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

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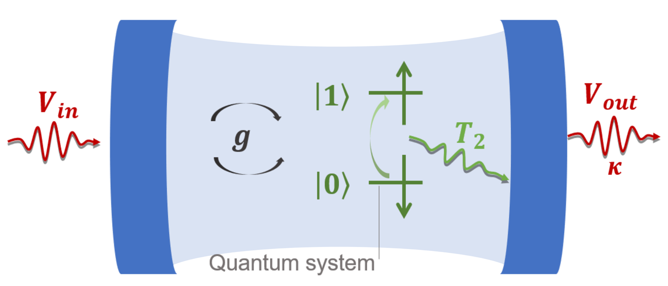
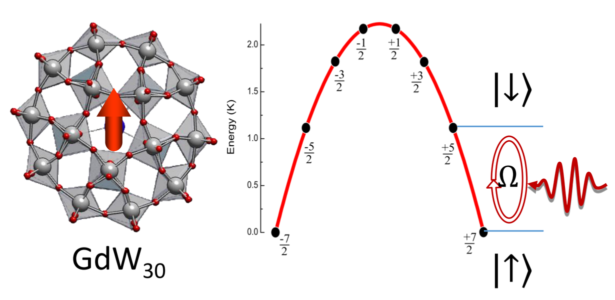
LERs FOR MOLECULAR SPIN QUANTUM PROCESSOR

Molecular spin quantum processor



- *Photons stored in **an on-chip superconducting resonator.***
- *Interaction (g) between **microwave photons** (ω_r) and **quantum mechanical two-level systems** (Ω).*

Molecular spin as qudit



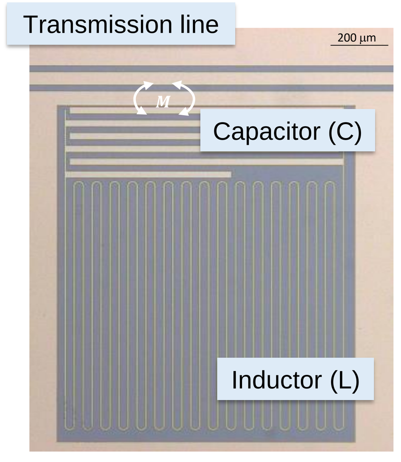
- ***Reproducibility:** identical microscopic qubits.* [1]
- ***Tunability:** fine tuning of qubit properties.* [2]
- ***Scalability:** Molecular NISQs.*

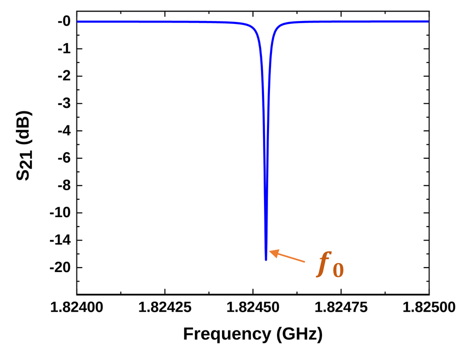
Non demolition read-out

Two Qubits entangling gates

Strong coupling regime: $g >> 1/T_\kappa, 1/T_2$

Lumped element resonator (LER) [3]





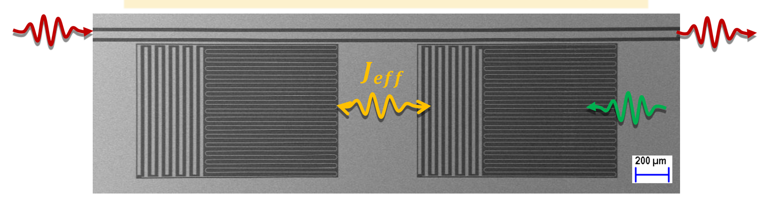
Resonance frequency f_0

$$f_0 = \frac{1}{\sqrt{L_T C}}$$

$$L_T = L_g + L_K$$

L_T → Total Inductance
L_g → Geometric Inductance
L_k → Kinetic Inductance

Frequency multiplexing



$$f_1 = \frac{1}{\sqrt{L_1 C_1}} \qquad f_2 = \frac{1}{\sqrt{L_2 C_2}}$$

Multiple LERs can be coupled to a single transmission line

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

Quality factor Q

$$Q = \omega \frac{Average\ energy\ stored}{Energy\ loss/cycle}$$

$$1/Q = 1/Q_i + 1/Q_c$$

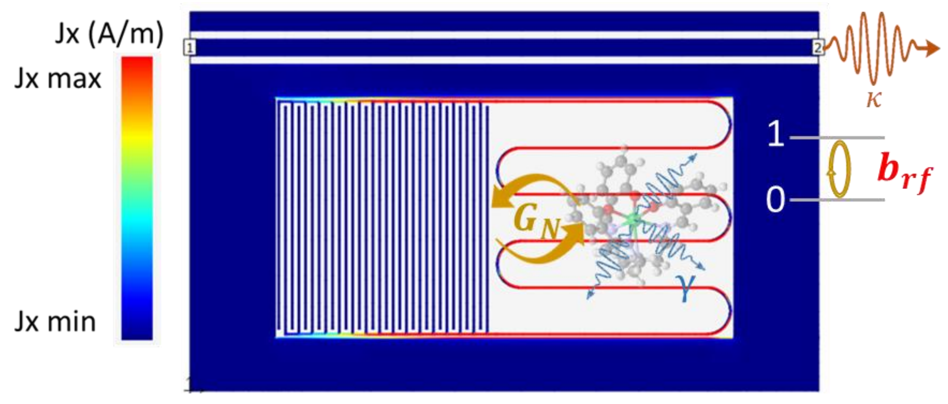
Q_i → Internal quality factor
Q_c → Coupling quality factor

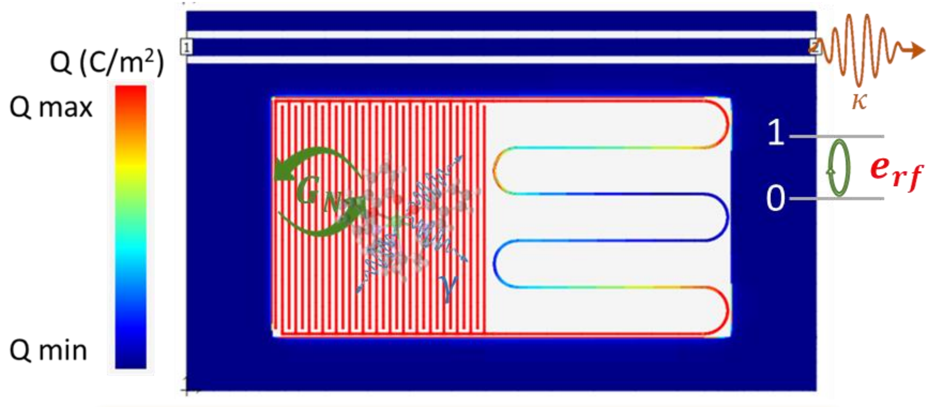
Impedance Z

$$Z = \sqrt{L/C}$$

Quantum electrodynamics on a chip

Microwave electromagnetic simulations





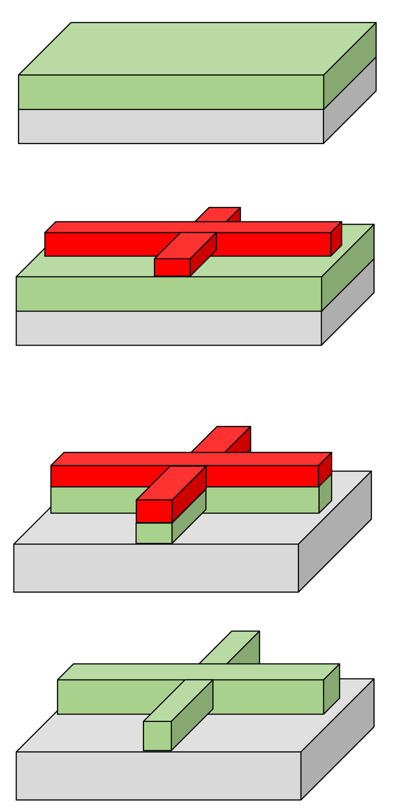
Spatially separated RF fields mode volumes

Molecules magnetic / electric coupling

SUPERCONDUCTING LUMPED ELEMENT RESONATORS (LERs)

Fabrication process

Substrate (Si) | Superconducting film | Resist



Sputtering
100 nm Nb / NbTiN

Laser lithography

Dry and wet etching

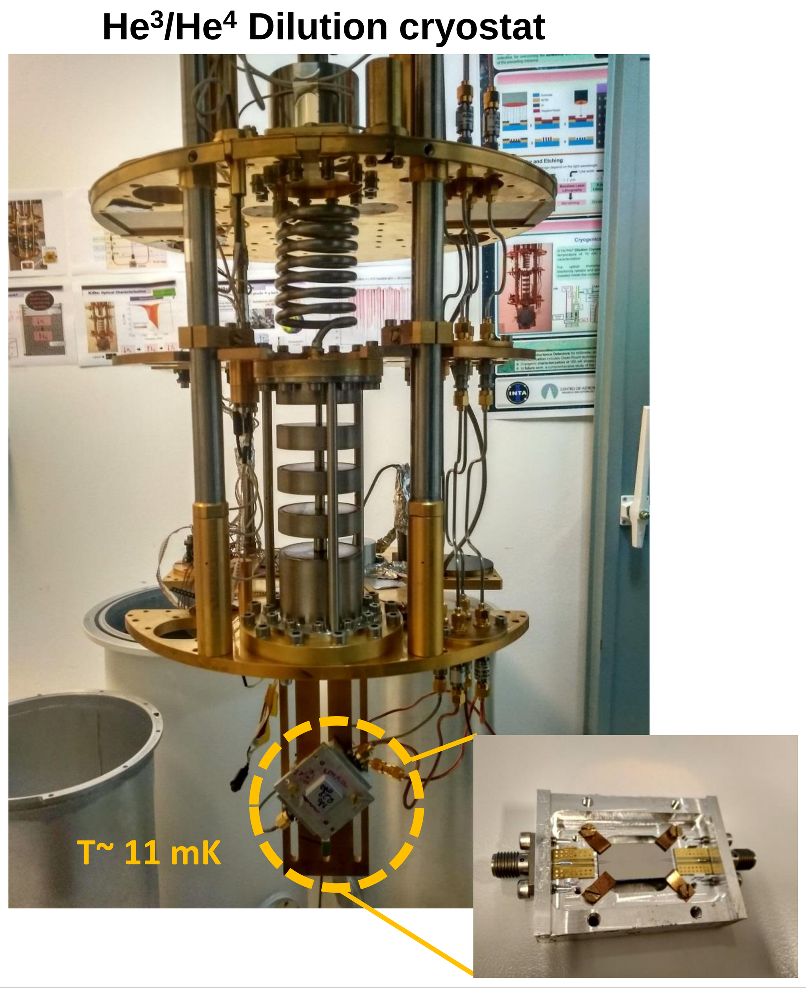
Oxygen plasma

*Pre-designed LERs can be integrated in a **single** chip.*

Measurement set up

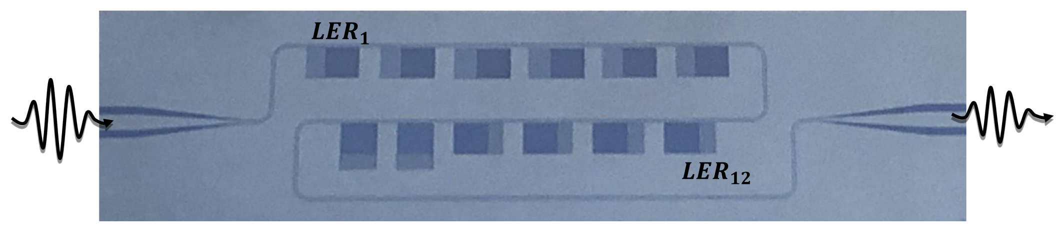
Low-frequency cryogenic characterization

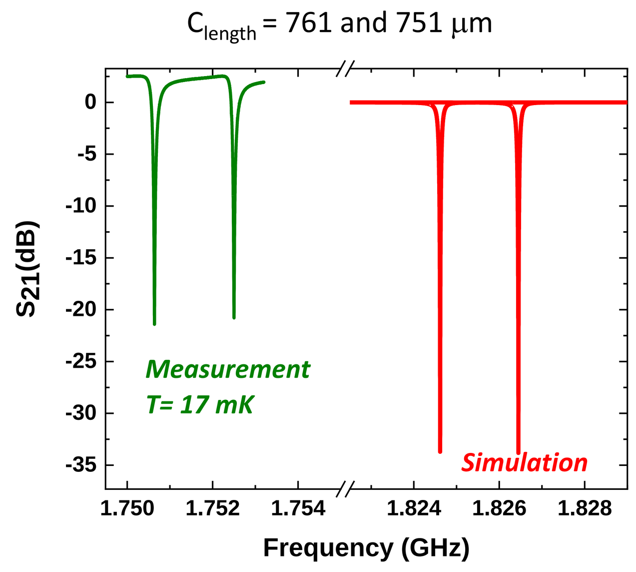
He^3/He^4 Dilution cryostat



Cryogenic spectroscopic characterization

LERs with different f_0, Q and L have been designed, fabricated and tested.



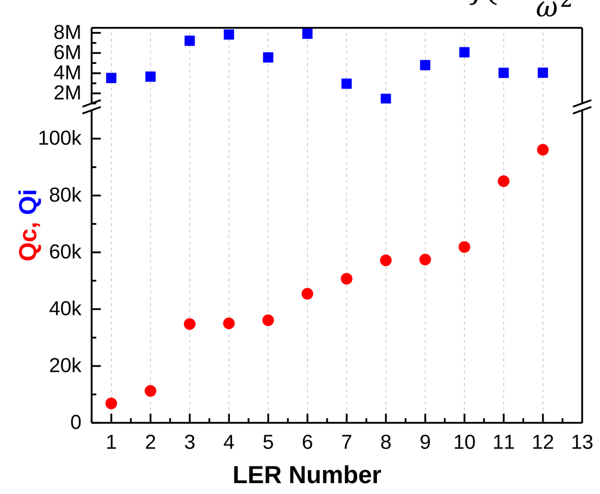


*Frequency shift in **measurements** from Sonnet simulations (L_k=0) due to kinetic inductance fraction.*

$$\alpha_{17mK} = \frac{L_k}{L_k + L_G} = 0.076$$

Quality factors from S_{21} fitting

$$S_{21} = 1 - \frac{Q}{Q_c} \frac{e^{i\phi}}{1 + 2j(\frac{\omega^2 - \omega_0^2}{\omega^2})}$$



Photon decay rate:

$$\frac{\kappa}{2\pi} = \frac{f_0}{Q}$$

- ***High internal quality factors** are obtained (long photon lifetimes).*
- *External quality factor can be tuned by design.*

FABRICATED LERs FOR CONTROL AND READ-OUT OF MOLECULAR SPIN QUBITS

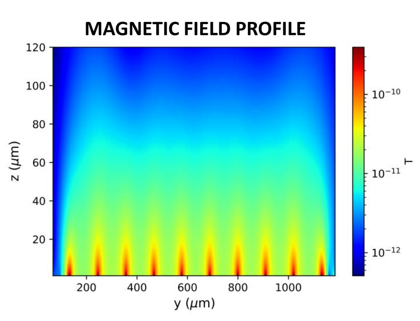
MAGNETIC COUPLING

Inductance geometry is tuned to couple to different spin systems

LERs for coupling to spin ensembles

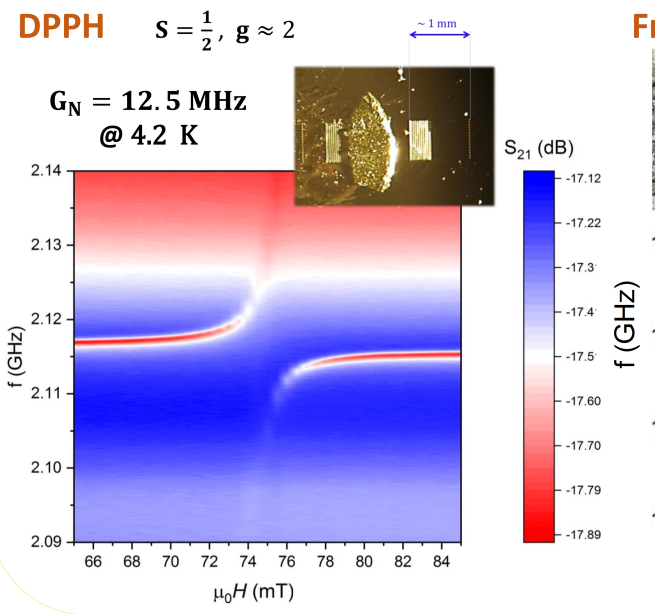
Increase the RF mode volume

$$g = \sqrt{N} \frac{g_e \mu_B b_{rf} \omega_{rf}}{\sqrt{8\hbar Z_r}}$$

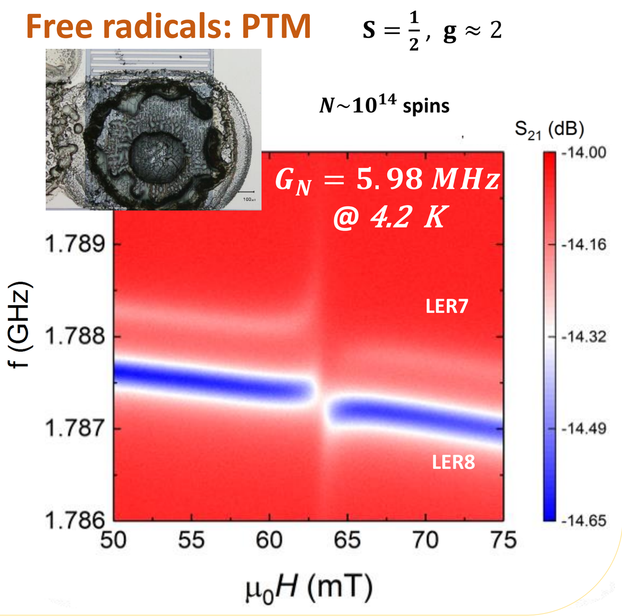


***Inductance geometry** controls magnetic field mode volume.*

DPPH $S = \frac{1}{2}$, $g \approx 2$



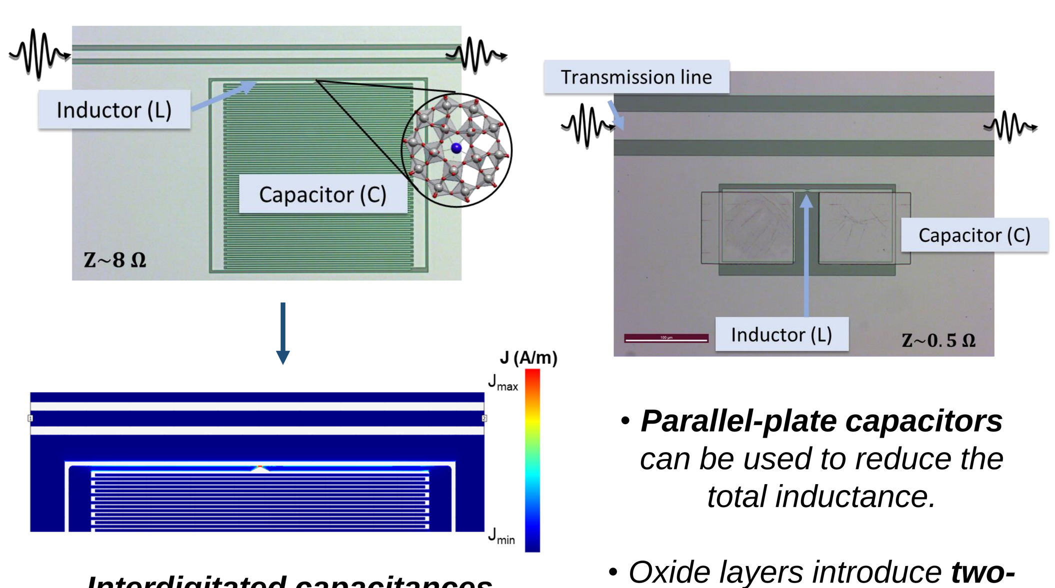
Free radicals: PTM $S = \frac{1}{2}$, $g \approx 2$



LERs for single (few) spin coupling

Decrease the RF mode volume

***Low impedance LERs** to concentrate the magnetic field in a nanoscale constriction.* [4]

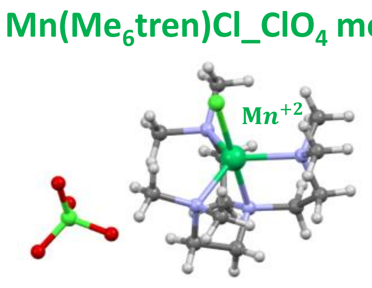


***Interdigitated capacitances** introduce large parasitic inductances.*

- ***Parallel-plate capacitors** can be used to reduce the total inductance.*
- *Oxide layers introduce **two-level system noise**.*

ELECTRIC COUPLING [5]

Mn(Me$_6$tren)Cl_ClO$_4$ molecule



Electronic Spin: $\mathbf{S} = \frac{5}{2}$ Nuclear Spin: $\mathbf{I} = \frac{5}{2}$

Spin Hamiltonian:

$$H = \mu_B g \vec{B} \cdot \vec{S} + \mu_I g_I \vec{B} \cdot \vec{I} + A\vec{S} \cdot \vec{I} + D_{||}(\vec{E}) S_Z^2 + D_{\perp}(\vec{E})(S_x^2 - S_y^2)$$

Magnetic spectroscopy numerical simulations

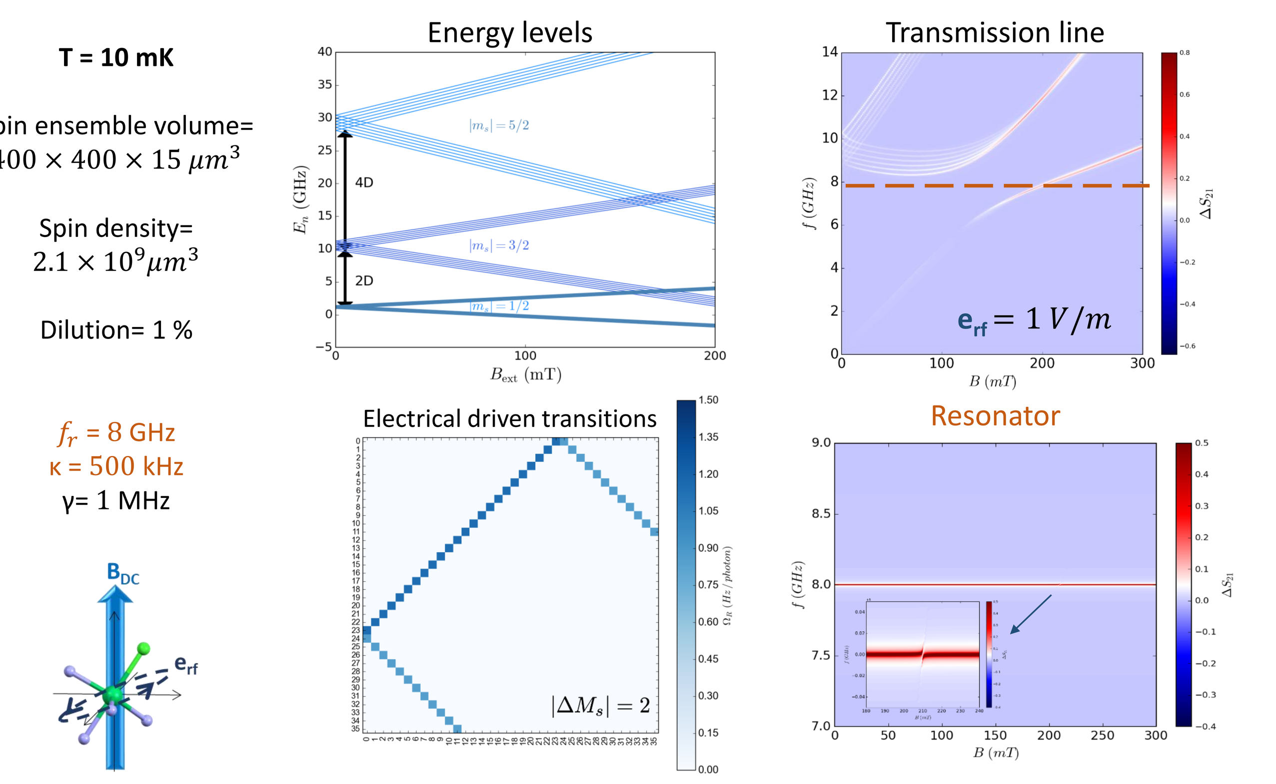
T = 10 mK

Spin ensemble volume= $400 \times 400 \times 15\ \mu m^3$

Spin density= $2.1 \times 10^9 \mu m^3$

Dilution= 1 %

f_r = 8 GHz
κ = 500 kHz
γ= 1 MHz



On going LERs optimization for electric spin control.

SUMMARY AND OUTLOOK

- LERs coupled to magnetic molecules are a promising scheme for scalable quantum processors.
- Several LERs have been developed to be coupled with magnetic molecules.
- Cryogenic characterization demonstrate the accuracy of the electromagnetic design and validates the developed nanofabrication process.
- Close to strong magnetic coupling of the spin ensembles ($G\sqrt{N} \sim 1 - 10$ MHz $\sim 1/T_2$) to different LERs is achieved.
- Low impedance LERs for single spin magnetic coupling.
- Promising high spin molecular system with axial anisotropy for electric spin control.

REFERENCES

[1] Nature chemistry 11 (4), 301-309 (2019)
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[4] NJP 15, 095007 (2013)
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