling

Free radical: PTM $S=1/2$



$N \sim 10^{10} - 10^{13}$ spins

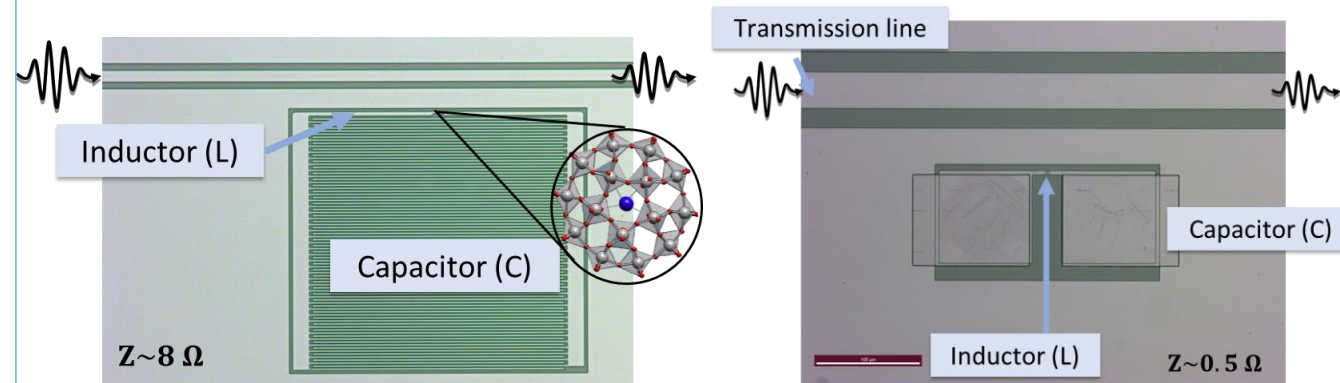
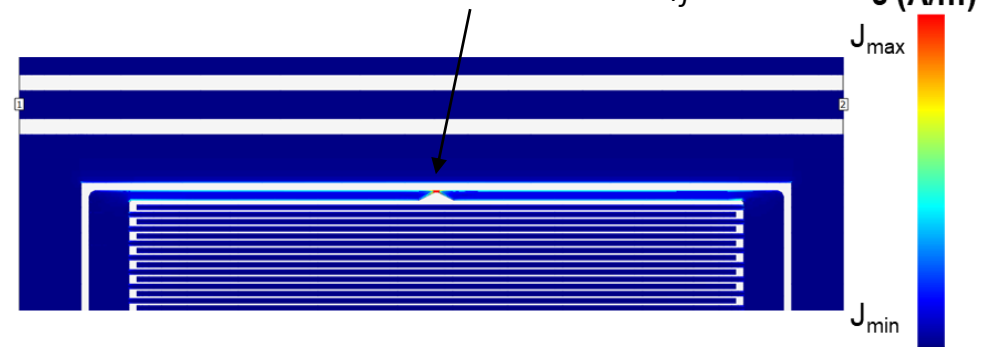
MAGNETOSCOPIC CHARACTERIZATION



LERs for single (few) magnetic spin coupling

Decrease the mode volume V_m (reducing L)

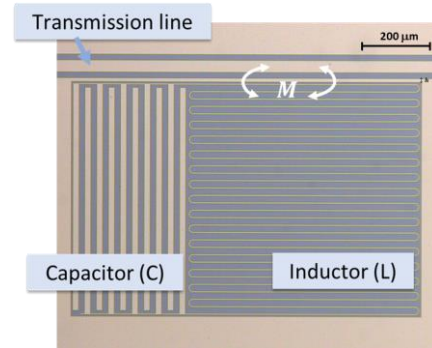
Localized b_{rf}



Conclusions and future work

Thank you for your attention!

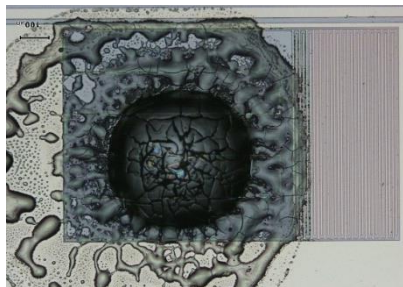
Superconducting lumped element resonators (LERs)



- ✓ Low losses.
- ✓ Long photon lifetimes.
- ✓ Frequency-multiplexable.
- ✓ Spatially separate magnetic and electric fields.

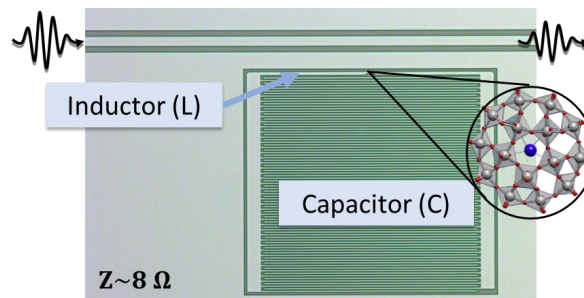
LERs for scalable quantum spin processors

Magnetic coupling



$N \sim 10^{10} - 10^{13}$ spins

LERs-Spin ensembles
strong coupling.



Low impedance LERs
for single spin coupling.

Future work

- Optimization of LERs for **single spin magnetic coupling**.
- Optimization of LERs for **electric coupling**.
- Development of superconducting circuits for **local pulses**.

We are a team



Marina Calero de Ory



David Rodriguez



Maria Teresa Magaz



Jesús Martin-Pintado



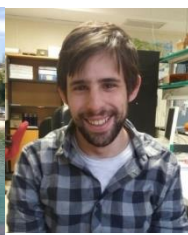
Daniel Granados
Nanofabrication team



Enrique Burzuri



Sebastián Roca



Victor Rollano



Ignacio Gimeno



Marcos Rubín



Sergio Martínez-Losa



David Zueco



María José Martínez



Fernando Luis

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IJC-2017-33991



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