Tunable Couplers for Superconducting Qubits

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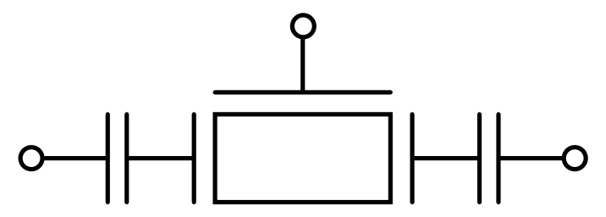
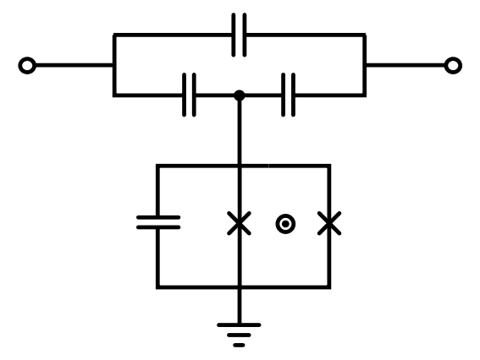
Voltage vs. Flux Biased Couplers

Voltage-controlled coupler



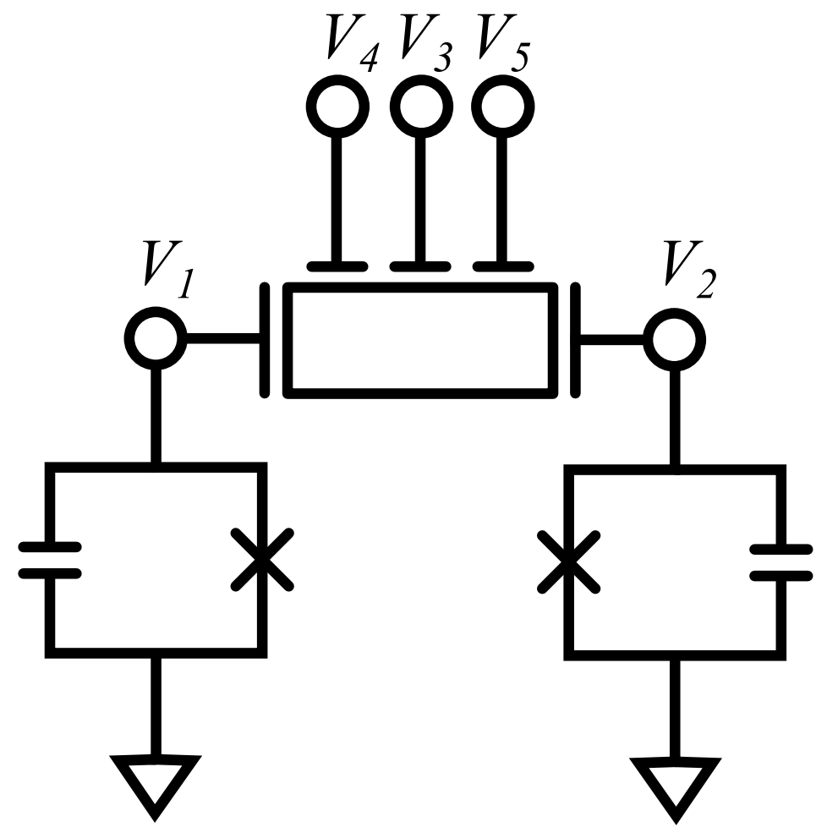
+ 2nd order sensitive to voltage bias
+ No heating introduced by voltage bias
+ Minimal cross-talk expected
- Not part of cQED fab, yet
- Dielectric loss from 2DEG possible

Flux-tunable coupler[1]

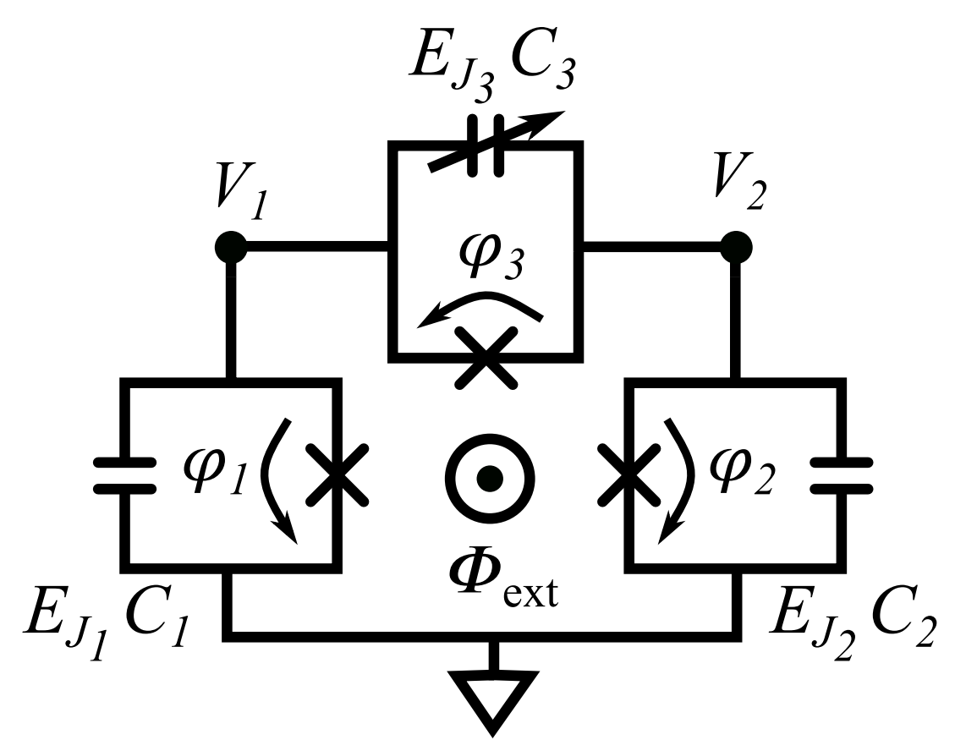


- 1st order sensitive to flux bias
- Current biases can heat system
- Cross-talk from stray magnetic fields
+ Compatible with cQED fab
+ Loss from distributed capacitors

[1] Adapted from J. Martinis, SQuInT 2020

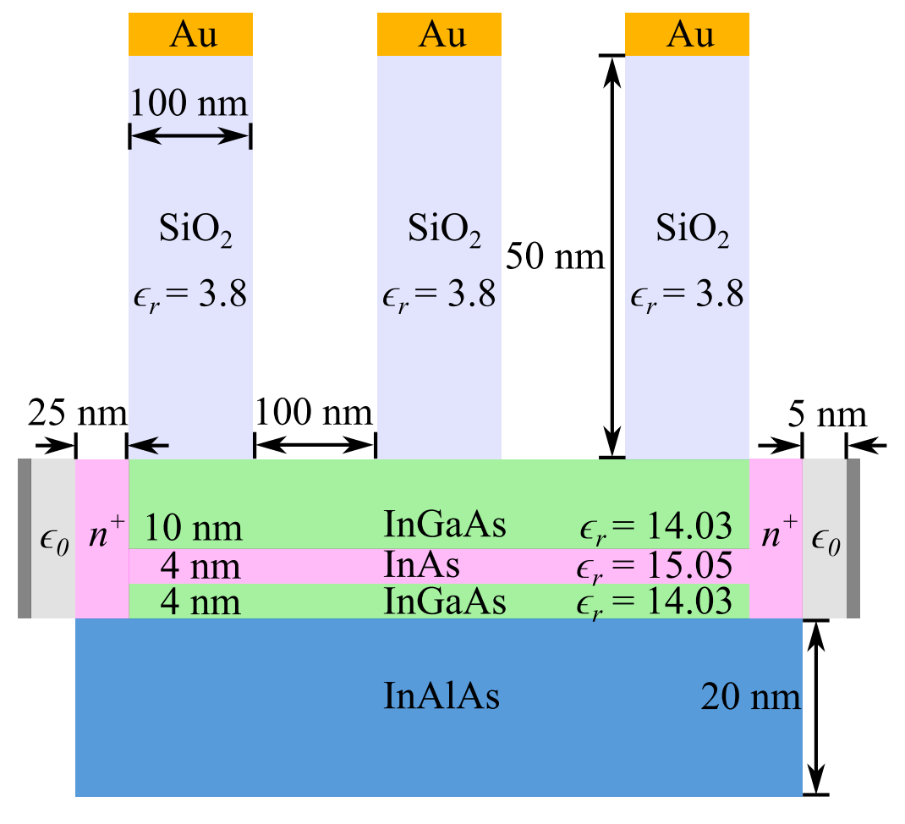


Capacitive Coupler Terminal Labeling

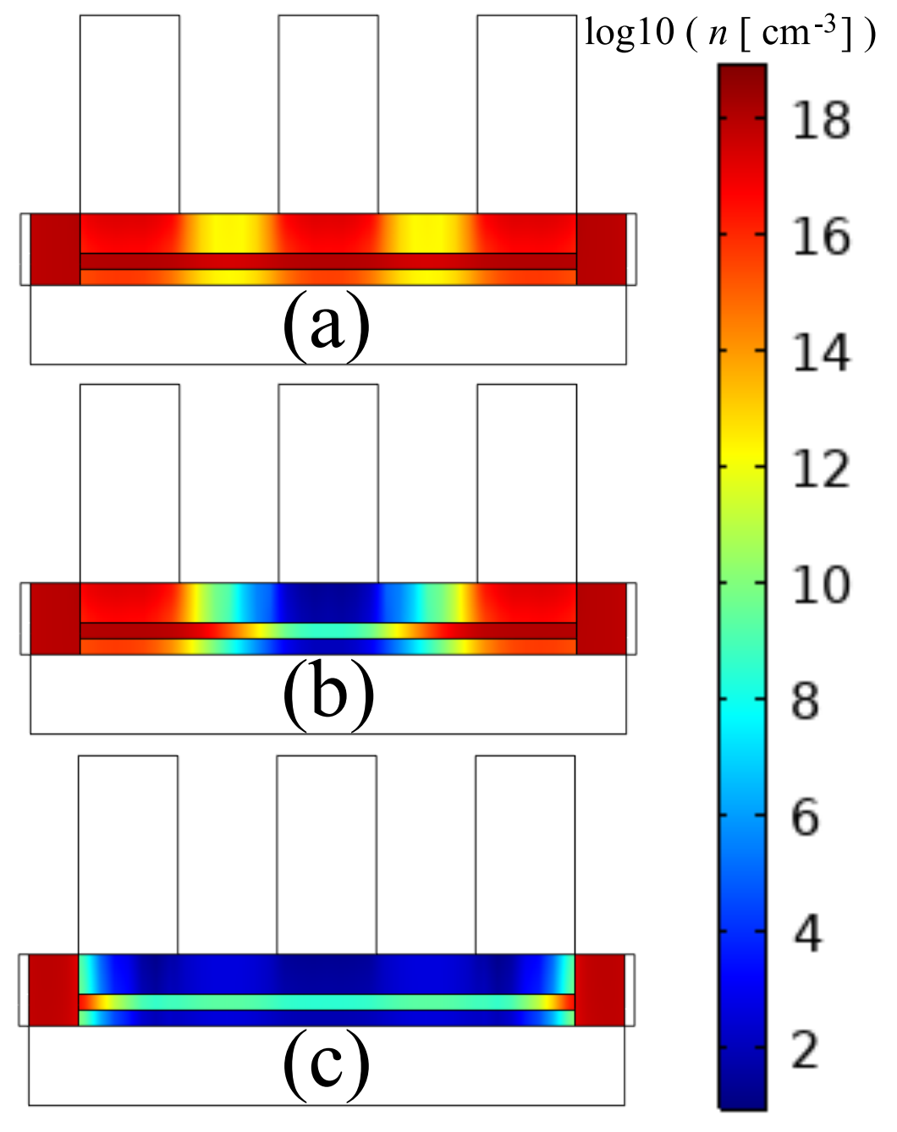


Tunable Coupler Equivalent Circuit

Device Design & Semiconductor Simulations



Materials Stack



COMSOL Electron Densities

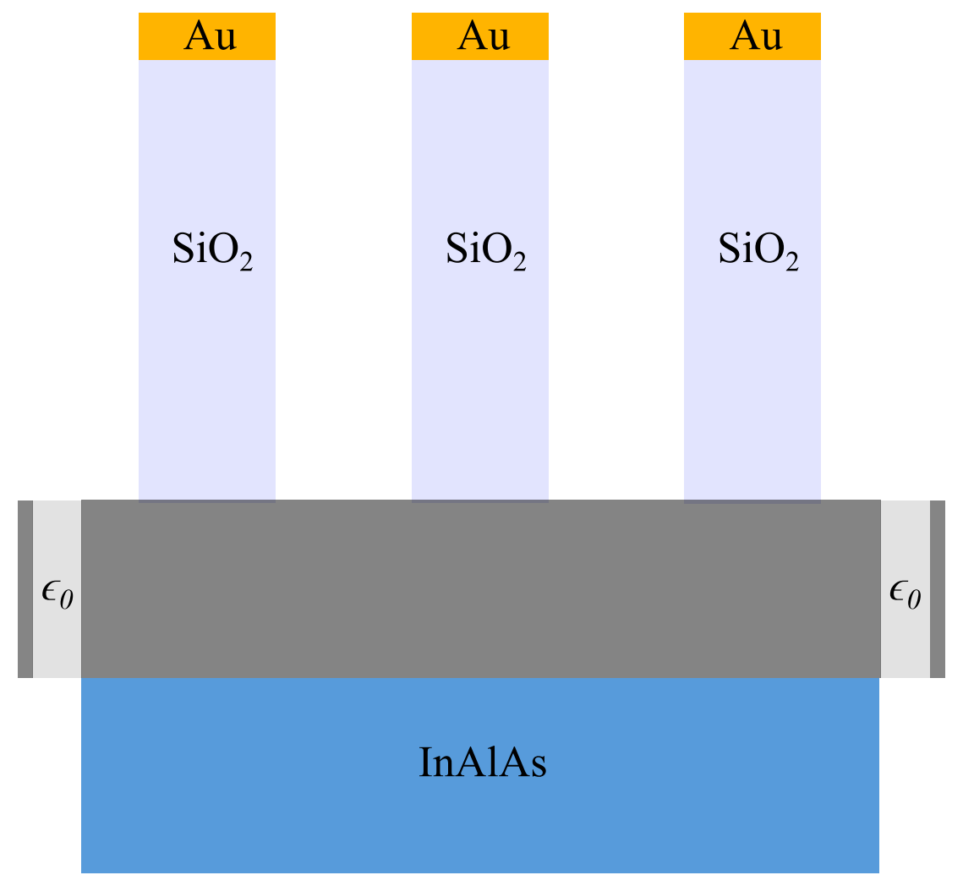
- III-V materials stack based on devices made by the Shabani group at NYU[2]
- Electron densities calculated from equilibrium solutions to the drift-diffusion equations with Fermi-Dirac statistics in COMSOL
- 2DEG confinement included with density gradients modifying the equilibrium electron densities[3]
- Electrostatic charge conservation applied to InAlAs, SiO$_2$, and air-gap dielectric regions
- Electron densities with gate biases (a) 0 V on all gates, (b) -3 V on center gate, 0 V on others, and -3 V on all three gates. Source bias set to 10 mV.
- End-to-end capacitance limited by air-gap capacitors (enlarged to reduce aspect ratio in COMSOL simulations)

[2] [Wickramasinghe et al., Applied Physics Letters **113**, 262104 (2018)]

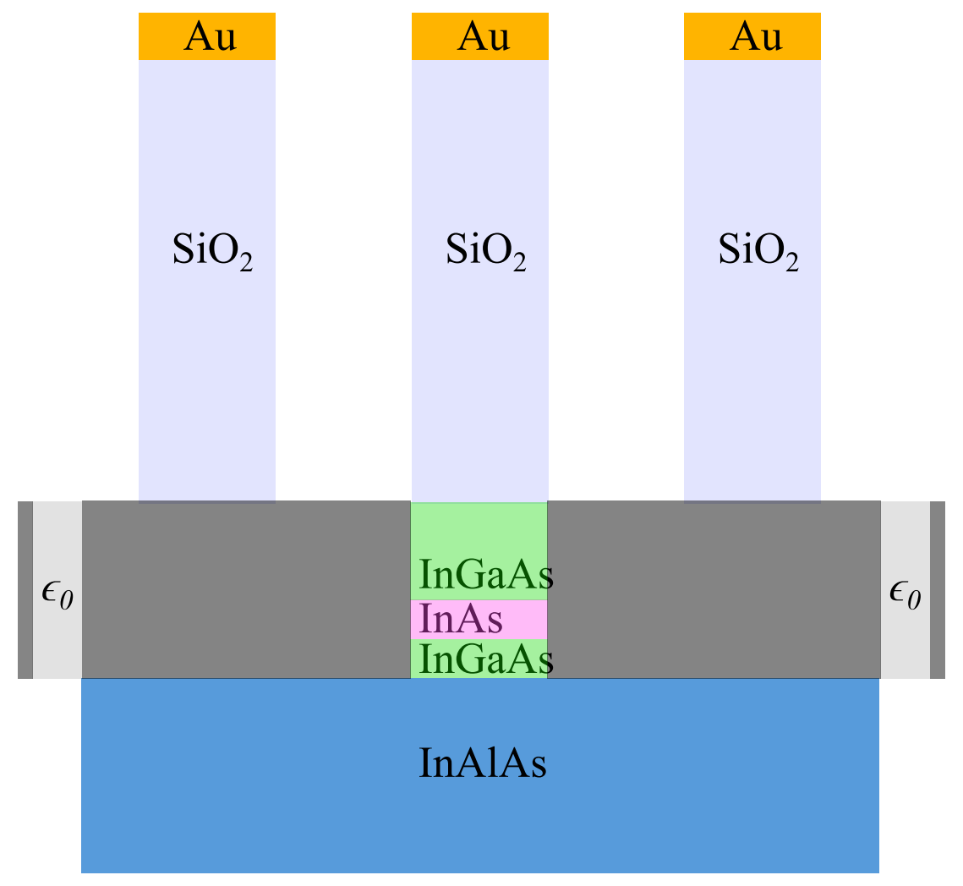
[3] [Ancona, Journal of Computational Electronics **10**, 65 (2011)]

Capacitance & Conductance Matrix Extraction

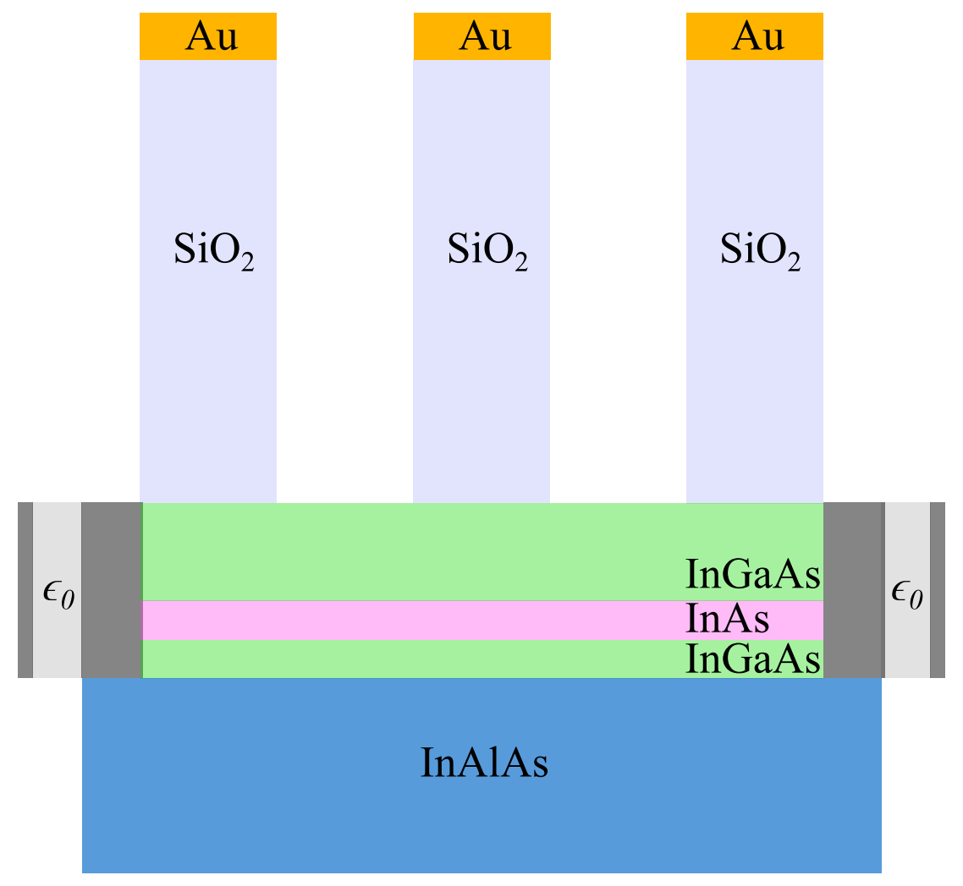
Fully Conducting Limit



Single Gate Depleted



Fully Depleted Limit



- Solve Poisson's equation with the charge continuity equation in 2D

$$-\nabla \cdot d\left(\varepsilon_0 \nabla V - \mathrm{P}\right) = \rho$$

- Extract Maxwell capacitance matrix

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_N \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & \dots & C_{1N} \\ C_{21} & C_{22} & \dots & C_{2N} \\ \vdots & \vdots & & \vdots \\ C_{N1} & C_{N2} & \dots & C_{NN} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{pmatrix}$$

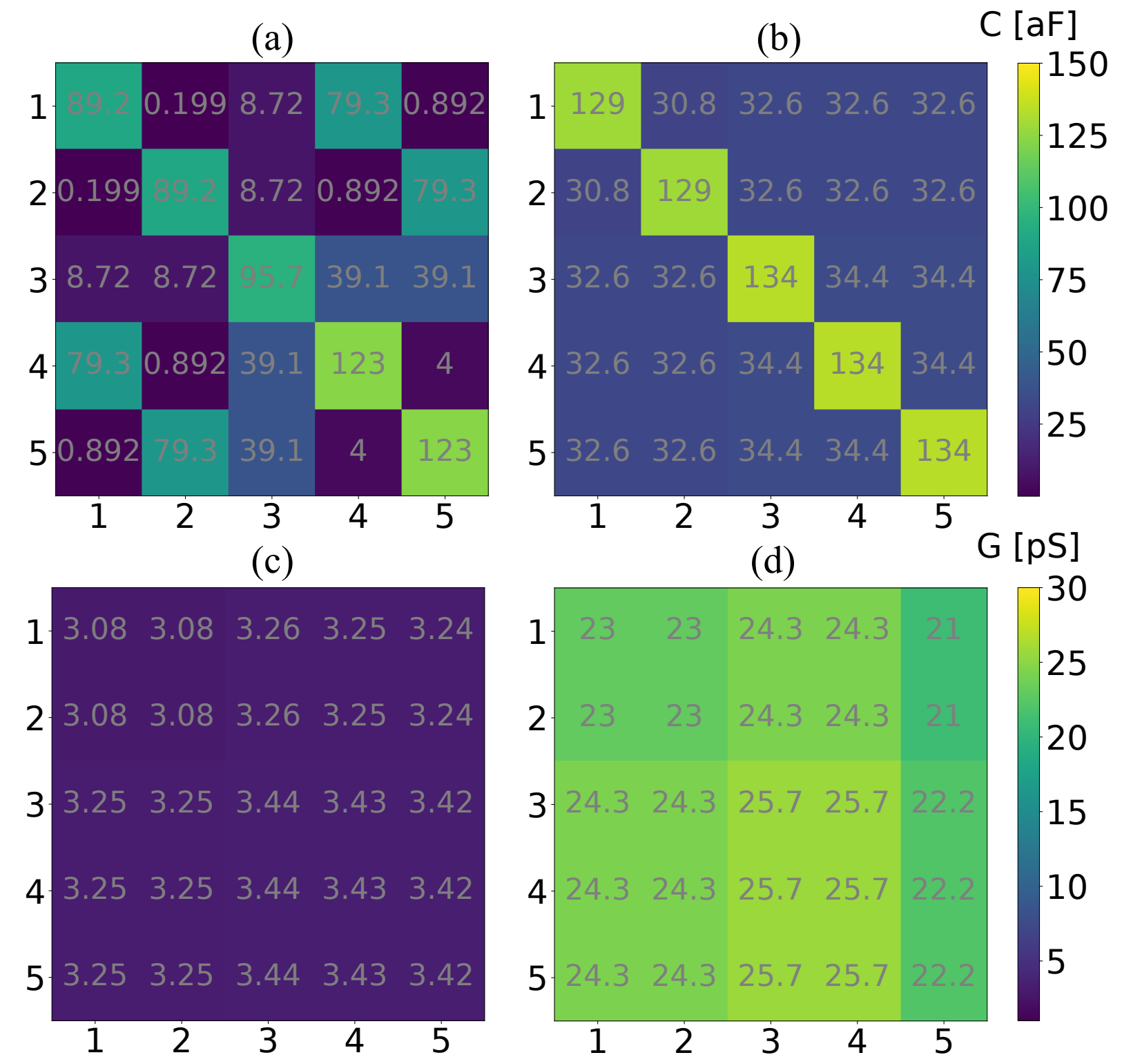
- Solve time harmonic equations

$$\nabla \cdot \left(\sigma \mathrm{E} + \mathrm{J}_e\right) + i\omega\rho = 0, \qquad \nabla \cdot \mathrm{D} = \rho$$

- Use terminal current, voltage solutions to compute admittance matrix, Y

$$\begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} & \dots & Y_{1N} \\ Y_{21} & Y_{22} & \dots & Y_{2N} \\ \vdots & \vdots & & \vdots \\ Y_{N1} & Y_{N2} & \dots & Y_{NN} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{pmatrix}$$

$$\mathrm{Y} = \mathrm{G} + i\omega\mathrm{C}$$



(a)

	1	2	3	4	5
1	89.2	0.199	8.72	79.3	0.892
2	0.199	89.2	8.72	0.892	79.3
3	8.72	8.72	95.7	39.1	39.1
4	79.3	0.892	39.1	123	4
5	0.892	79.3	39.1	4	123

(b)

	1	2	3	4	5
1	129	30.8	32.6	32.6	32.6
2	30.8	129	32.6	32.6	32.6
3	32.6	32.6	134	34.4	34.4
4	32.6	32.6	34.4	134	34.4
5	32.6	32.6	34.4	34.4	134

(c)

	1	2	3	4	5
1	3.08	3.08	3.26	3.25	3.24
2	3.08	3.08	3.26	3.25	3.24
3	3.25	3.25	3.44	3.43	3.42
4	3.25	3.25	3.44	3.43	3.42
5	3.25	3.25	3.44	3.43	3.42

(d)

	1	2	3	4	5
1	23	23	24.3	24.3	21
2	23	23	24.3	24.3	21
3	24.3	24.3	25.7	25.7	22.2
4	24.3	24.3	25.7	25.7	22.2
5	24.3	24.3	25.7	25.7	22.2

Dielectric Loss Estimation

- Estimation of dielectric loss-limited T_1[4,5]

$$T_1^{-1} = \frac{\omega}{Q} = \omega \sum_j \frac{p_j}{Q_j} + \Gamma_0$$

$$Q_j^{-1} = \tan\delta_j$$

$$p_j = \frac{t_j \varepsilon_{1,j} \int_{S_j} |\mathrm{E}|^2\, dS}{\int_V |\mathrm{E}|^2 dV}$$

- III-V loss tangents approximated with GaAs[6]
- Limited by SiO$_2$, pending measurement of III-Vs

	t_j [nm]	p_j	$\tan\delta_j$	T_1 [μs]
InGaAs	10	2.08E-5	4.8E-5	3190
InAs	4	3.18E-5	4.8E-5	20800
InGaAs	4	2.86E-5	4.8E-5	23200
InAlAs	20	5.64E-4	4.8E-5	1180
SiO$_2$[7]	50	4.44E-3	2.00E-3	3.58
Total	-	-	-	3.57

[4] [Wenner et al., Applied Physics Letters **99**, 113513 (2011)]

[5] [Wang et al., Applied Physics Letters **107**, 162601 (2015)]

[6] [McRae et al., arXiv e-prints, arXiv:2009.10101 (2020)]

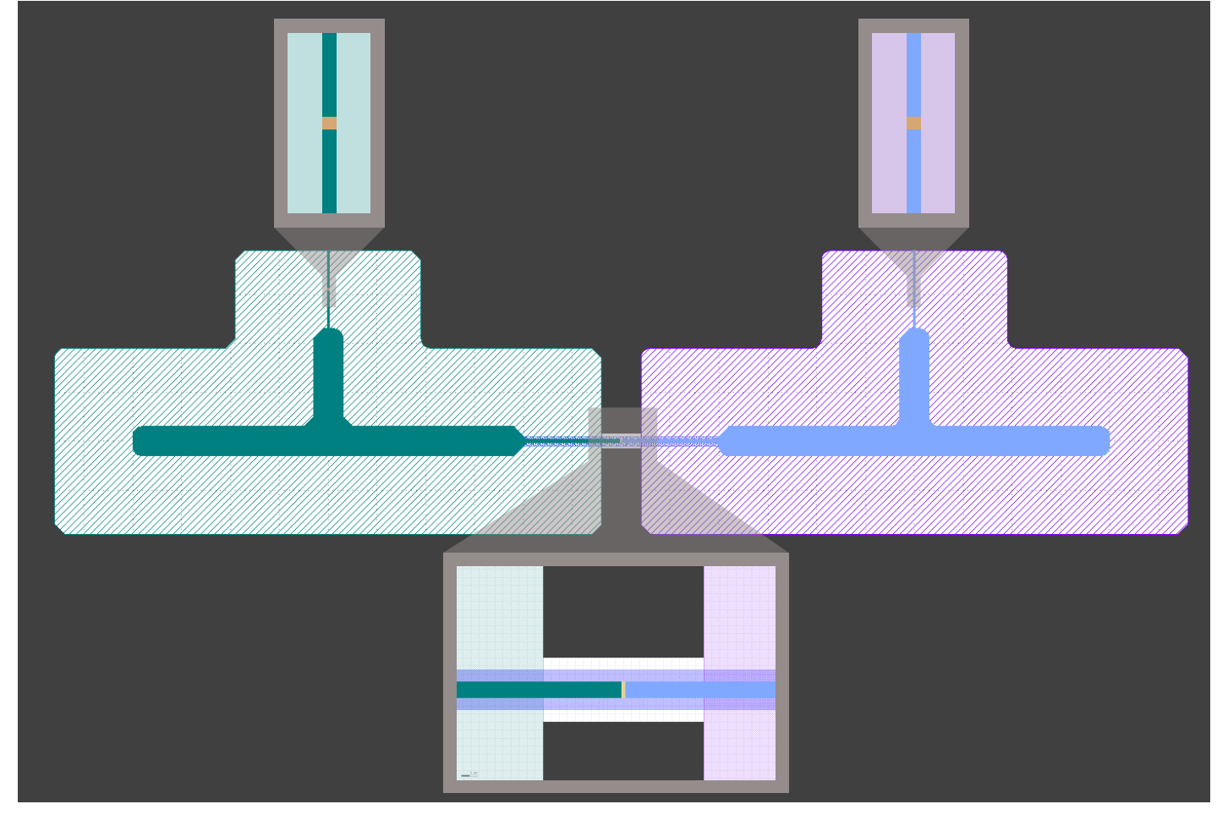
[7] [Li et al., IEEE Transactions on Applied Superconductivity **23**, 1501204 (2013)]

EPR & Exchange Interaction Matrix Elements

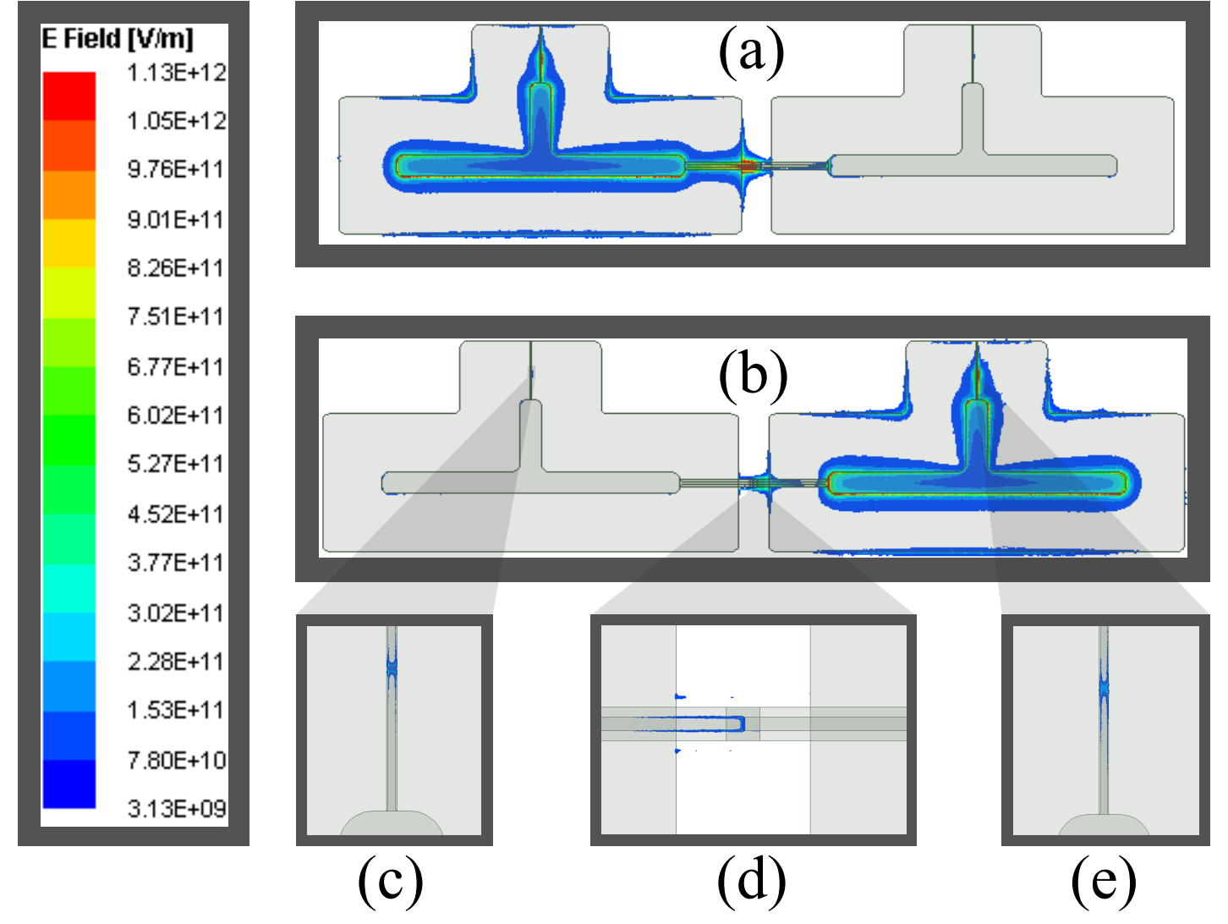
EPR Matrix Elements

Mode No.	$\omega/2\pi$ [GHz]	Q		$\chi/2\pi$ [MHz]	
1 (d)	5.667	4.5E8	**226**	62.5	0.965
2 (d)	5.838	1.3E9	62.5	**226**	1.11
3 (d)	8.614	1.8E13	0.965	1.11	**0.002**
1 (c)	5.669	4.5E8	**223**	67.1	0.974
2 (c)	5.840	1.3E9	67.1	**223**	1.12
3 (c)	8.612	1.8E13	0.974	1.12	**0.002**

HFSS Model with Lumped Element Insets



HFSS Eigenmode Solutions



Exchange Interaction Matrix Elements

Qubit Index	Matrix Elements	[MHz]
1 (d)	226	**0.0005**
2 (d)	0.0005	226
1 (c)	226	**0.079**
2 (c)	0.079	226

- HFSS Eigenmodes → EPR → Matrix Elements[8,9]
- Josephson junction inductances, capacitances as inputs
- Coupler modeled as lumped element capacitor
- Parametric sweep over the coupler capacitance to extract self- and cross-Kerr matrix elements
- Retain anharmonicities for exchange interaction matrix elements
- Extract exchange $Q_i Q_j$ interaction matrix elements $C^{-1}/2$ from[10,11]

$$H = \frac{1}{2}\mathrm{Q}^T C^{-1}\mathrm{Q} + \sum_j E_{J_j}\left(1 - \cos\varphi_j\right)$$

$$C = \begin{pmatrix} C_1 + C_3 & -C_3 \\ -C_3 & C_2 + C_3 \end{pmatrix}$$

$$C_k = \frac{e^2}{2E_C} \simeq -\frac{e^2}{2\alpha_k} = -\frac{e^2}{2\chi_{kk}}$$

- Exchange interaction matrix elements recover ≈160 on/off ratio

[8] [Minev, arXiv e-prints, arXiv:1902.10355 (2019)]

[9] [Minev et al., arXiv e-prints, arXiv:2010.00620 (2020)]

[10] [Orlando et al., Phys. Rev. B **60**, 15398 (1999)]

[11] [Koch et al., Phys. Rev. A **76**, 042319 (2007)]

Future Work

- Finish experimental measurements of loss in III-V materials
- Begin testing tunable resonators with voltage-controlled III-V stack
- Fabricate and measure two qubits coupled by the III-V 2DEG coupler

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