SCIENCE ADVANCES | RESEARCH ARTICLE

APPLIED PHYSICS

Electrically driven optical interferometry with spins in silicon carbide

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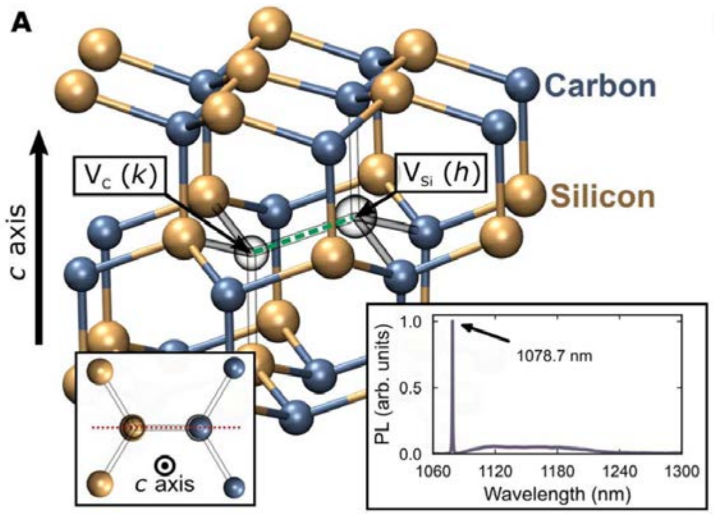
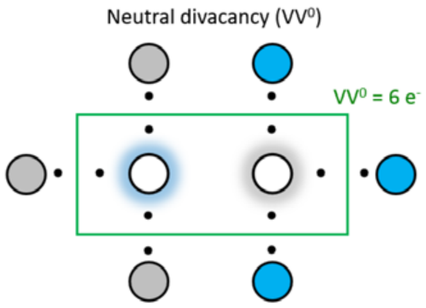
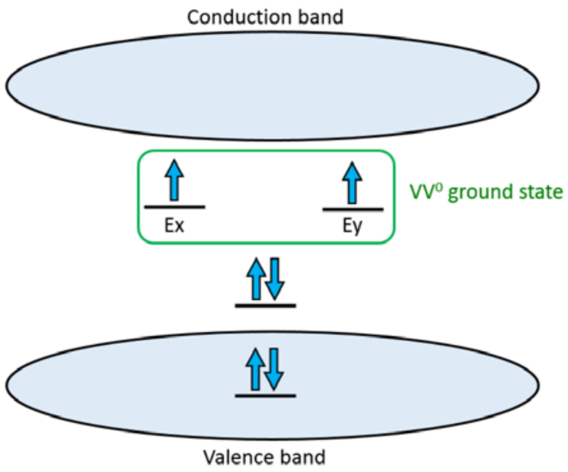
Ground state spins: weak coupling to environment, good coherence

Excited-state orbitals: stronger coupling to photonic & E fields

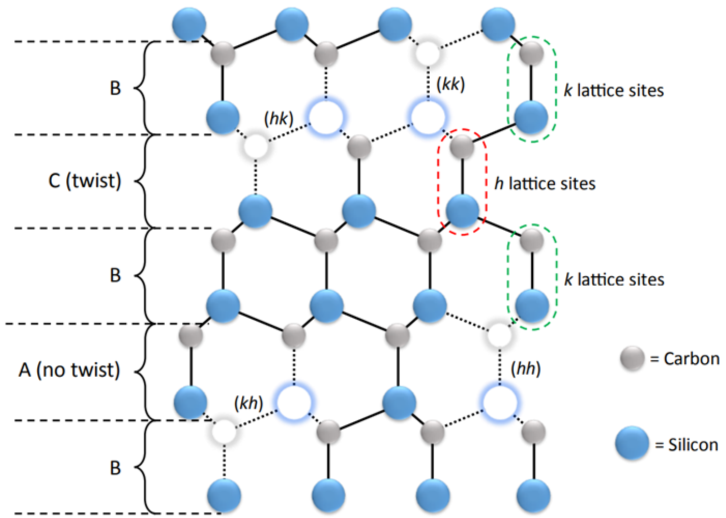
Neutral divacancy in silicon carbide





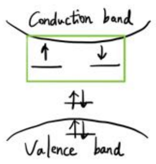


a localized C_{1h}
symmetry system



Hamiltonian of divacancy

Ground State Hamiltonian of divacancy



Triplet $\begin{cases} \uparrow\uparrow = |1,1\rangle \\ \frac{\uparrow\downarrow+\downarrow\uparrow}{\sqrt{2}} = |1,0\rangle \\ \downarrow\downarrow = |1,-1\rangle \end{cases}$

Singlet $\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}} = |0,0\rangle$.

qubit basis could be

$m_s = \{|0\rangle, |1\rangle\}$ or $m_s = \{|0\rangle, |-1\rangle\}$

$\boxed{① \text{ Zero-field } H : \text{SOC \& spin-spin interaction}}$

$$H_g = \frac{1}{\hbar}(\vec{S}\cdot\vec{D}\cdot\vec{S})$$ Zero field splitting tensor $\vec{D} = \begin{pmatrix} D_{xx} & & \\ & D_{yy} & \\ & & D_{zz} \end{pmatrix}$

$$= \frac{1}{\hbar}(S_x D_{xx} S_x + S_y D_{yy} S_y + S_z D_{zz} S_z)$$

$$= \frac{1}{\hbar}(D_x S_x^2 + D_y S_y^2 + D_z S_z^2)$$

$S_z^2 = \begin{pmatrix} 1 & & \\ & 0 & \\ & & 1 \end{pmatrix}$ $S_x^2 = \begin{pmatrix} \frac{1}{2} & & \frac{1}{2} \\ & 1 & \\ \frac{1}{2} & & \frac{1}{2} \end{pmatrix}$ $S_y^2 = \begin{pmatrix} \frac{1}{2} & & -\frac{1}{2} \\ & 1 & \\ -\frac{1}{2} & & \frac{1}{2} \end{pmatrix}$

$D = \frac{3}{2}D_z,\ E = \frac{D_x - D_y}{2}$

D traceless

$$= \hbar\begin{pmatrix} \frac{D}{3} & & E \\ & -\frac{2}{3}D & \\ E & & \frac{D}{3} \end{pmatrix} = \hbar\left\{D\left[\hat{S}_z^2 - \frac{S(S+1)}{3}\right] + E\left(\underbrace{\hat{S}_+^2 + \hat{S}_-^2}_{=2(S_x^2 - S_y^2)}\right)\right\}.$$

With eigen energy & states :

$-\frac{2}{3}D\hbar,\ \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$; $\left(\frac{D}{3}-E\right)\hbar,\ \begin{pmatrix} -1 \\ 0 \\ 1 \end{pmatrix}$; $\left(\frac{D}{3}+E\right)\hbar,\ \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}$;

$|m_s = 0\rangle$ $|-\rangle$ $|+\rangle$

$\boxed{② \text{ Effect of static magnetic field}}$

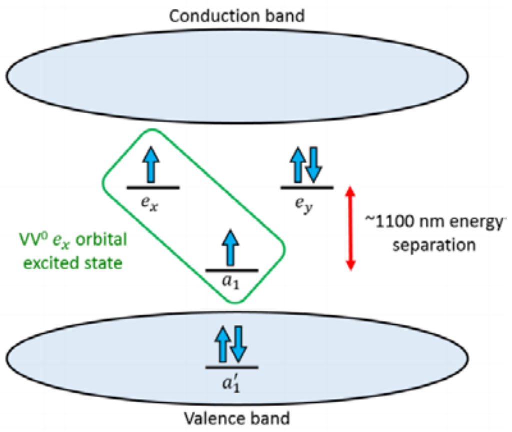
$$V_B = \mu_B g^{\parallel} S_z B_z + \mu_B g^{\perp}(S_x B_x + S_y B_y)$$

$$= \mu_B \begin{pmatrix} g^{\parallel} B_z & \frac{g^{\perp}}{\sqrt{2}}(B_x - iB_y) & 0 \\ \frac{g^{\perp}}{\sqrt{2}}(B_x + iB_y) & 0 & \frac{g^{\perp}}{\sqrt{2}}(B_x - iB_y) \\ 0 & \frac{g^{\perp}}{\sqrt{2}}(B_x + iB_y) & -g^{\parallel} B_z \end{pmatrix}$$

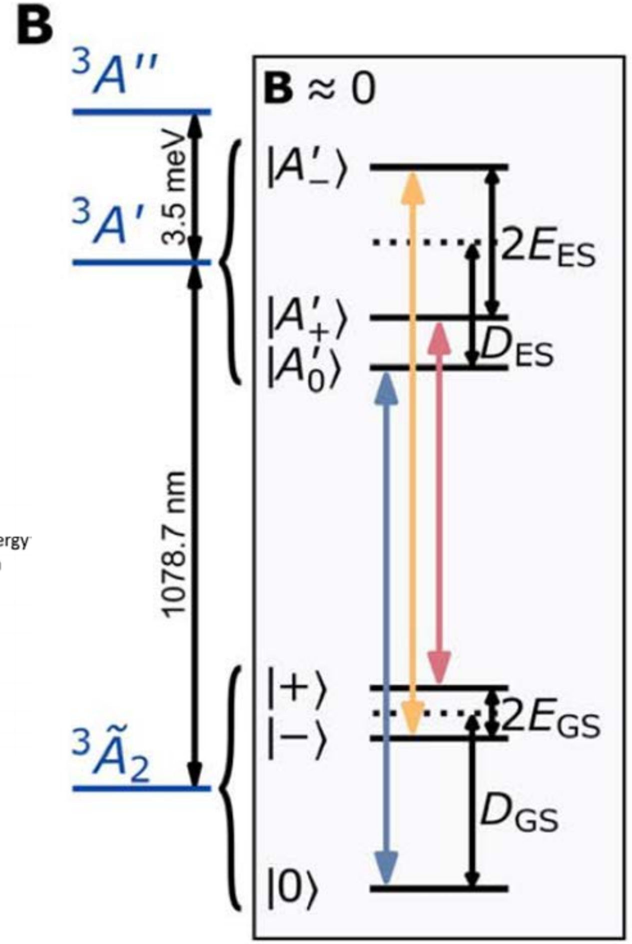
$\boxed{③ \text{ Nuclear spins}}$

$$V_{nuclear} = A_g^{\parallel}\, \hat{S}_z \otimes \hat{I}_z + A_g^{\perp}(\hat{S}_x \otimes \hat{I}_x + \hat{S}_y \otimes \hat{I}_y)$$

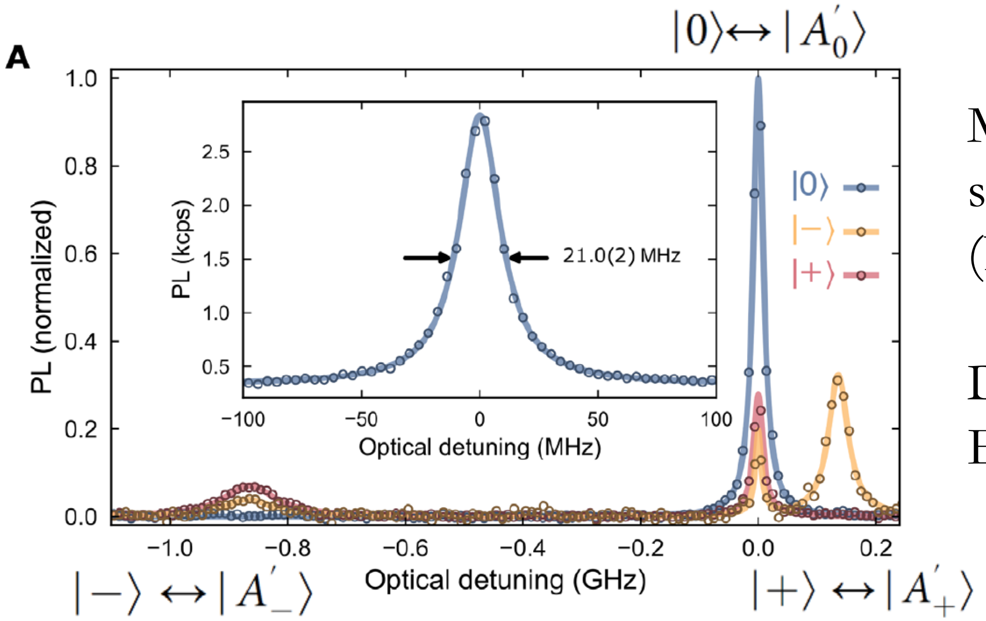
$$= \sum_i \hat{S}\cdot A_i \cdot \hat{I}_i$$



Excitated state longitudinal and transverse zero-field splittings D_{ES} and E_{ES}

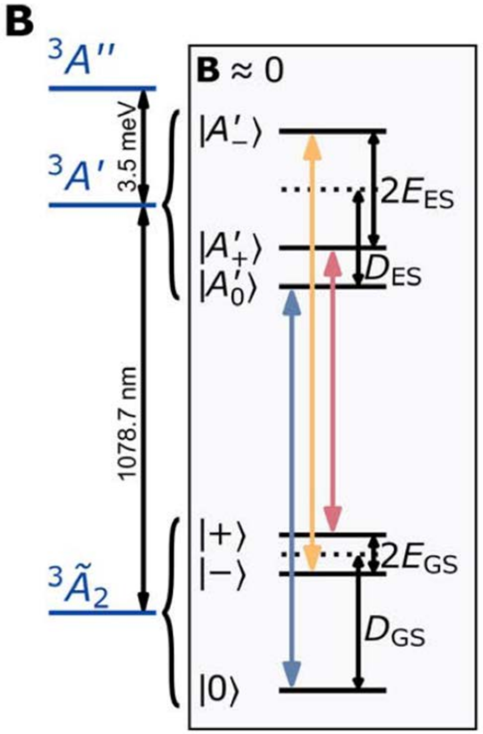


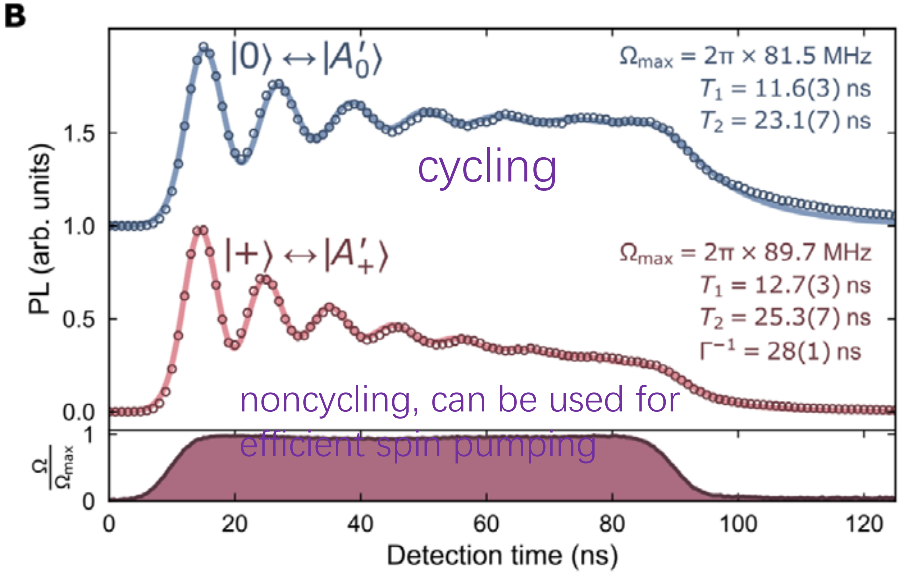
optical properties characterization



Map the fine structure of 3A'
spin-dependent PL excitation (PLE) spectroscopy

D_{ES} : +970 MHz
E_{ES} : −483 MHz





Probe the excited-state dynamics
time-correlated fluorescence measurements

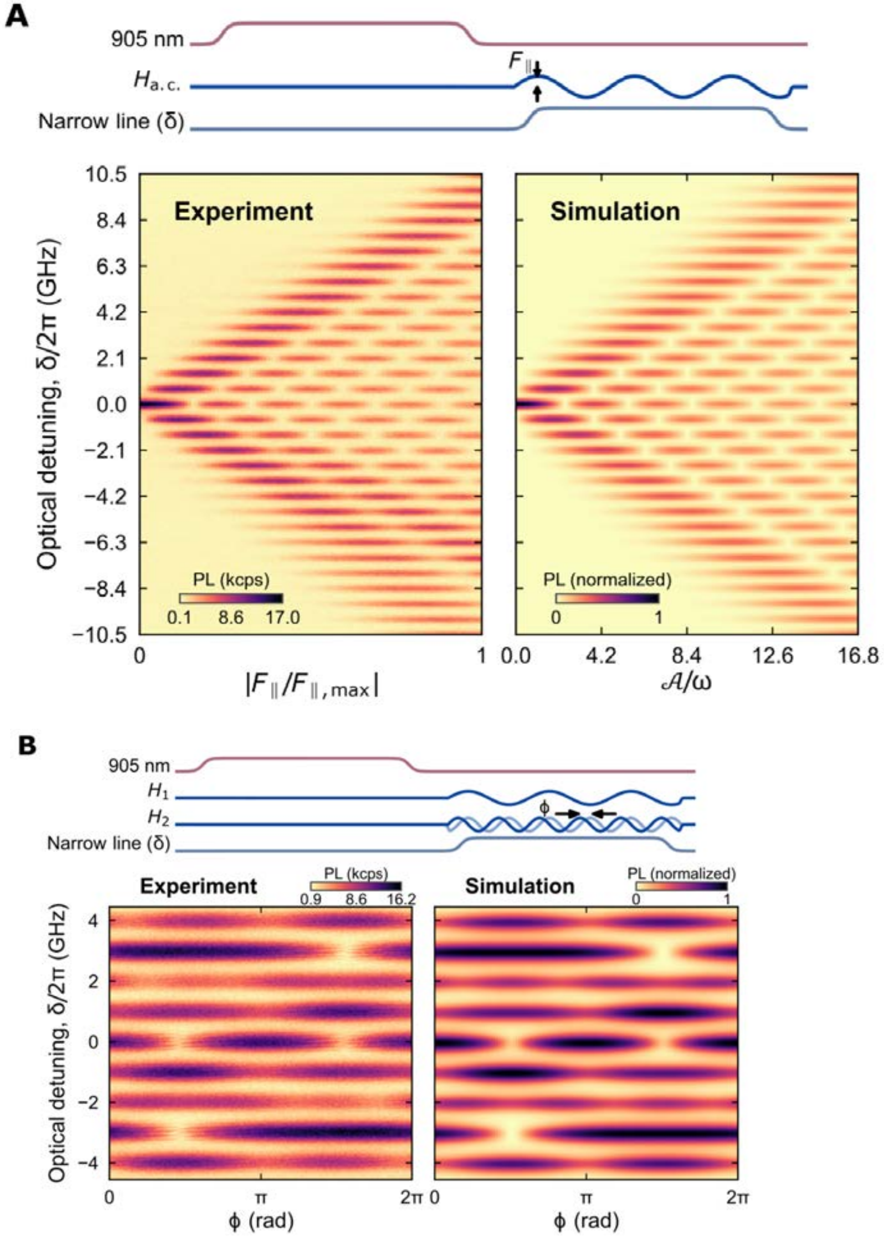
Optical TLS has near-lifetime-limited coherence

$$H(t)/\hbar = \frac{\Omega\cos(\omega_{opt} t)}{2}\sigma_x + \frac{\omega_0}{2}\sigma_z$$

$$\dot{\rho}(t) = -\frac{i}{\hbar}[H(t), \rho(t)] + \frac{1}{2}\sum_n \left(2C_n\rho C_n^\dagger - \{C_n^\dagger C_n, \rho\}\right)$$

Ω: optical Rabi frequency
δ : laser detuning

LZS interference



$$|0\rangle \leftrightarrow |A_0'\rangle$$

Arises when the TLS is repeatedly brought through an avoided crossing diabatically, Stückelberg phase between each crossing

Optical driving

Stark effect

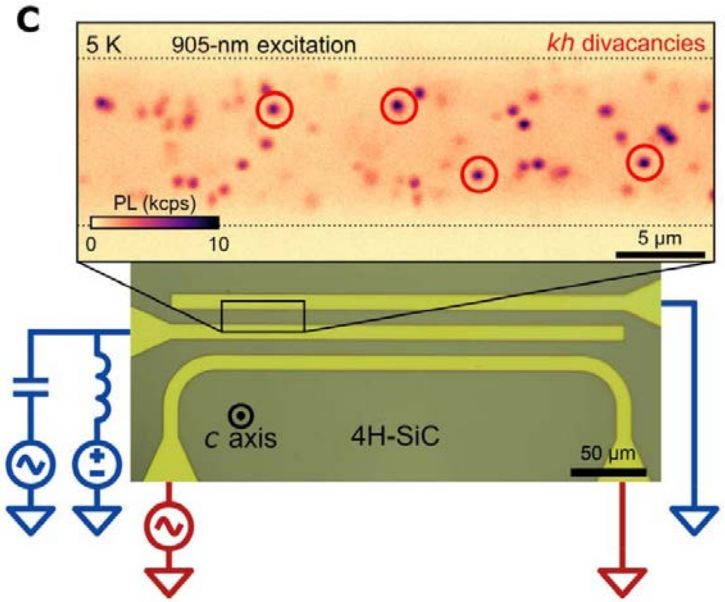
Multiphoton(15) resonances at detunings equal to integer multiples of drive frequency

F: Amplitude of E drive

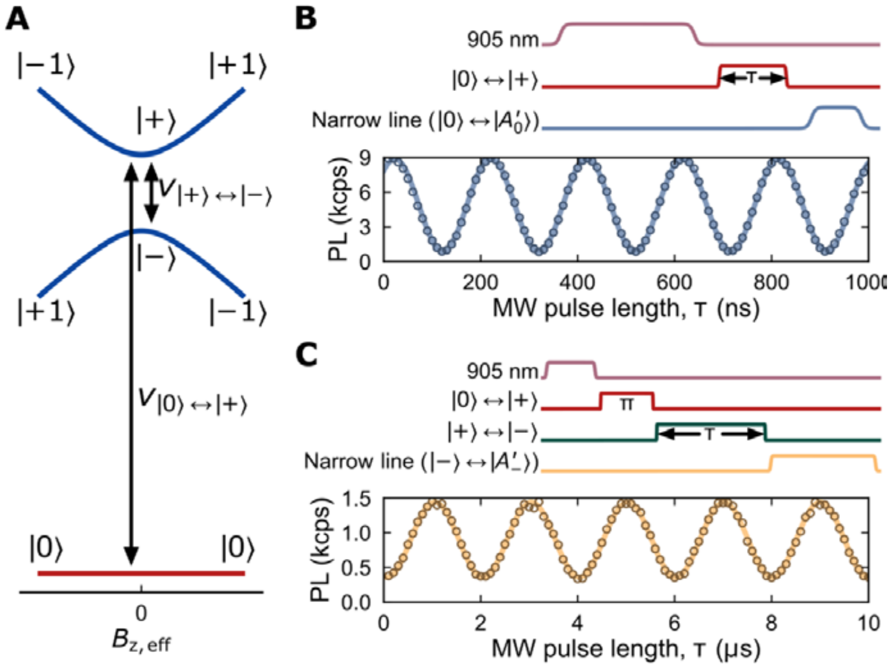
$\mathcal{A}$: induced Stark shift amp

dc Stark shifts of excited-state orbital levels

GHz ac electric field drive concurrently with the resonant excitation



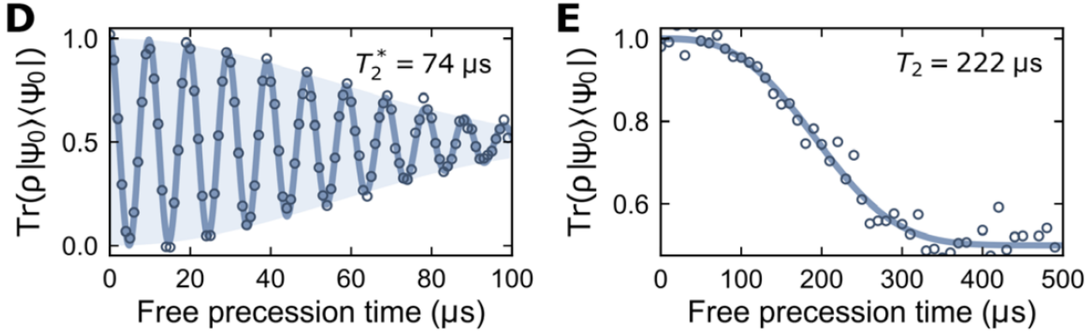
ground-state spin system in single kh VVs



magnetically driven transitions between all three spin states

Rabi oscillations marked by high PL contrast

Ramsey interferometry $\frac{1}{\sqrt{2}}(|0\rangle + |+\rangle)$



ZEFOZ

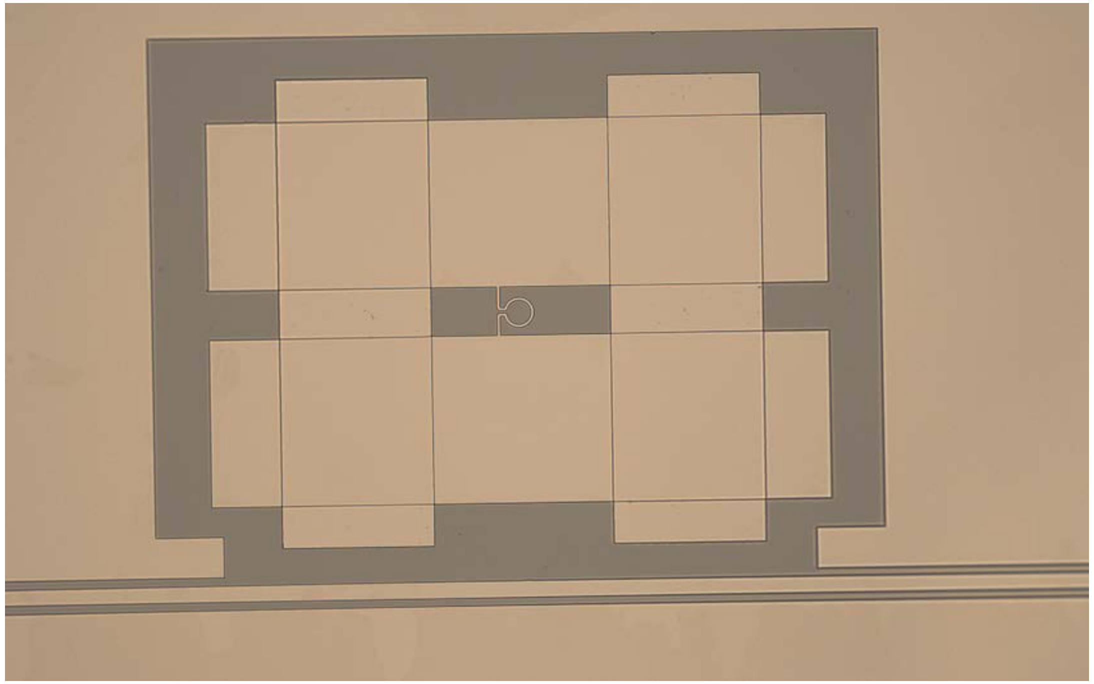
$$\mathrm{eigvec}(H/h) = \begin{cases} \frac{E}{C_+ + \sqrt{C_+^2 + E^2}} |+1\uparrow\rangle + |-1\uparrow\rangle, & |1\rangle \\ \frac{E}{C_- + \sqrt{C_-^2 + E^2}} |+1\downarrow\rangle + |-1\downarrow\rangle, & |2\rangle \\ \frac{E}{C_+ - \sqrt{C_+^2 + E^2}} |+1\uparrow\rangle + |-1\uparrow\rangle, & |3\rangle \\ \frac{E}{C_- - \sqrt{C_-^2 + E^2}} |+1\downarrow\rangle + |-1\downarrow\rangle, & |4\rangle \\ |0\uparrow\rangle, & |5\rangle \\ |0\downarrow\rangle, & |6\rangle \end{cases}$$

When a nonzero nuclear spin couples to the VV0

$$H/h = D\left(\hat{S}_z^2 - \frac{S(S+1)}{3}\right) + E(\hat{S}_+^2 + \hat{S}_-^2) + g\mu_B \mathbf{B}\cdot\hat{\mathbf{S}} + \sum_i \hat{\mathbf{S}}\cdot\mathbf{A}_i\cdot\hat{\mathbf{I}}_i$$

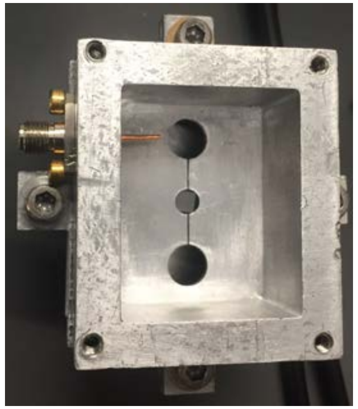
Research Update:

2D superconducting EPR spectrometer



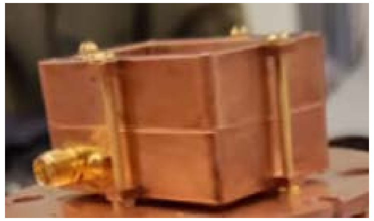
Overview of EPR spectrometer in lab

3D cavity: measure bulk samples

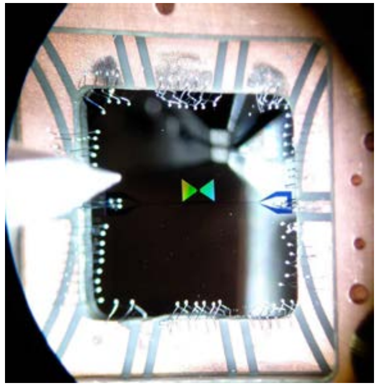


Al

Cu



2D on-chip resonator: local probe of spins



Interdigited Capacitor design

Parallel plate design

2D superconducting EPR spectrometer

Motivation:

Larger coupling $\rightarrow$ higher sensitivity, cooperativity, echo efficiency

Ability to probe lossy films/substrate

Reduce parasitic inductance $\rightarrow$ Reduce the coupling to spins/defects outside mode volume

2D superconducting EPR spectrometer

Motivation:

$$g_0 = b_1 g \mu_B \omega_{\text{res}} / \sqrt{8\hbar Z}$$

Larger coupling $\rightarrow$ higher sensitivity, cooperativity, echo efficiency

Low impedance design
9 Ω → 3 Ω
Could still be lower

Ability to probe lossy films/substrate

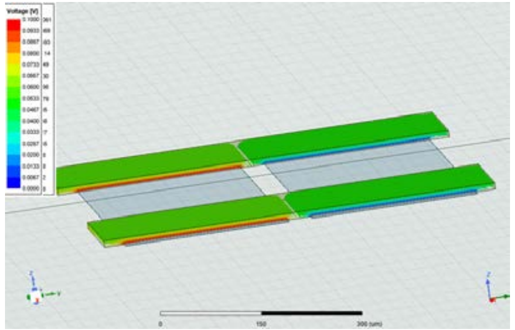
Reduce parasitic inductance → Reduce the coupling to spins/defects outside mode volume

2D superconducting EPR spectrometer

Motivation:

Larger coupling → higher sensitivity, cooperativity, echo efficiency

Ability to probe lossy films/substrate



Reduce parasitic inductance → Reduce the coupling to spins/defects outside mode volume

2D superconducting EPR spectrometer

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Larger coupling $\rightarrow$ higher sensitivity, cooperativity, echo efficiency

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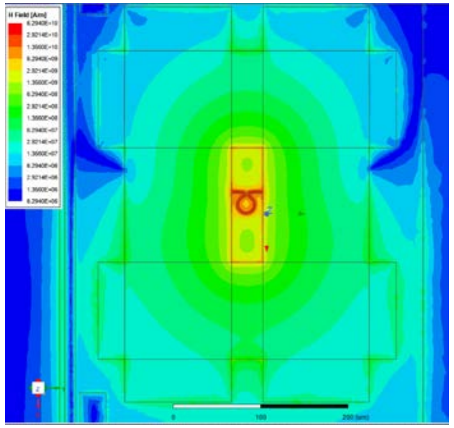
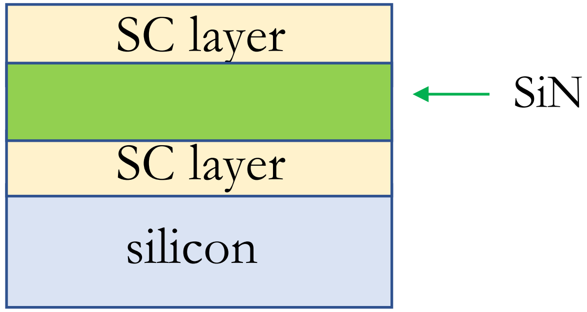


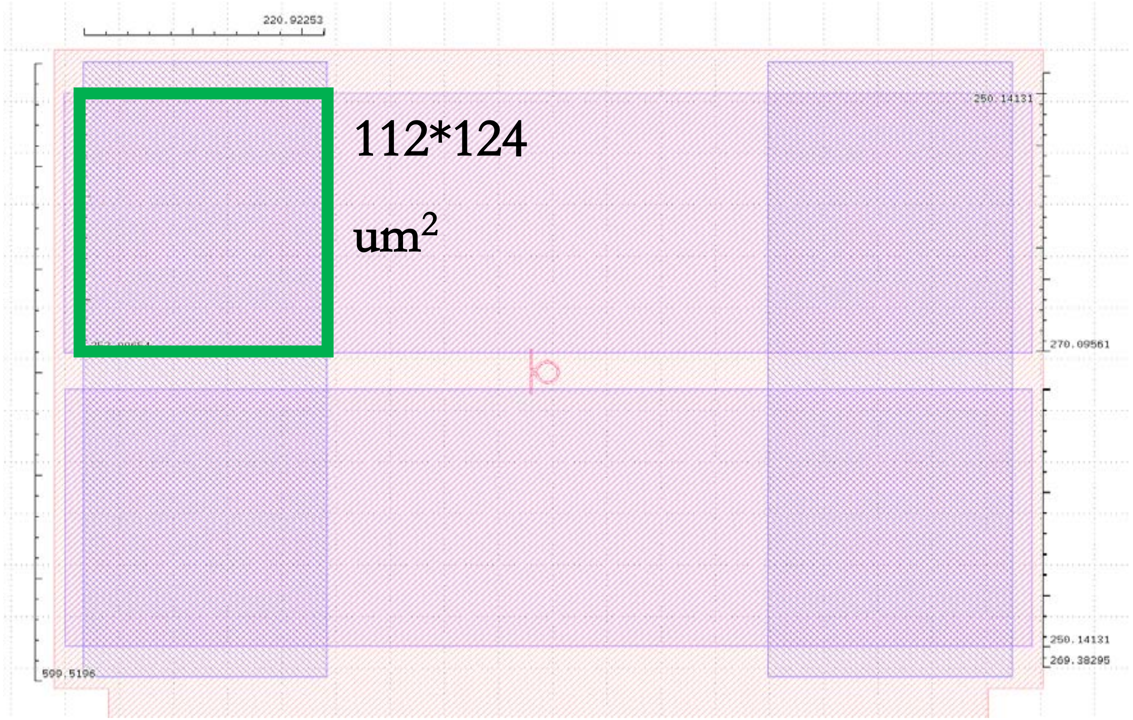
$$I_{\mathrm{ac}} = \sqrt{(\bar{n} + 1/2)\hbar\omega_0/L_{\mathrm{tot}}}$$

Proposed design:



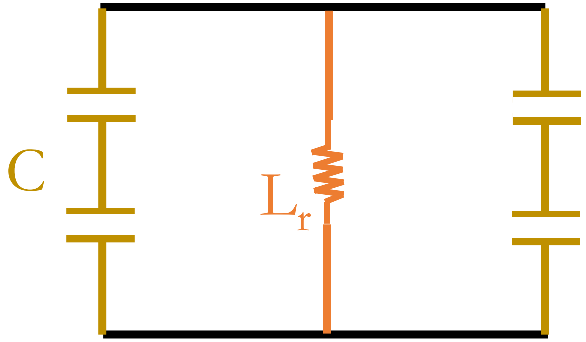
SiN Thickness = 95 nm

Permittivity: 6.5



$C \approx 8.41$ pF

$Lr \approx 96$ pH



Parameter estimation

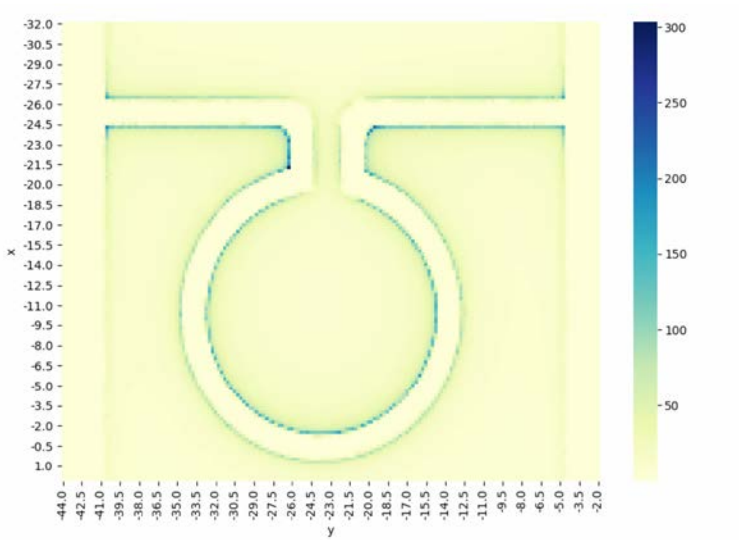
C $\approx$ 8.41 pF

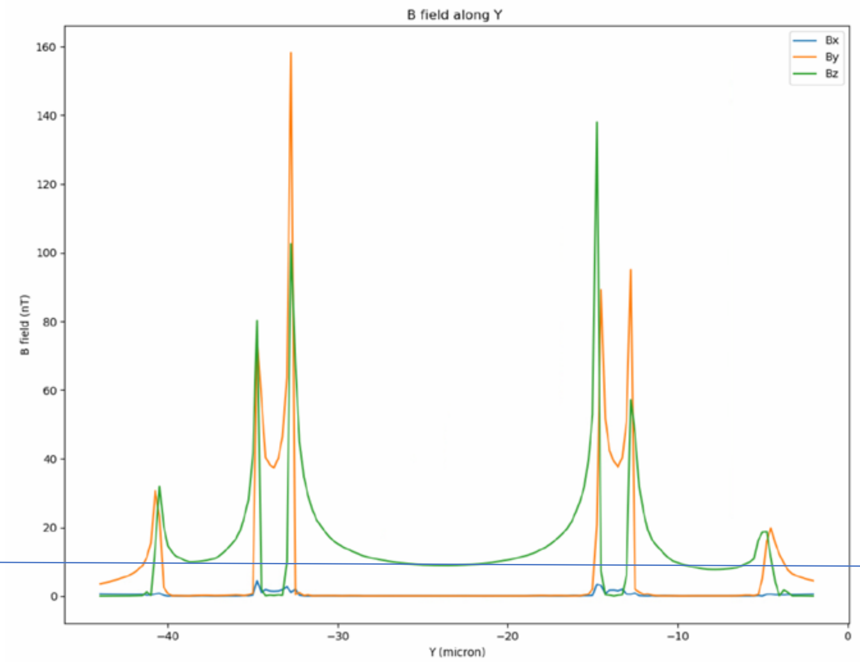
L $\approx$ 96 pH

$$f = \frac{1}{2\pi\sqrt{LC}} = 5.60 \text{ GHz}$$

Characteristic impedance
of resonator:

$$Z = \sqrt{\frac{L_r}{C_r}} = \text{sqrt}(96/8.41) = \boxed{3.38\ \Omega}$$



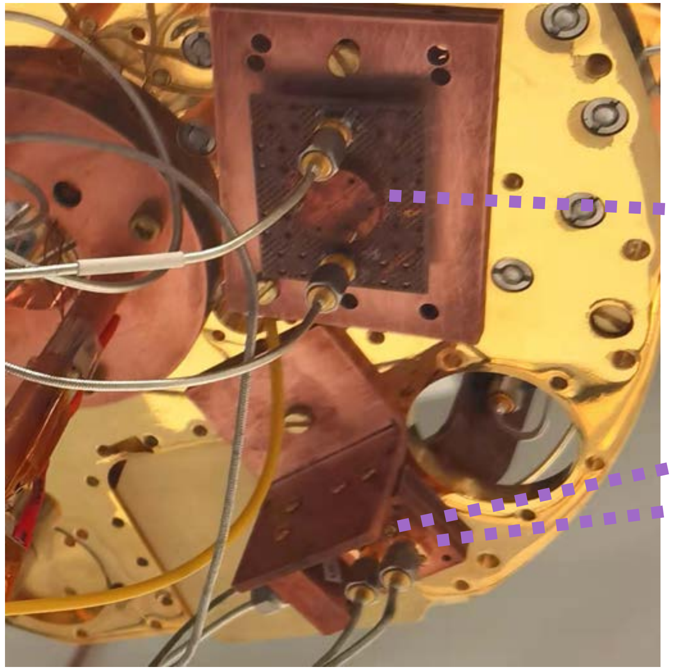


9.02 nT at the center

Average single spin coupling~1.6 kHz

Measurement setup:

Interdigital Capacitance Device

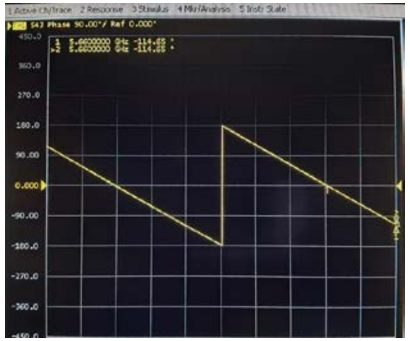


Parallel Plate
Dev1 & Dev3

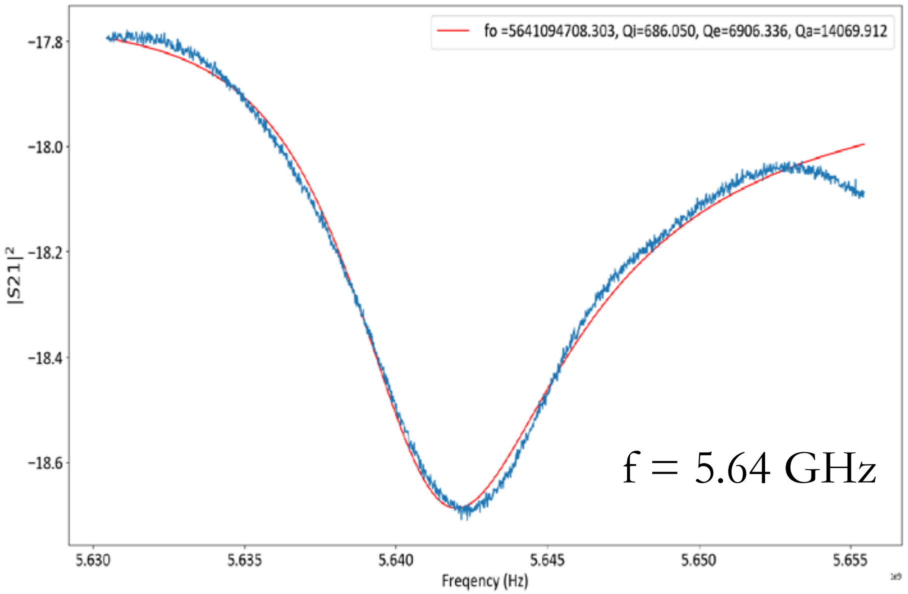
Measurement result:

Possibly highly undercoupled device

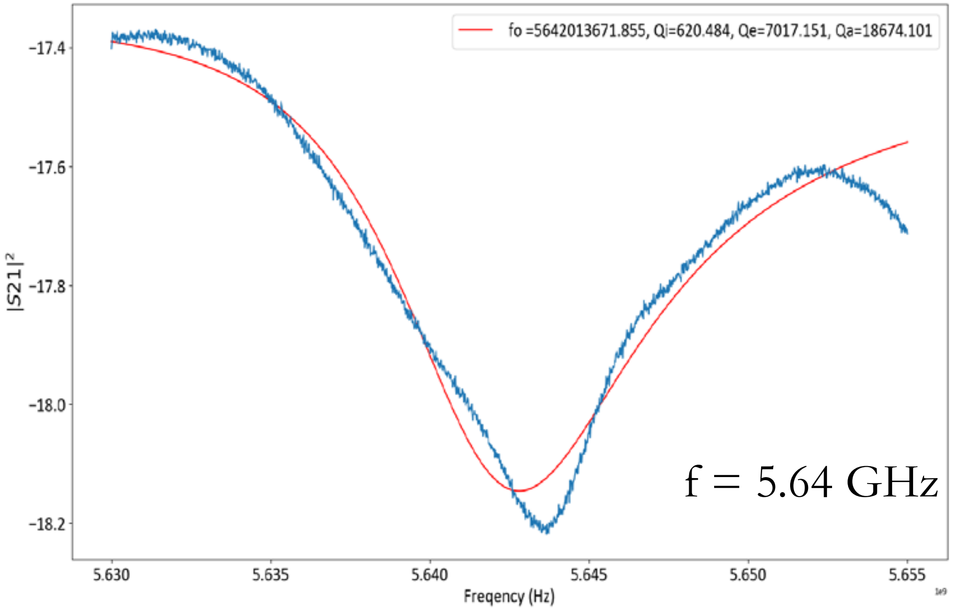
No noticeable phase shift detected.
Should measure again with phase delay cancelled.



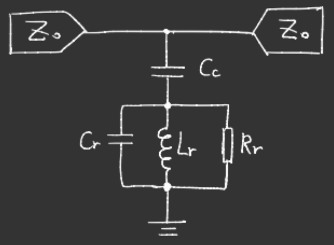
Dev 3: S21 Measurement
@ T = 4 K, MW Power = -10 dBm



Dev 3: S21 Measurement
@ T under 7 mK, MW Power = -10 dBm



Trouble shooting:



$$S_{11} = \frac{Z_r - Z_0}{Z_r - Z_0}$$

$$Z_r = \frac{1}{i\omega C_c} + \left(\frac{1}{R_r} + \frac{1}{i\omega L_r} + i\omega C_r\right)^{-1}$$

$$\Rightarrow \quad S_{11} = \frac{1 - \omega^2 L_r\left[C_r + C_c\left(1 - \frac{Z_0}{R_r}\right)\right] + i\omega\left[\frac{L_r}{R_r} - Z_0 C_c\left(1 - \omega^2 L_r C_r\right)\right]}{1 - \omega^2 L_r\left[C_r + C_c\left(1 + \frac{Z_0}{R_r}\right)\right] + i\omega\left[\frac{L_r}{R_r} + Z_0 C_c\left(1 - \omega^2 L_r C_r\right)\right]}$$

At resonance impedance vanishes:

$$\frac{1}{i\omega_0 C_c} + \frac{1}{i\omega_0 C_r + \frac{1}{i\omega_0 L_r}} = 0.$$

resonance freq $\Rightarrow \omega_0 = 1/\sqrt{L_r(C_r + C_c)}$.

$\boxed{\text{Assuming } R_r \gg Z_0,}$ on resonance:

$$|S_{11}(\text{res})| = \left| \frac{\frac{L_r}{Z_0 R_r C_r} - \frac{x^2}{1+x}}{\frac{L_r}{Z_0 R_r C_r} + \frac{x^2}{1+x}} \right|,$$

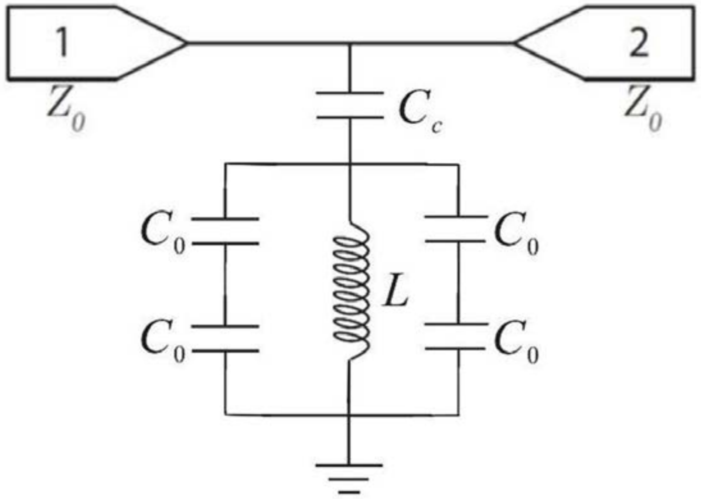
ratio of $\frac{\text{coupling } C}{\text{resonator } C}$

with $x = \frac{C_c}{C_r}$.

Z: characteristic impedance of resonator

$$= \left| \frac{\boxed{\frac{Z^2}{Z_0}\frac{1}{R_r} - \frac{x^2}{1+x}}}{\frac{Z^2}{Z_0}\frac{1}{R_r} + \frac{x^2}{1+x}} \right|.$$

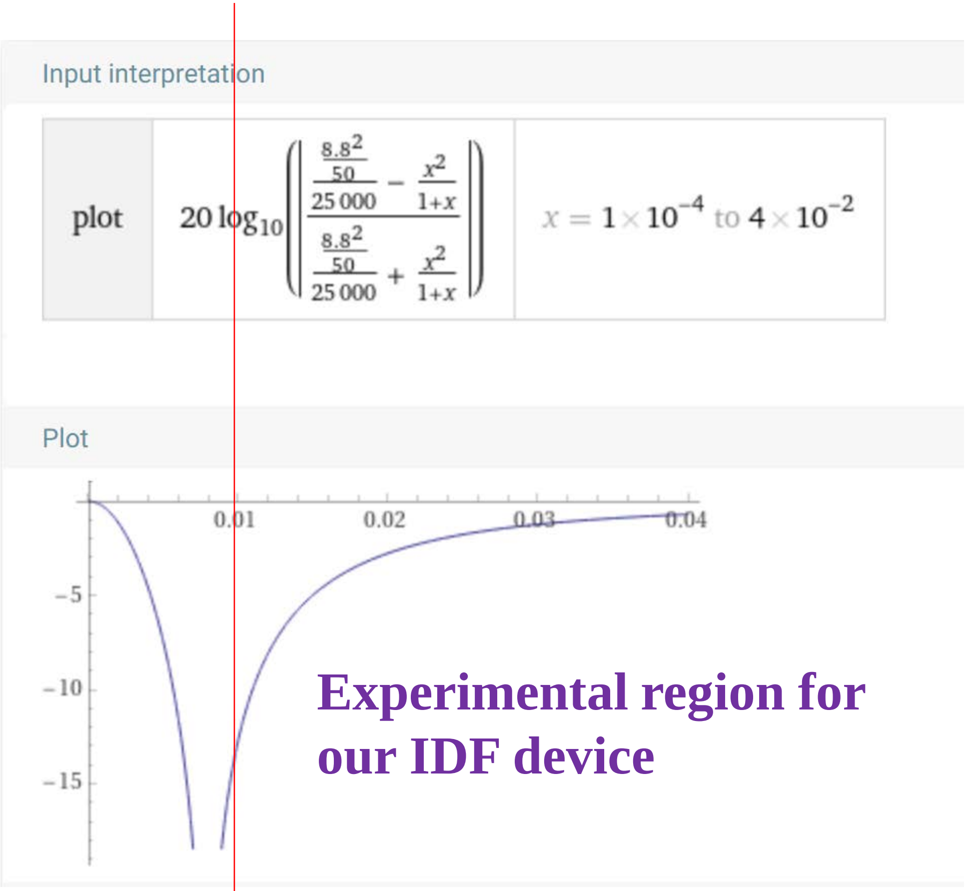
Capacitive coupling model



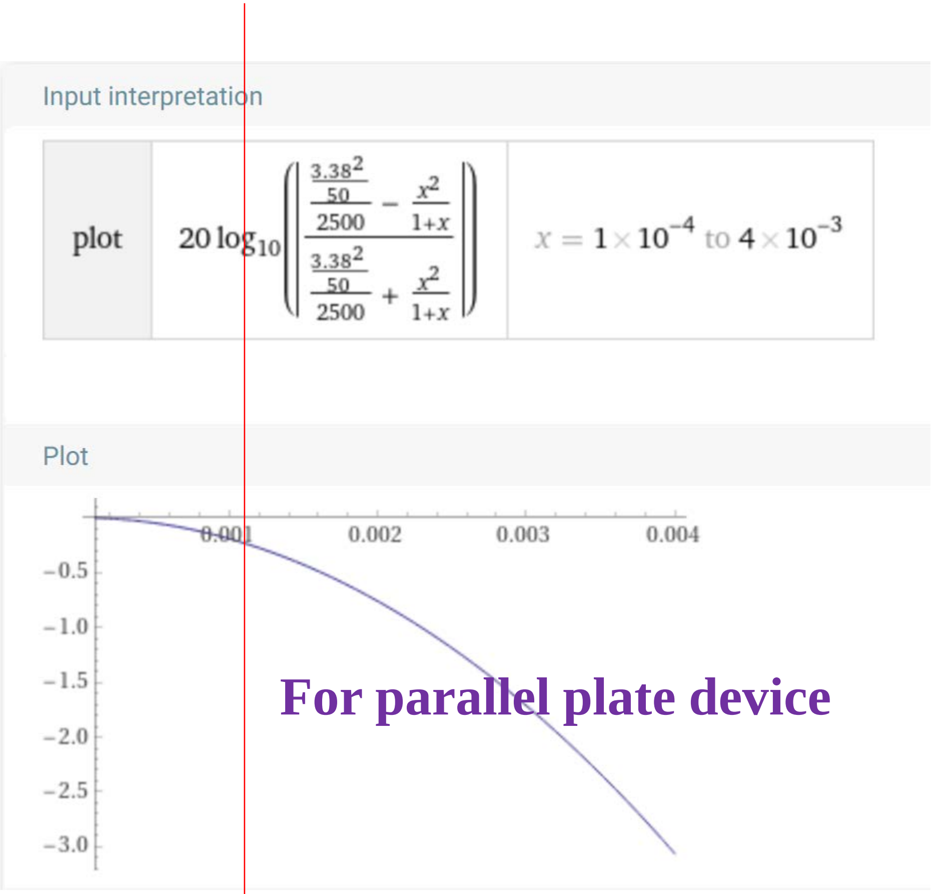
To get critically coupled device, this two terms should be comparable

Device working schemes

x: ratio of Cc/Cr

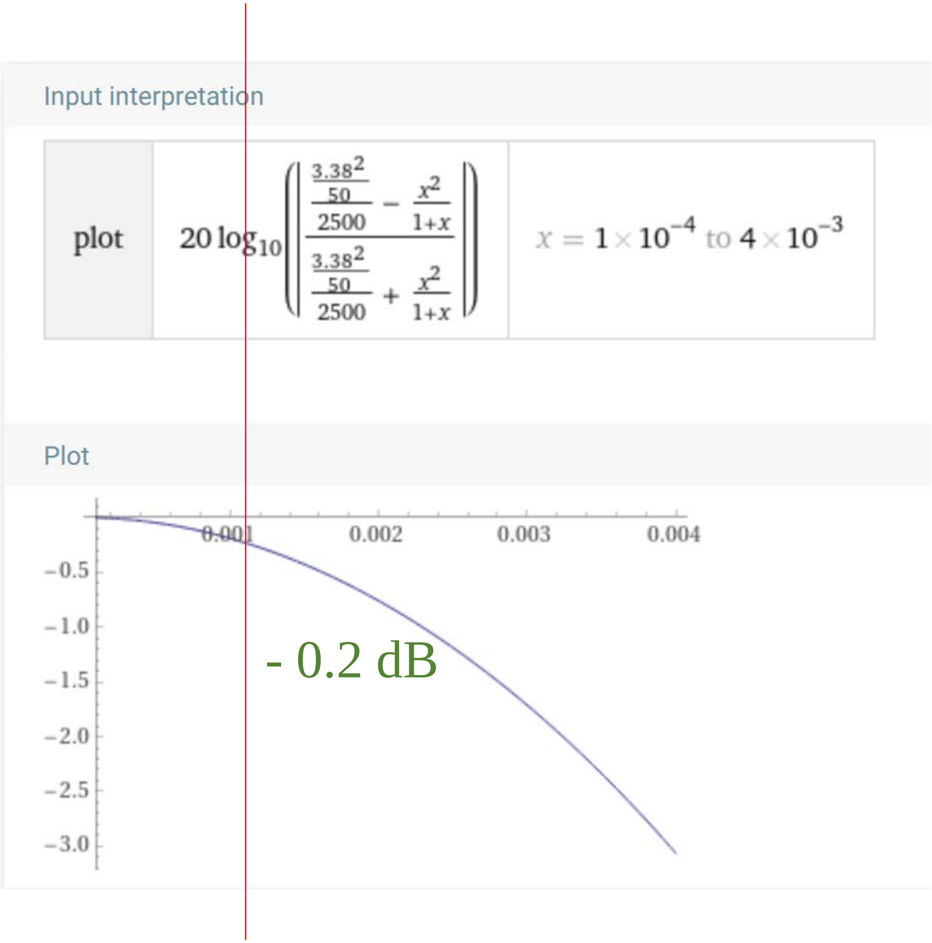


Scheme of IDF design:
Cr ~ 2.9 pF, Lr ~ 223 pH, Z ~ 8.8Ω
Cc~ 30 fF, x ~ 0.01. **Rr = 25 kΩ (moderate loss)**

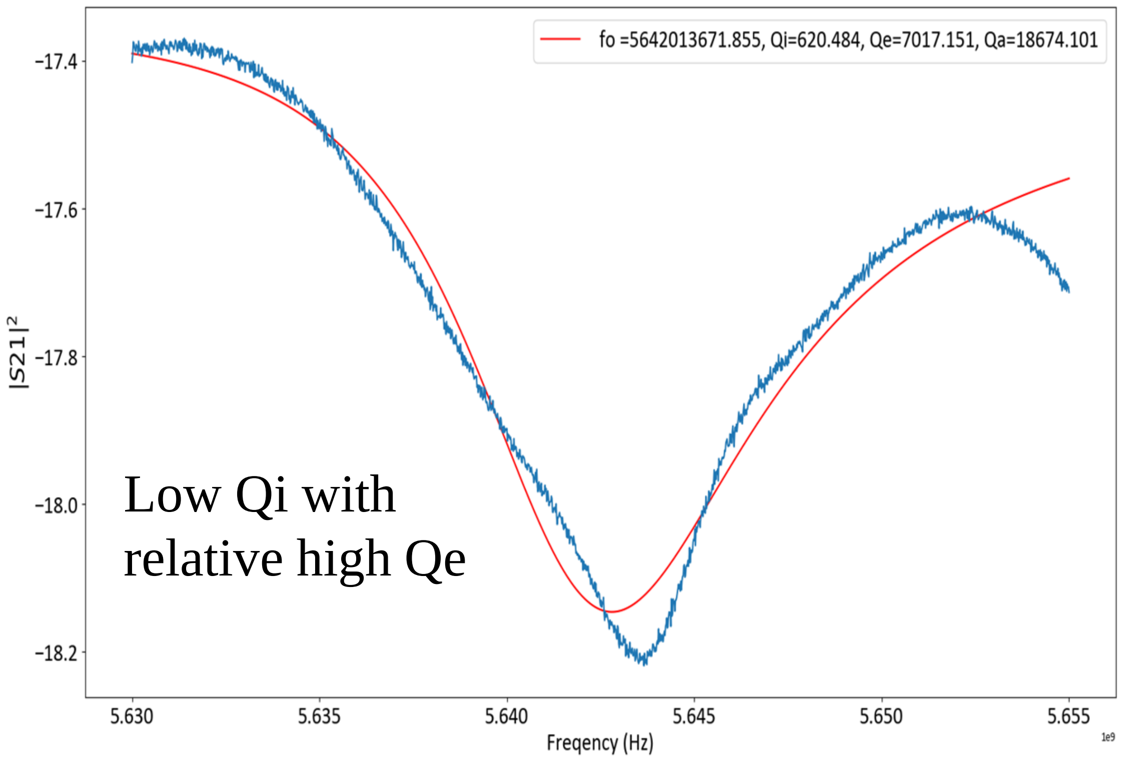


Scheme of Parallel Plate design:
Cr ~8.41pF, Lr ~ 96 pH, Z ~ 3.38 Ω
Cc~ 8 fF, x ~ 0.001. **Lossy, Rr = 2500 Ω**

Possibly highly undercoupled device:



Increase Cc!



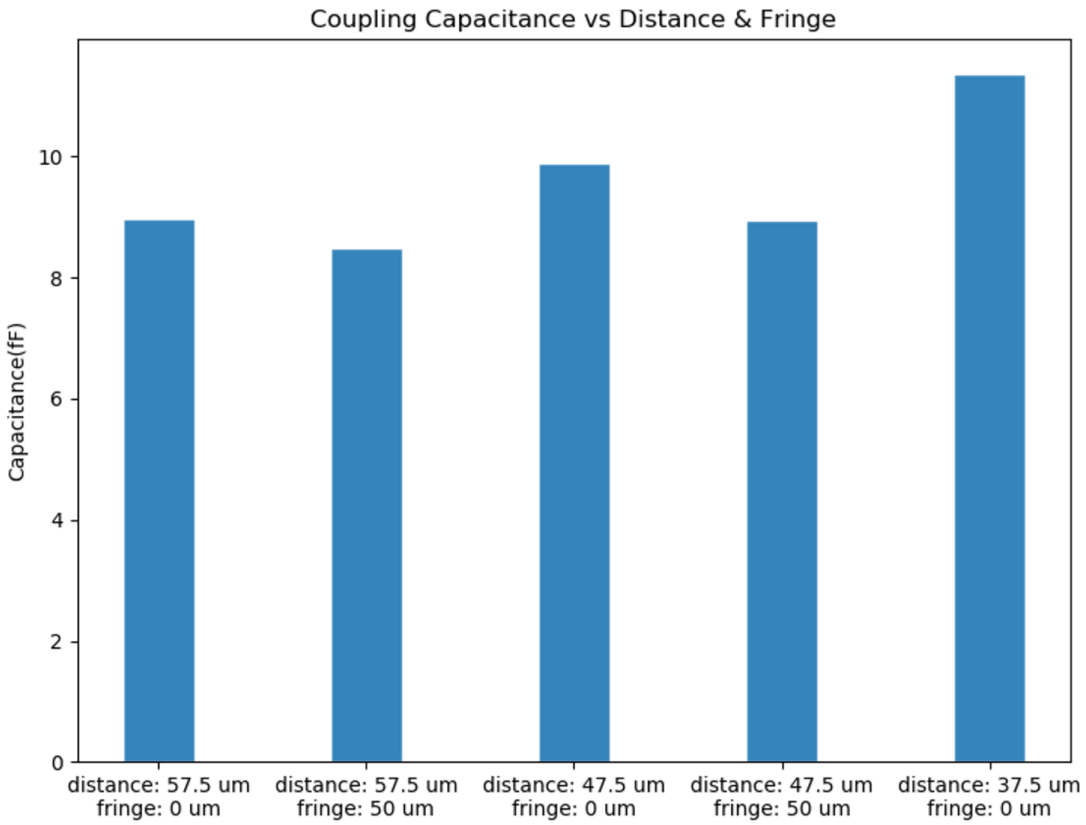
Scheme of Parallel Plate design:
Cr ~8.41pF, Lr ~ 96 pH, Z ~ 3.38 Ω
Cc~ 8 fF, x ~ 0.001

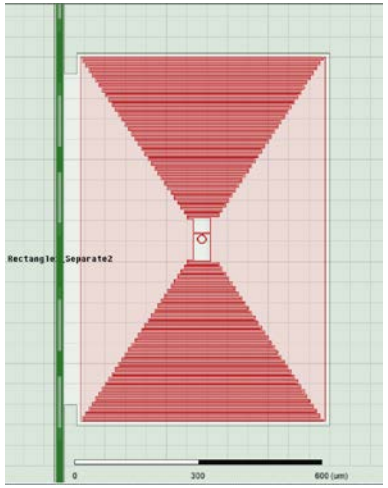
Characterization of coupling capacitance Cc:

To increase Cc:

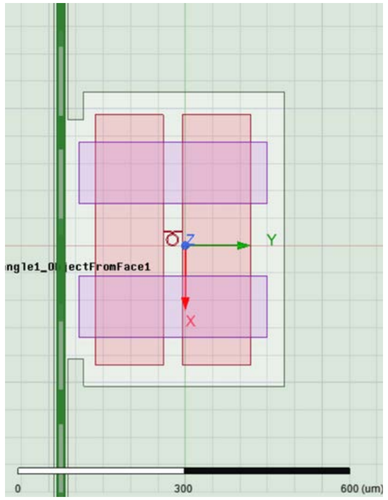
- Decrease distance with TL
- Remove fringe

Not enough!





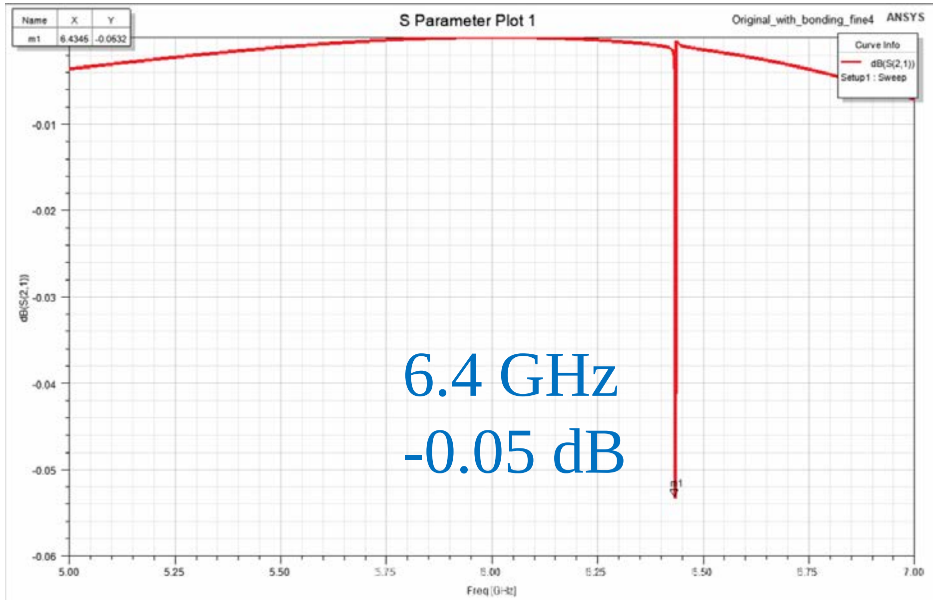
Cc ~ **30 fF**

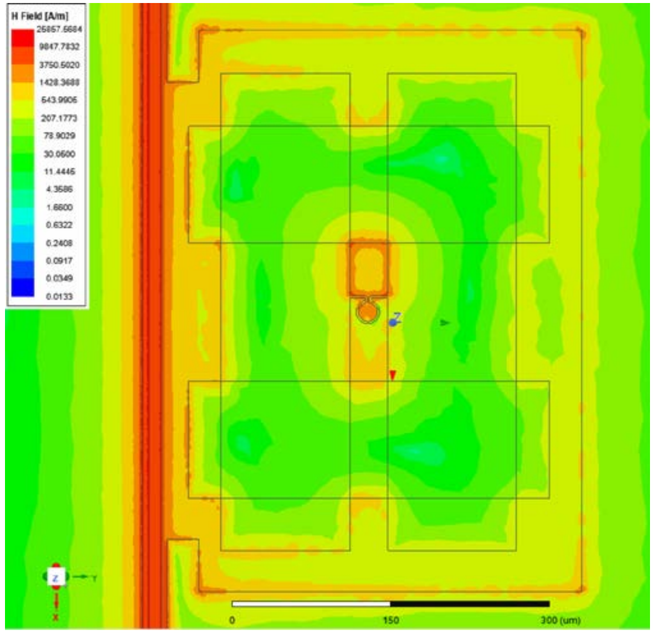


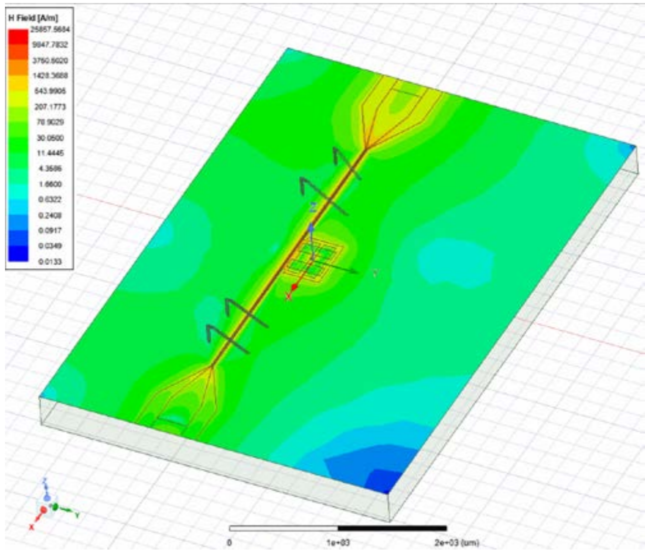
Cc ~ **8.49 fF**

Driven modal results:

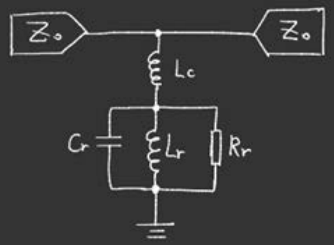
- Highly undercoupled
- Stray fields emerge (or weak coupling)







Trouble shooting:



$$S_{11} = \frac{Z_r - Z_0}{Z_r - Z_0} \qquad C_c \rightarrow -\frac{1}{\omega^2 L_c}$$

$$Z_r = i\omega L_c + \left(\frac{1}{R_r} + \frac{1}{i\omega L_r} + i\omega C_r\right)^{-1}$$

$$\Rightarrow \quad S_{11} = \frac{1-\omega^2 L_r C_r + \frac{L_r}{L_c}\left(1-\frac{Z_0}{R_r}\right) + i\left[\omega\frac{L_r}{R_r} + \frac{Z_0}{\omega L_c}\left(1-\omega^2 L_r C_r\right)\right]}{1-\omega^2 L_r C_r + \frac{L_r}{L_c}\left(1+\frac{Z_0}{R_r}\right) + i\left[\omega\frac{L_r}{R_r} - \frac{Z_0}{\omega L_c}\left(1-\omega^2 L_r C_r\right)\right]}$$

At resonance impedance vanishes:

$$i\omega_0 L_c + \frac{1}{i\omega_0 C_r + \frac{1}{i\omega_0 L_r}} = 0.$$

resonance freq $\Rightarrow \quad \omega_0 = \sqrt{\frac{1}{C_r\left(\frac{1}{L_c}+\frac{1}{L_r}\right)}}$

$\boxed{\text{Assuming } R_r \gg Z_0,}$ on resonance:

$$|S_{11}(\text{res})| = \left|\frac{\frac{L_r}{Z_0 R_r C_r} - \frac{1}{x(x+1)}}{\frac{L_r}{Z_0 R_r C_r} + \frac{1}{x(x+1)}}\right|, \quad \text{with } x = \frac{L_c}{L_r}.$$

ratio of $\frac{\text{coupling } L_c}{\text{resonator } L_r}$

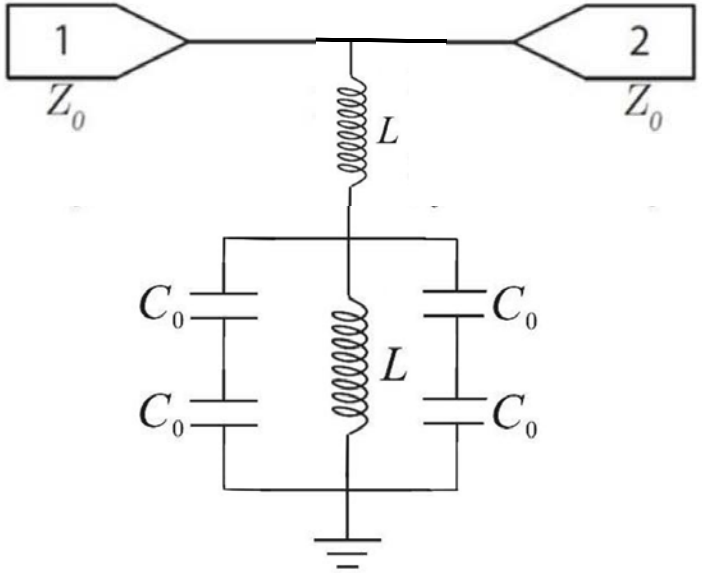
Z: characteristic impedance of resonator

$$= \left|\frac{\boxed{\frac{Z^2}{Z_0}\frac{1}{R_r} - \frac{1}{x(x+1)}}}{\frac{Z^2}{Z_0}\frac{1}{R_r} + \frac{1}{x(x+1)}}\right|.$$

length $\nearrow$ $L_c \nearrow$

diameter $\downarrow$ $L_c \nearrow$

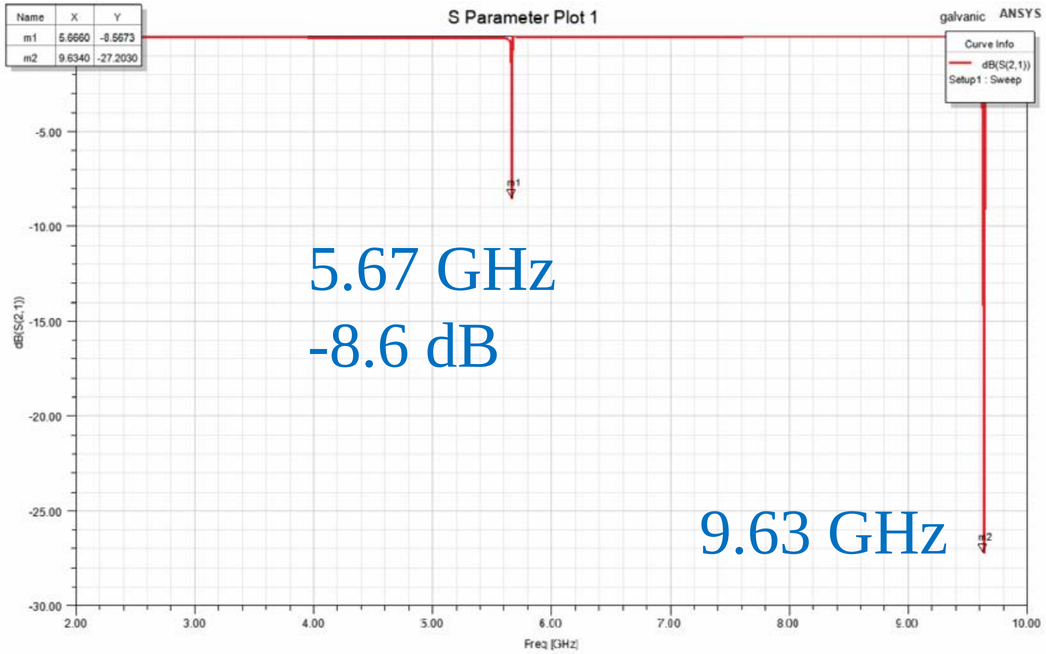
Galvanic coupling model

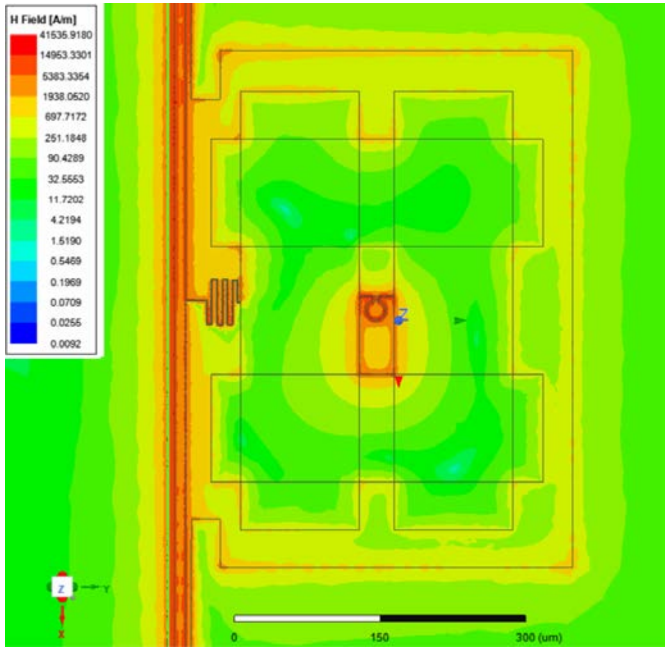


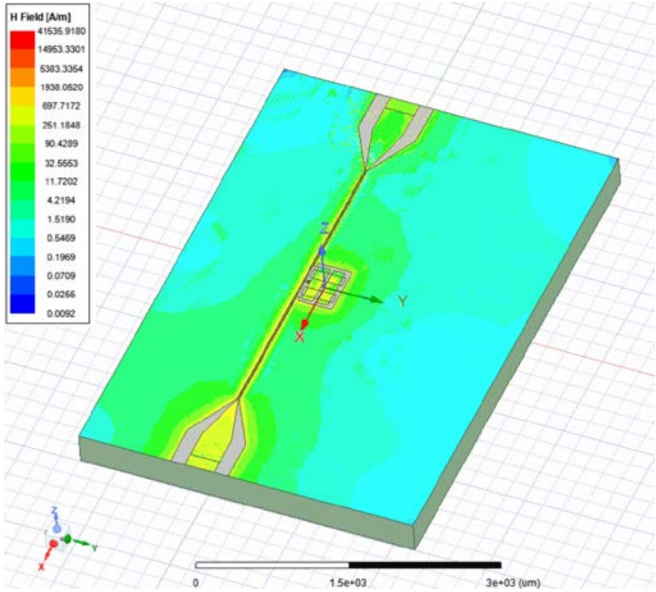
To get critically coupled device, this two terms should be comparable

Galvanic coupling:

- Increased coupling between resonator and TL
- Lower Qe







The reason we get undercoupled device:

Capacitive Coupling

(Maybe) high loss

Easier with moderate loss (High Qi) or small impedance Z

Should increase Cc or lower Z for lossy material (low Qi)

Cc decreased with
small resonator size

Galvanic Coupling

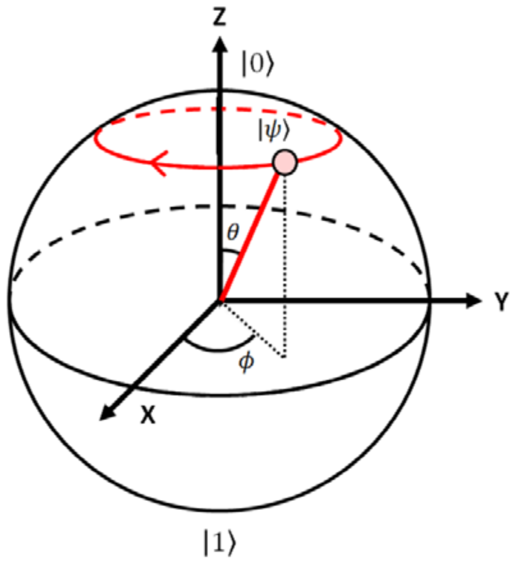
Easier with high loss (low Qi) or high impedance

Should increase Lc or enhance Z for lossy material (low Qi)

Further optimizatioin:

- Galvanic coupling might reduce Qi, or contribute to L_{tot}, need further verification
- If is the case, possible solution might be Purcell filter
- Reduce stray field at corner by butterfly or round shape
- Could further decrease Z

Questions on mind hope to solve next month:



- A full QM description of (pulsed) EPR
- How different components of spins couples to enveloped MW
- What is echo efficiency/sensitivity and what are limiting factors? Why TWPA?
- Why called Rabi frequency? What is transition dipole? Why interaction picture?

Rabi frequency?

$$\omega_1 = -\gamma B_1$$

tip angle