Superconducting microwave resonators for spin-photon coupling in silicon

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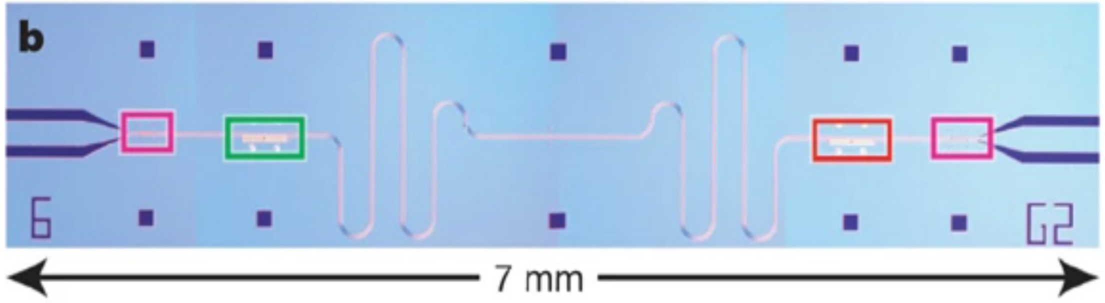
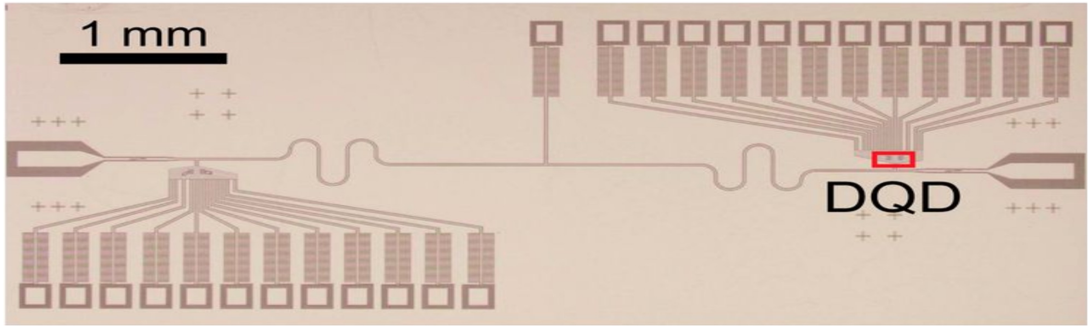
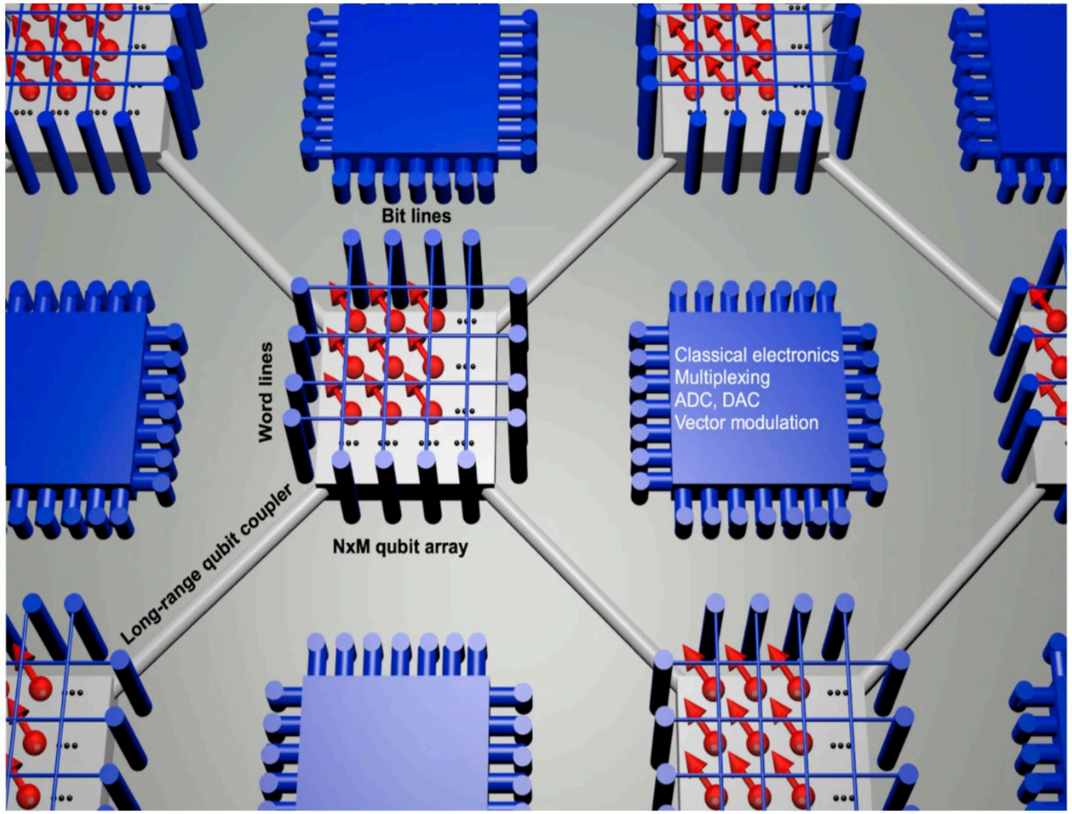
Superconducting microwave resonators

- Superconducting wires in various shapes
- Long distance qubit coupling [1]
- Scale up of Quantum computing architecture [2]







1. Majer, J., Chow, J., Gambetta, J. *et al.* Coupling superconducting qubits via a cavity bus. *Nature* **449**, 443–447 (2007).
2. Mi, X. and Cady, J. V. and Zajac, D. M. and Deelman, P. W. and Petta, J. R. - Science (2017)
3. Vandersypen, L.M.K., Bluhm, H., Clarke, J.S. *et al.* Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent. *npj Quantum Inf* **3,** 34 (2017).

Boron In silicon

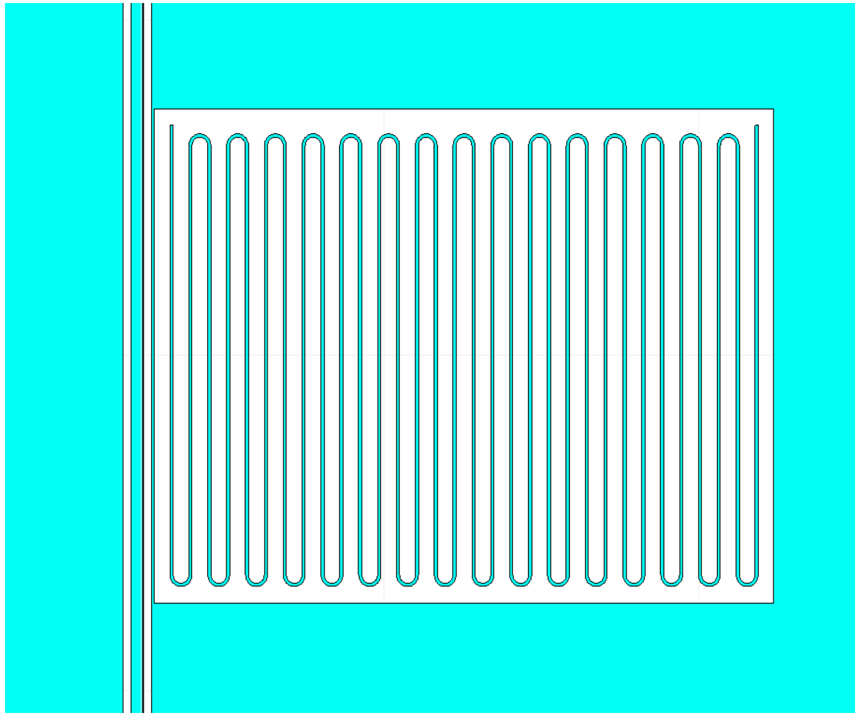
- Intrinsic spin orbit coupling
- Past results show comparable coherence times with other spin systems in Silicon [1].
- Easy integration into established Silicon foundry.

- Electric drive of Boron in Silicon using Superconducting Microwave resonators.
- Strong Electric field in resonators means stronger coupling to dopants.
- Resonators facilitate driving and readout of dopant qubits.

1. Kobayashi, T., Salfi, J., Chua, C. *et al.* Engineering long spin coherence times of spin–orbit qubits in silicon. *Nat. Materials.* **20**, 38–42 (2021)

Required properties of superconducting resonators

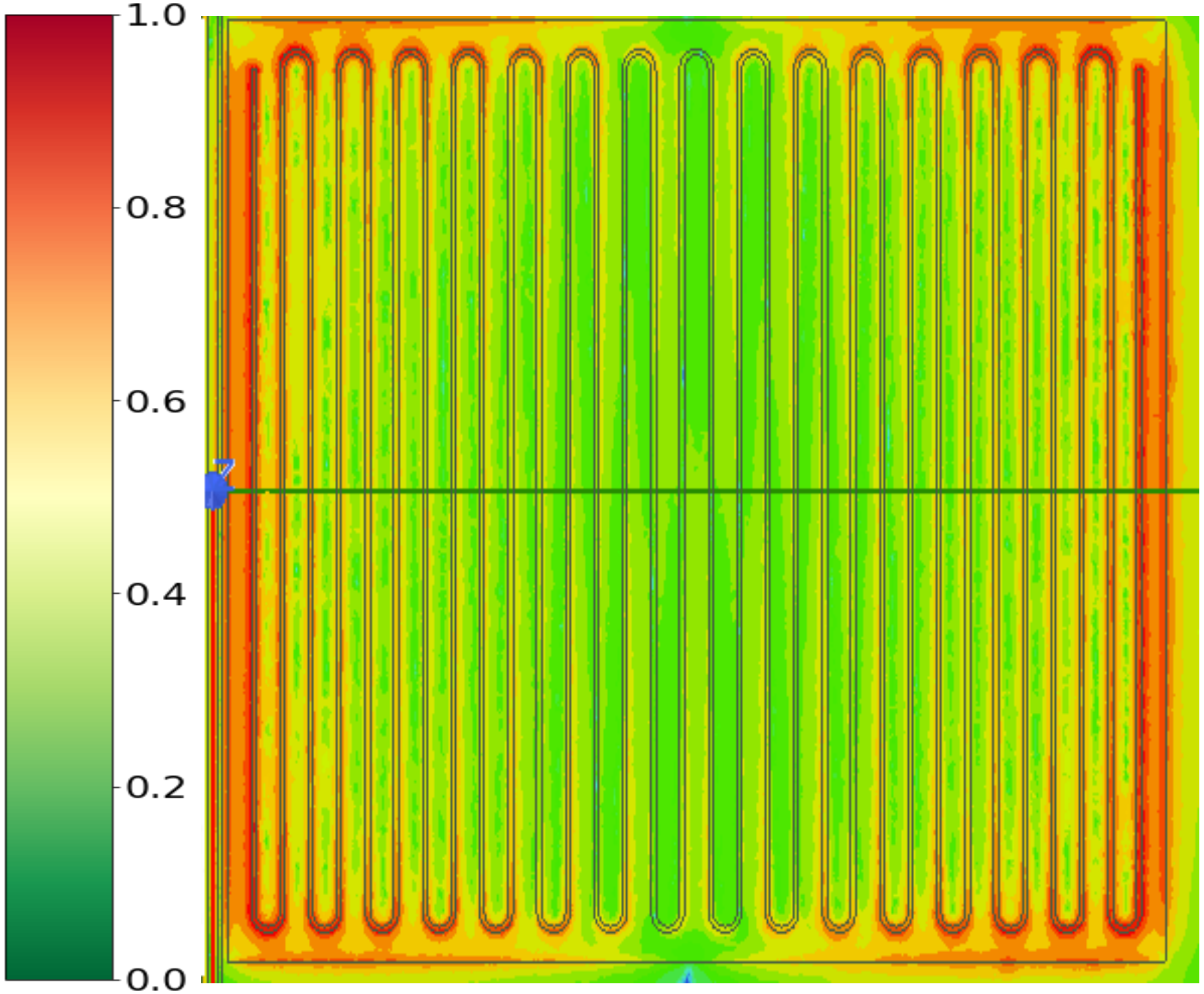
- Resonance Tunability for ESR applications [1]



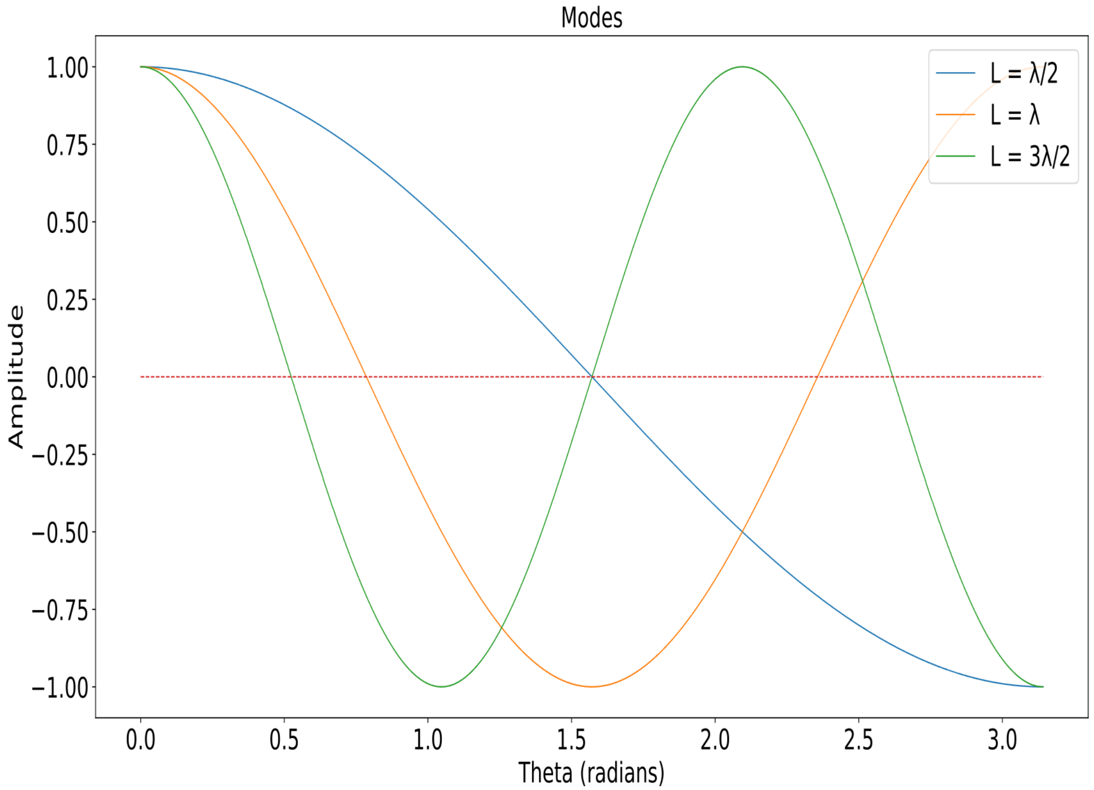
- Magnetic Field resilient[2]
- High Electric field in small mode volumes

1. Sumedh Mahashabde, Ernst Otto, Domenico Montemurro, Sebastian de Graaf, Sergey Kubatkin, and Andrey Danilov Phys. Rev. Applied **14**, 044040
2. Cécile Xinqing Yu*,* Simon Zihlmann*,* Gonzalo Troncoso Fernández-Bada*,* Jean-Luc Thomassin*,* Frédéric Gustavo*,* Étienne Dumur*, and* Romain Maurand , "Magnetic field resilient high kinetic inductance superconducting niobium nitride coplanar waveguide resonators", Appl. Phys. Lett. 118, 054001 (2021)

Superconducting microwave resonators



$$f_{resonance} = \frac{1}{\sqrt{L_l C_l}} \frac{1}{2l}$$



Superconducting resonator

$$f_{resonance} = \frac{1}{\sqrt{L_l C_l}} \frac{1}{l}$$

$$L_l = L_{Geometric} + L_{kinetic}$$

$$L_{kin} = \frac{\hbar R_{\blacksquare}}{\pi \Delta_0}$$

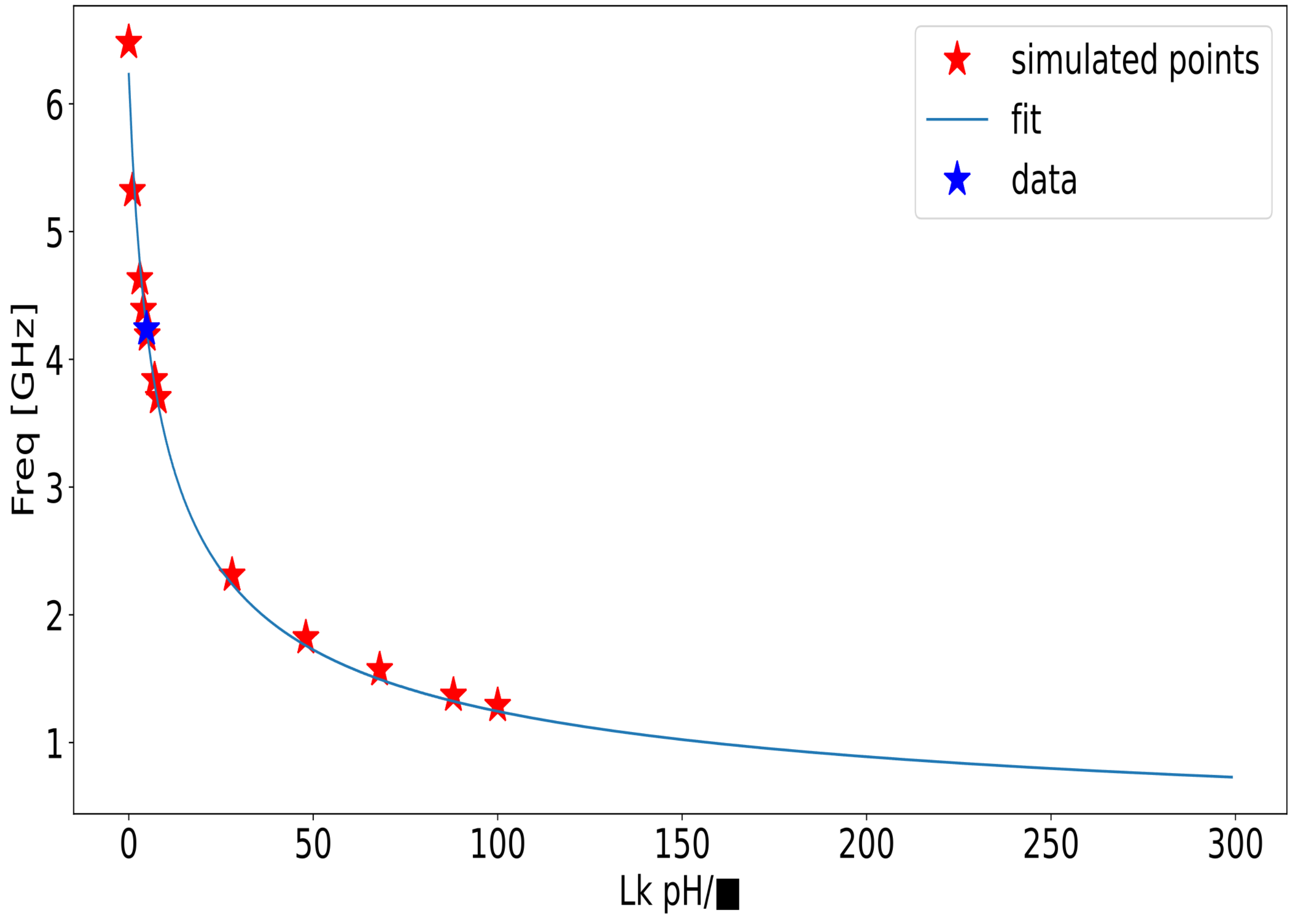
$$\Delta_0 = superconducting\ energy\ gap \propto Tc$$

$$Z_o = \sqrt{\frac{L_l}{C_l}}$$

$$V_{rms} \propto \sqrt{Z_0}$$

- $L_{kinetic}$ a property of a superconductor
- Can move resonant frequency of resonator
- Can affect the electric field in the mode volume of resonator

Lk vs film thickness simulation / experimental



$$y = \frac{1}{\sqrt{ax + b}}$$

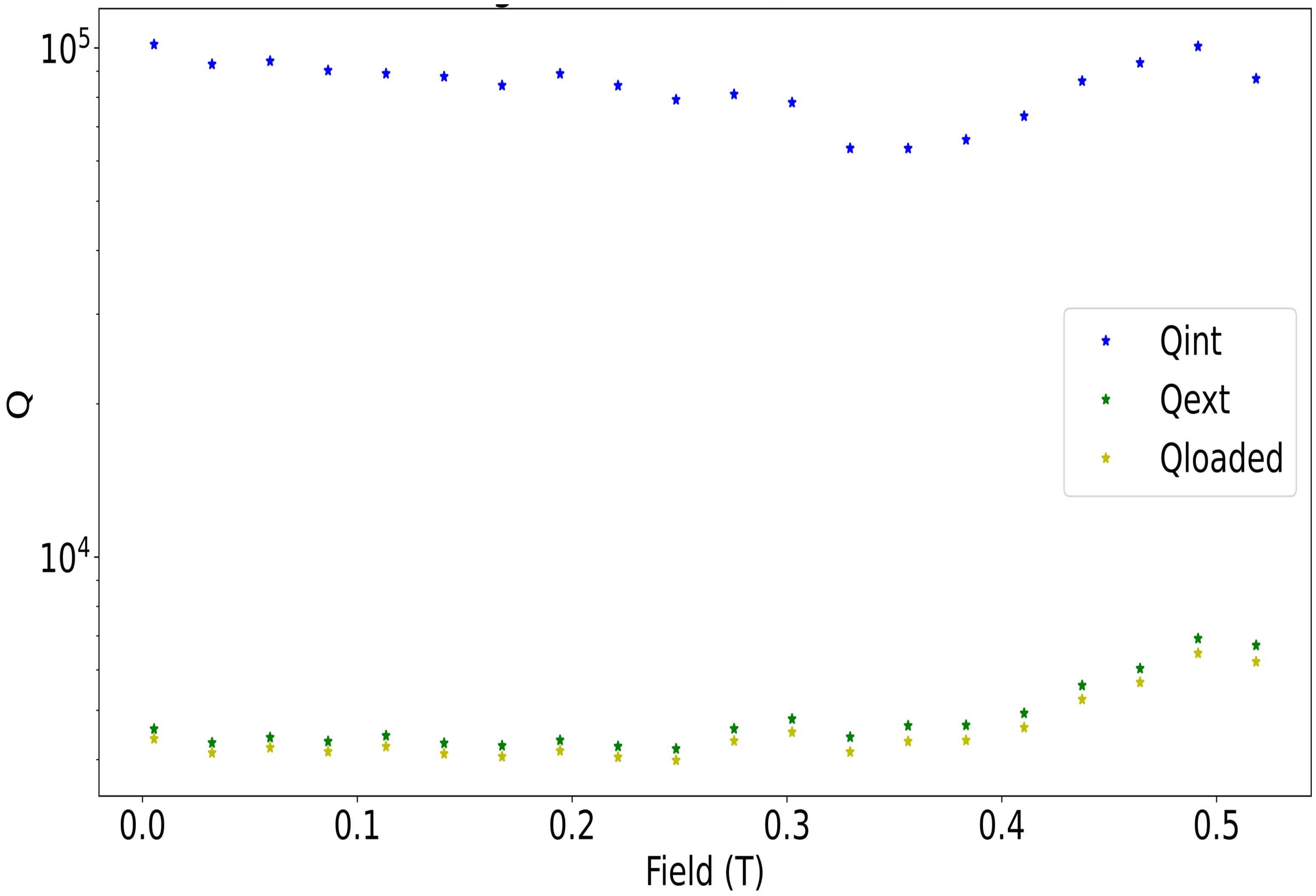
- 50nm NbTiN film
- Freq= 4.2376 GHz
- Lk = 4.83 pH/square

Name	Thickness [nm]	Sheet Kinetic inductance [pH/square]
NbTiN	8-12	13
WSi	16-20	33.5

Superconducting resonator

- Internal Q
- External Q
- Loaded Q

$$\frac{1}{Q_L} = \frac{1}{Q_{internal}} + \frac{1}{Q_{external}}$$

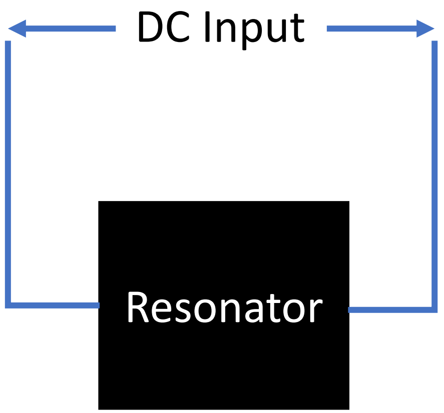


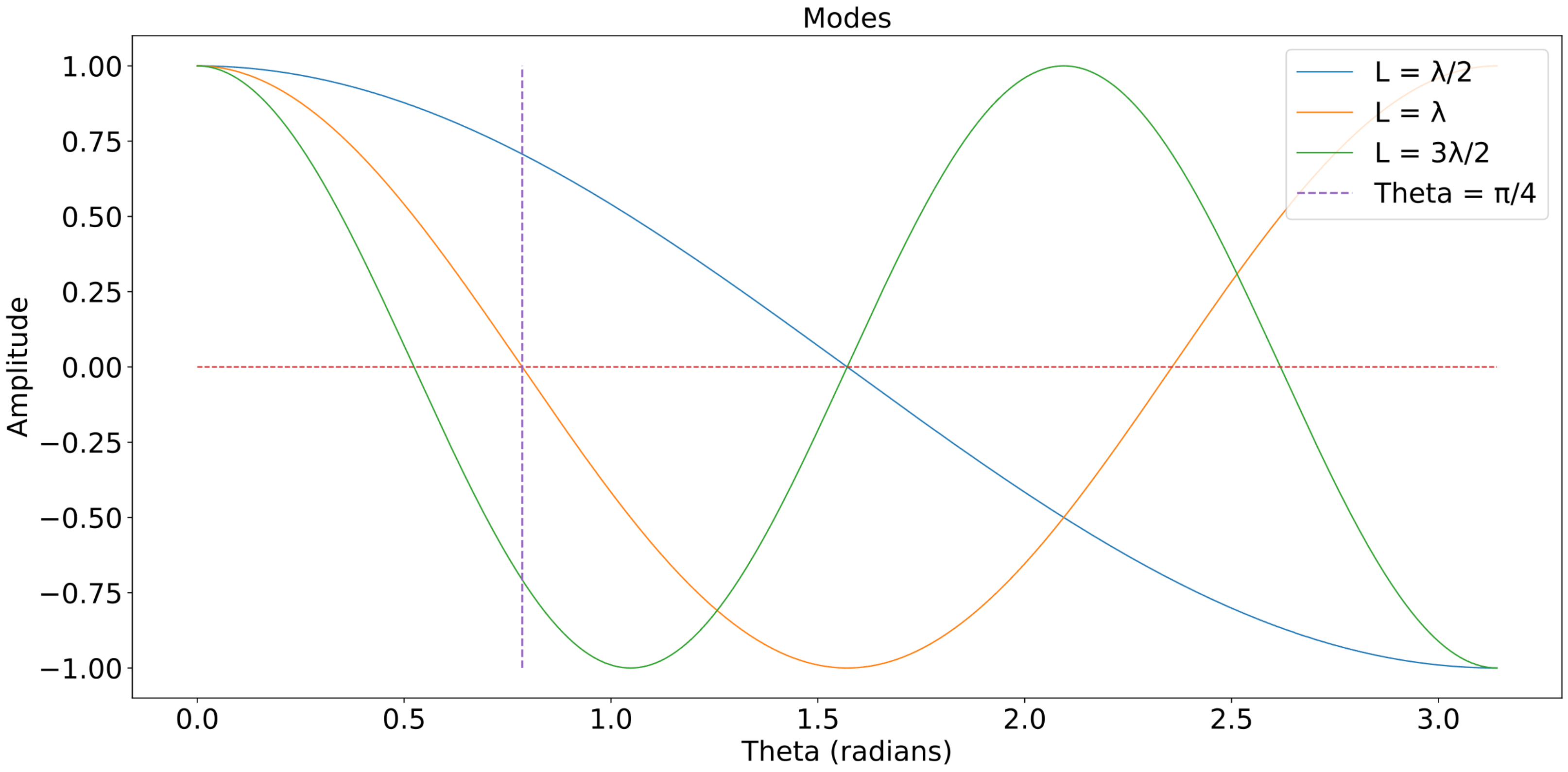
Conclusion

- The resonators were found to be B resilient, which is important for ESR experiments.
- High internal Qs resilient to magnetic fields
- High Lk guarantees better E field localization.

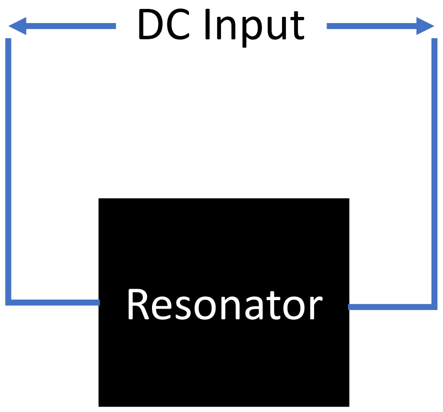
Outlook

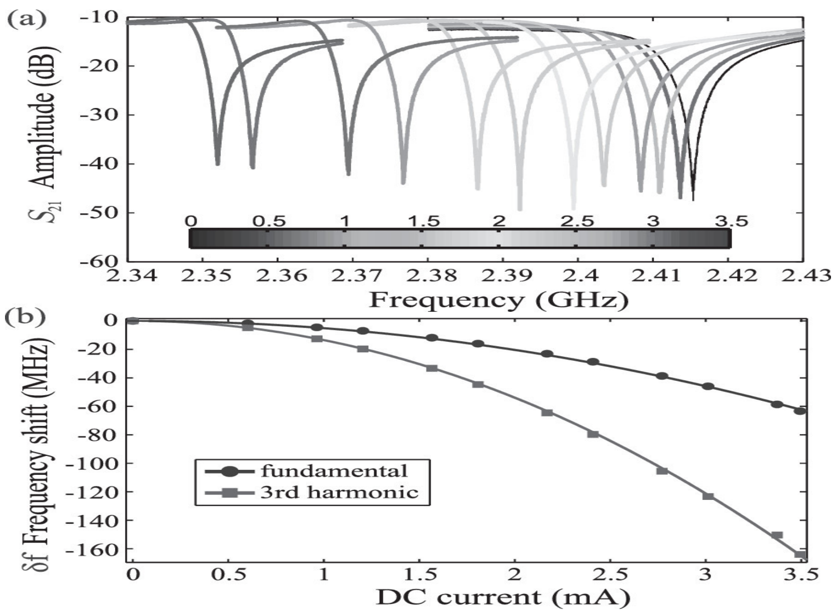
- Resonance tuning
- Electric drive of Dopant systems with spin orbit coupling





Towards Tunable resonators





$$L_k = L_k(0)\left(1 + \left(\frac{I}{I_*}\right)^2\right)$$ [1]

1. A. A. Adamyan, S. E. Kubatkin, *and* A. V. Danilov, "Tunable superconducting microstrip resonators", Appl. Phys. Lett. 108, 172601 (2016)