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Parameter extraction from electromagnetic eigenmode simulations of multimodal cavities using MFEM

Christopher Eyre, Ryan Camacho, Keith Cartwright

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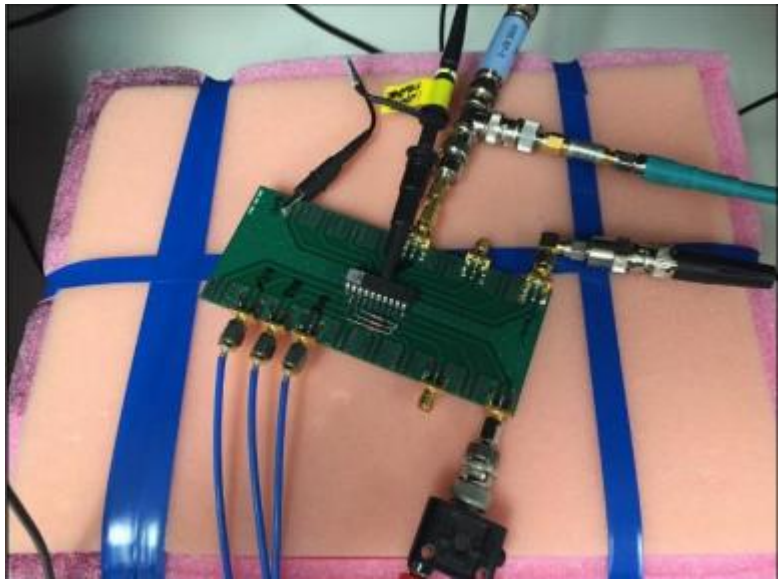
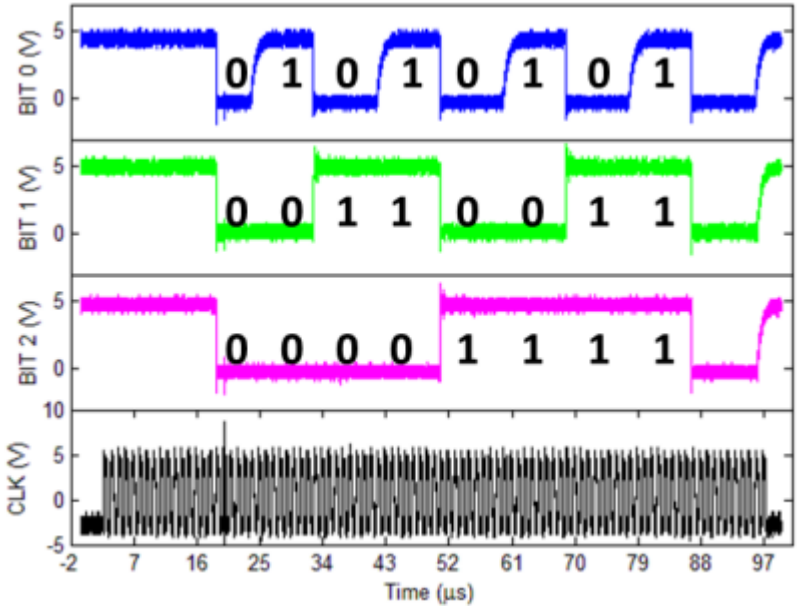
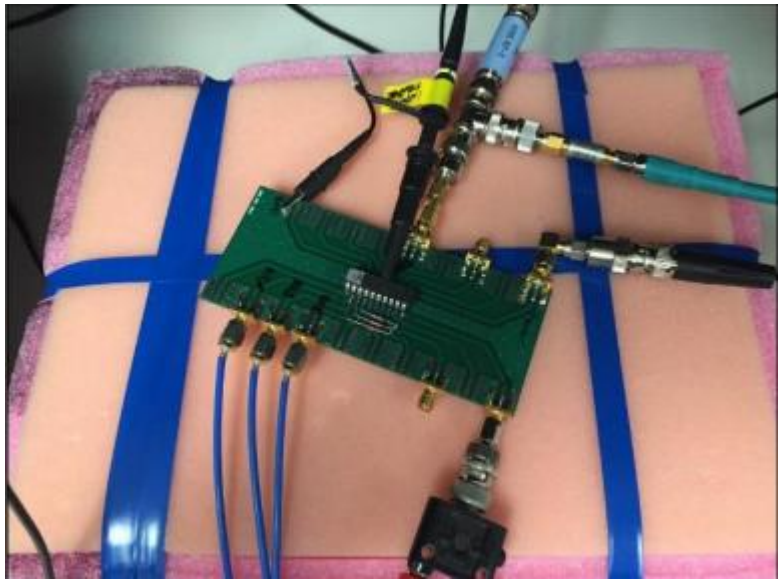
Motivation

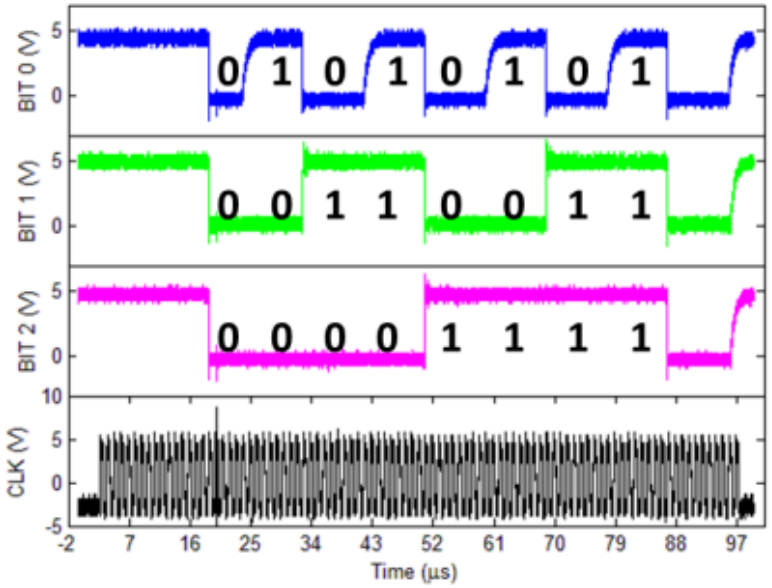




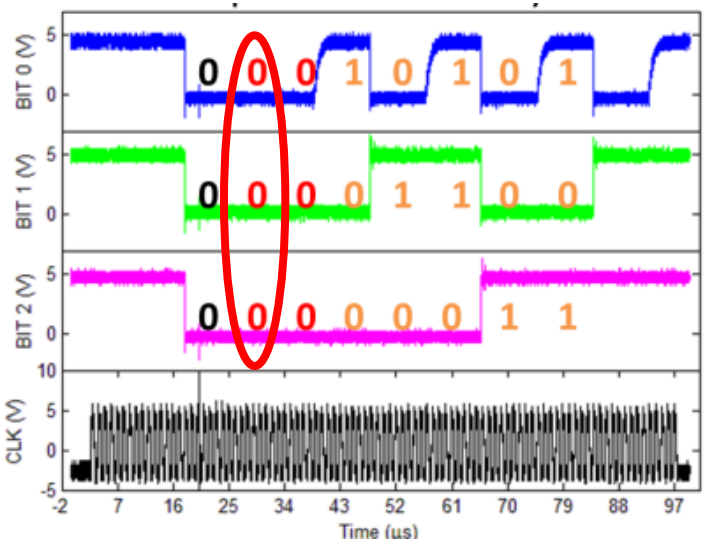
Images copied from:
Guillette, D., & Clarke, T. (2019). *Intentional electromagnetic irradiation on a microcontroller: Review of upset variation with respect to chip instance.* Air Force Research Lab.

Motivation





Bit Flip!!!!



Images copied from:
Guillette, D., & Clarke, T. (2019). *Intentional electromagnetic irradiation on a microcontroller: Review of upset variation with respect to chip instance.* Air Force Research Lab.

We want to model circuits that are inside cavities

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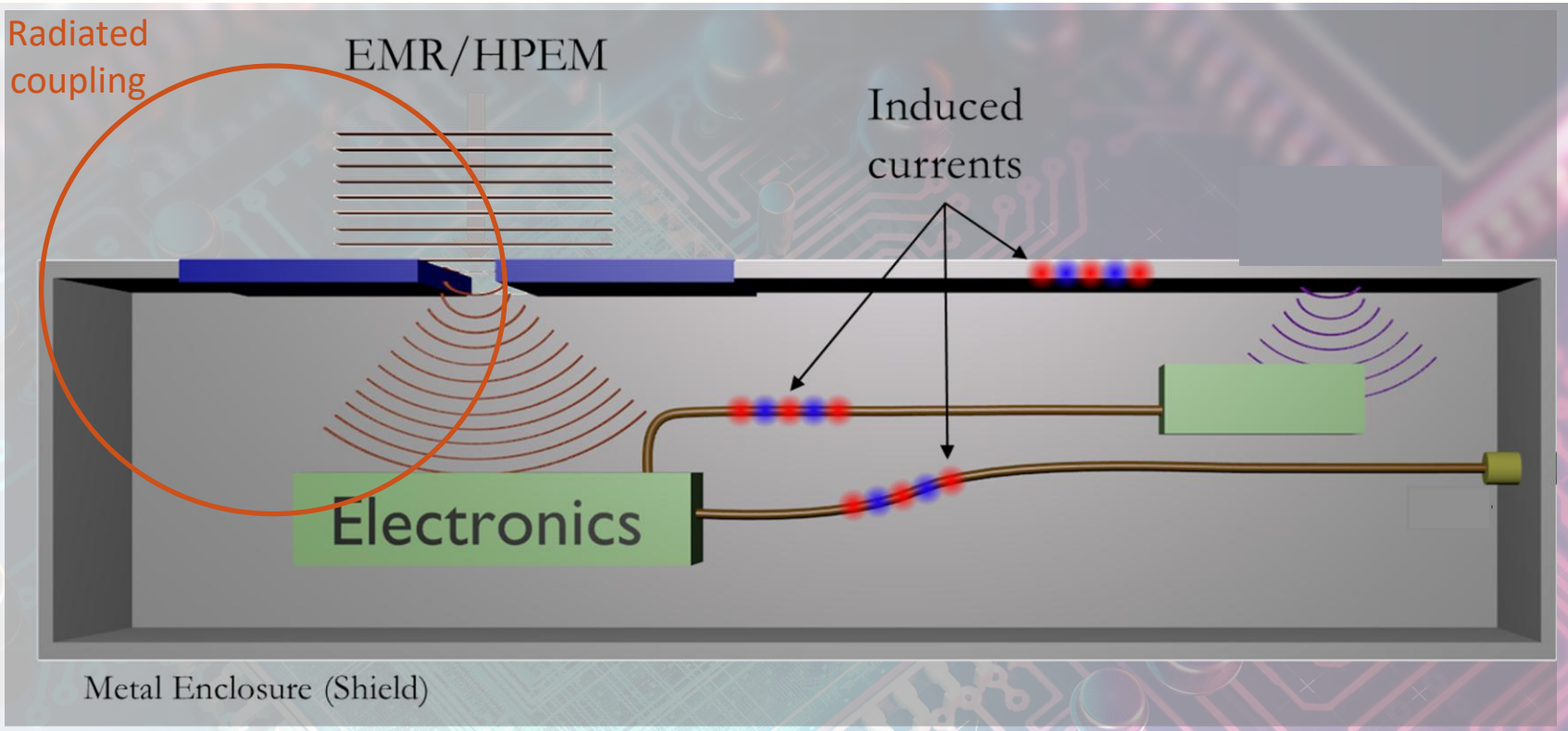
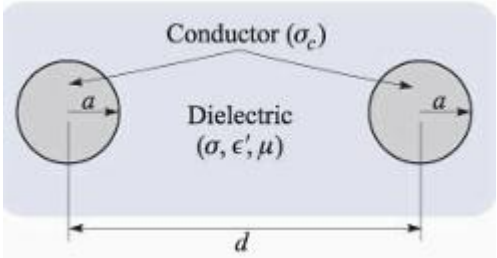
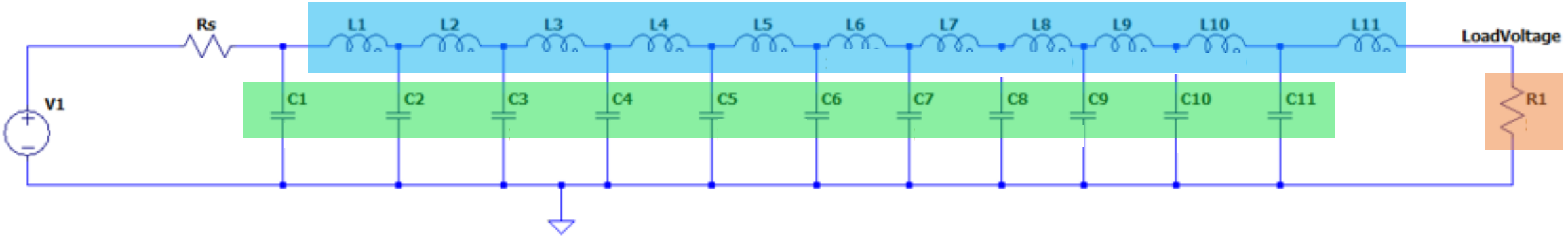


Circuit simulator for Transmission line

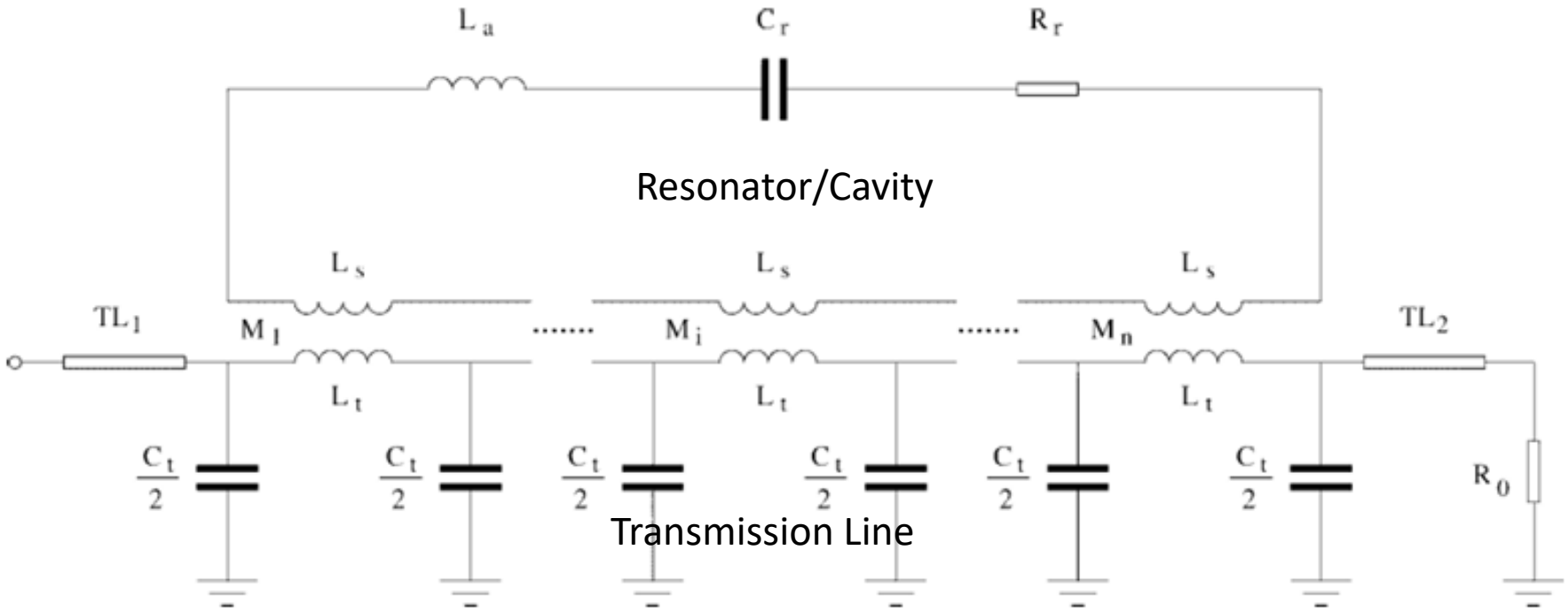


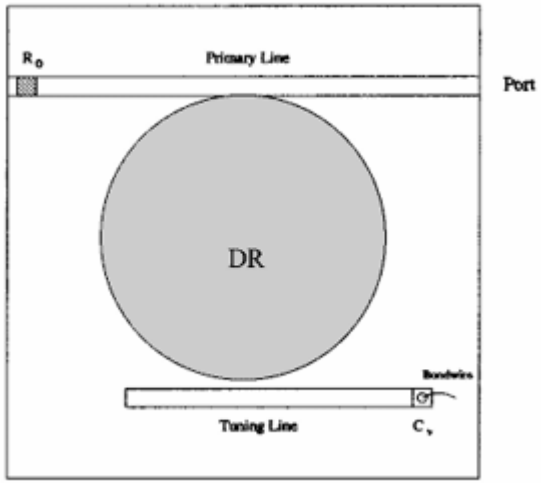


Circuit Modeling done in LTSPICE (M. Engelhardt, LTspice/SwitcherCAD III, Linear Technology Corporation, 2024)
Two wire cross section from Hayt, William, and John Buck. "Engineering electromagnetics." (2012).

Distributed Coupling

$$\Phi_m = \iint_\Sigma \mathbf{B}\cdot\mathbf{dS} \quad \Phi_d = \iint_\Sigma \mathbf{D}\cdot\mathbf{dS} \quad I = 2\pi f_r \Phi_d \quad M = \Phi_m / I \quad L_r = W/I^2 \quad C_r = \frac{1}{(2\pi f_r)^2 L_r}$$





X. Xu and R. Sloan, “Distributed Coupling Model of the Dielectric Resonator to Microstrip Line” IEEE Microwave and Guided Wave Letters, 9, 348-350, 1999.

X. Xu and R. Sloan, "Improved tuning prediction for the microstrip coupled dielectric resonator using distributed coupling," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 3, pp. 553-555, March 2001

Modelling Coupling in a Circuit Simulator

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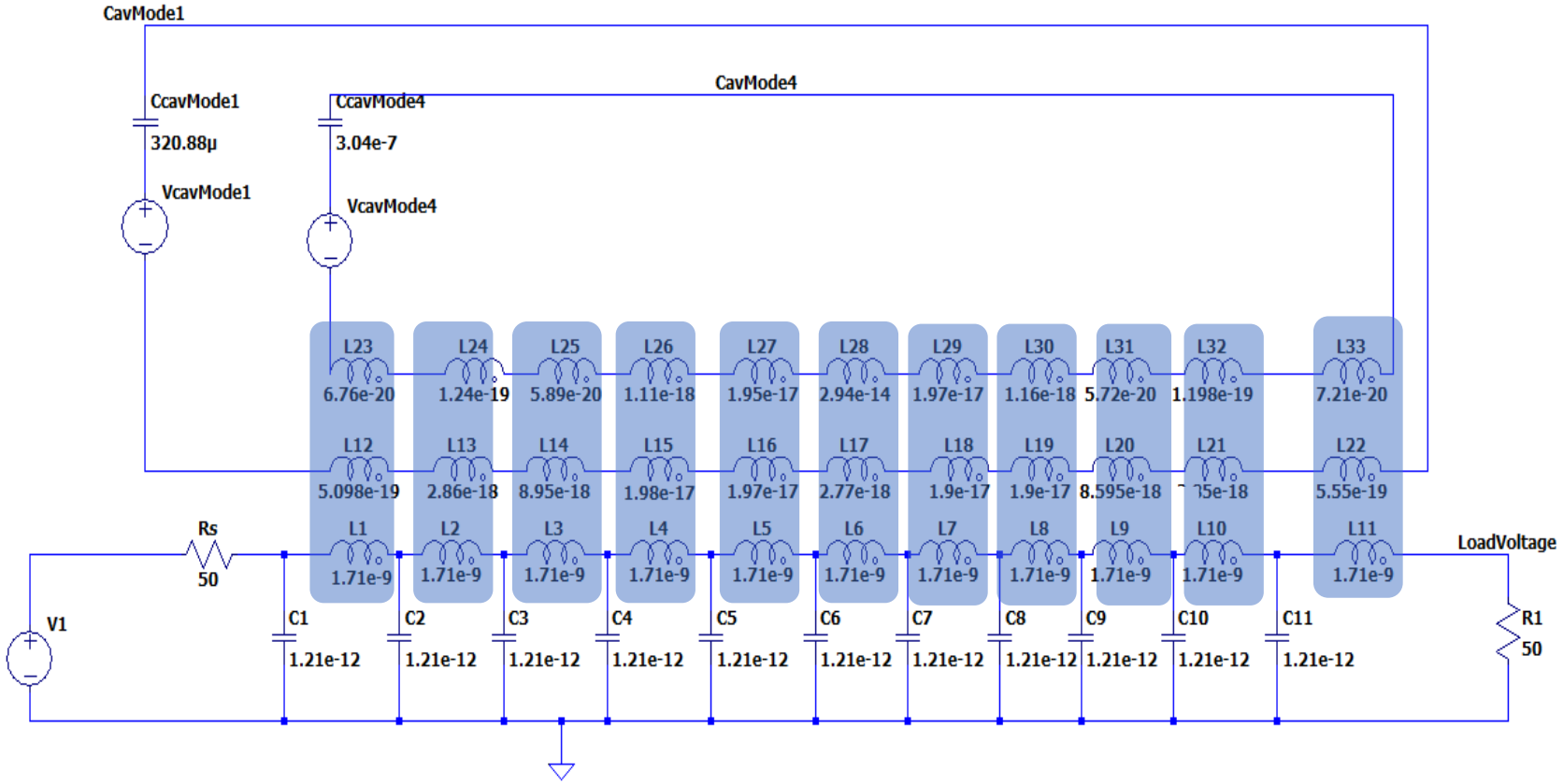
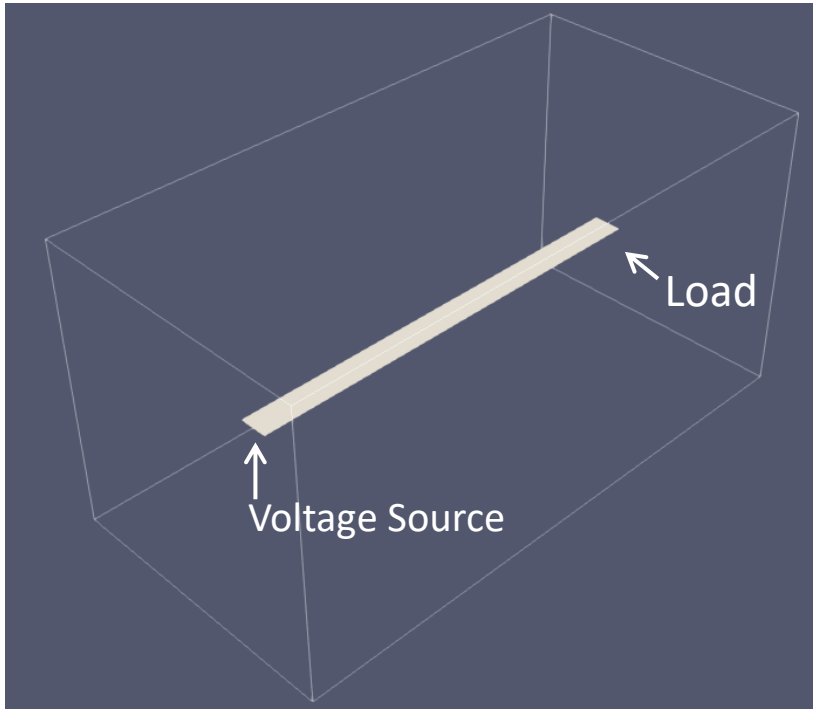
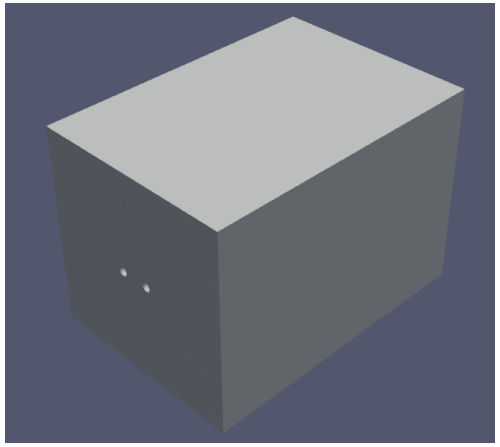


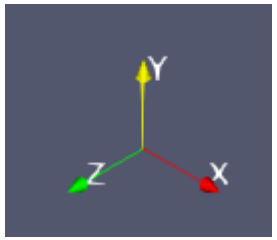
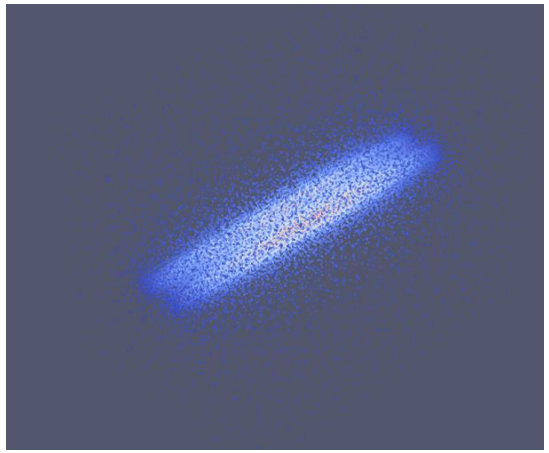
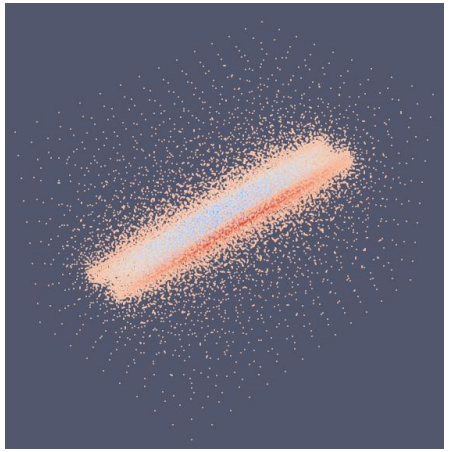
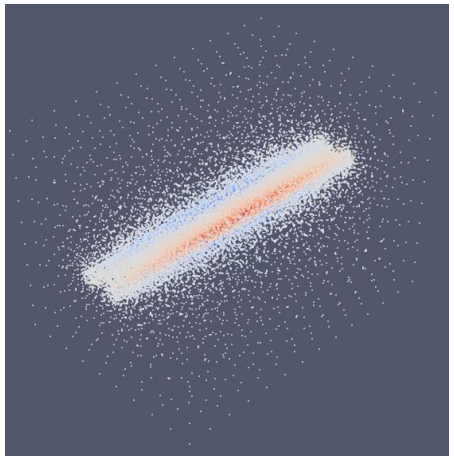
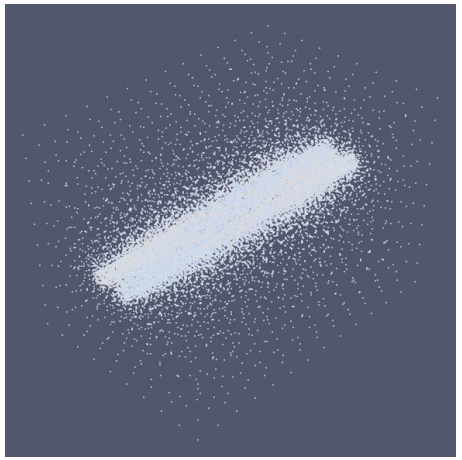


Circuit Modeling done in LTSPICE (M. Engelhardt, LTspice/SwitcherCAD III, Linear Technology Corporation, 2024)

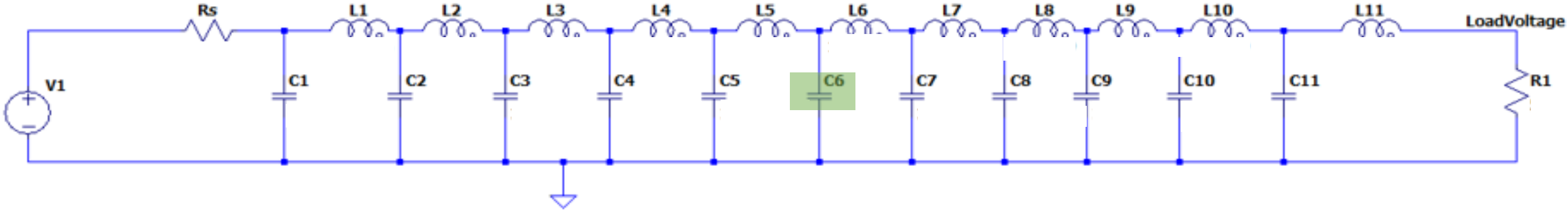
Eigenmodes from MFEM example 13

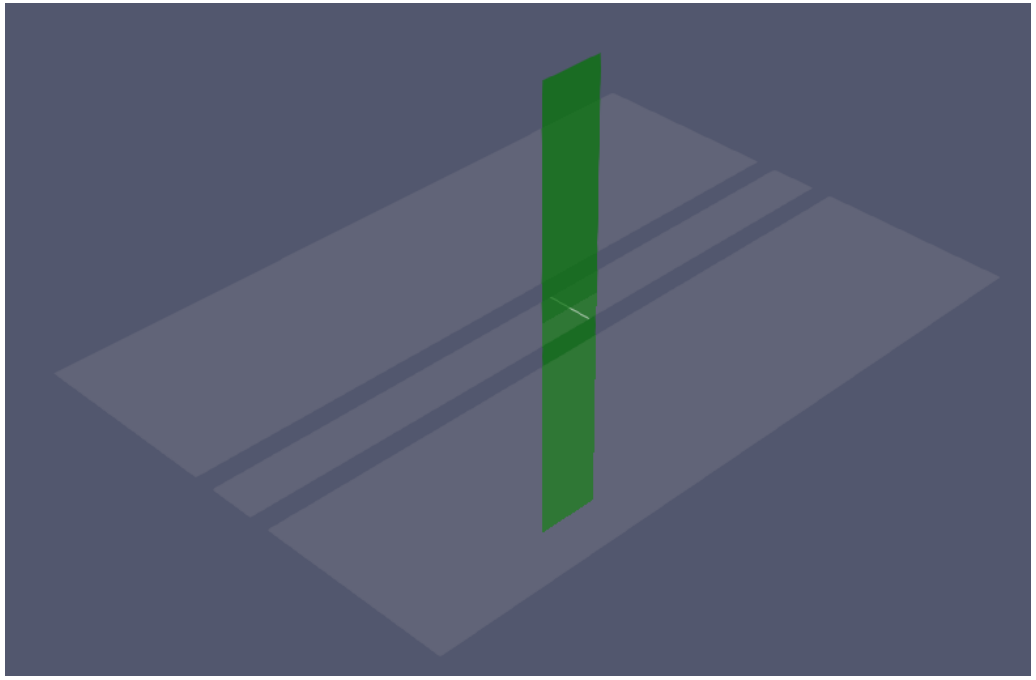


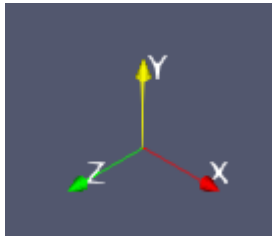
$$\nabla \times \nabla \times E = k^2 E \qquad \omega = ck = c\sqrt{\lambda}$$

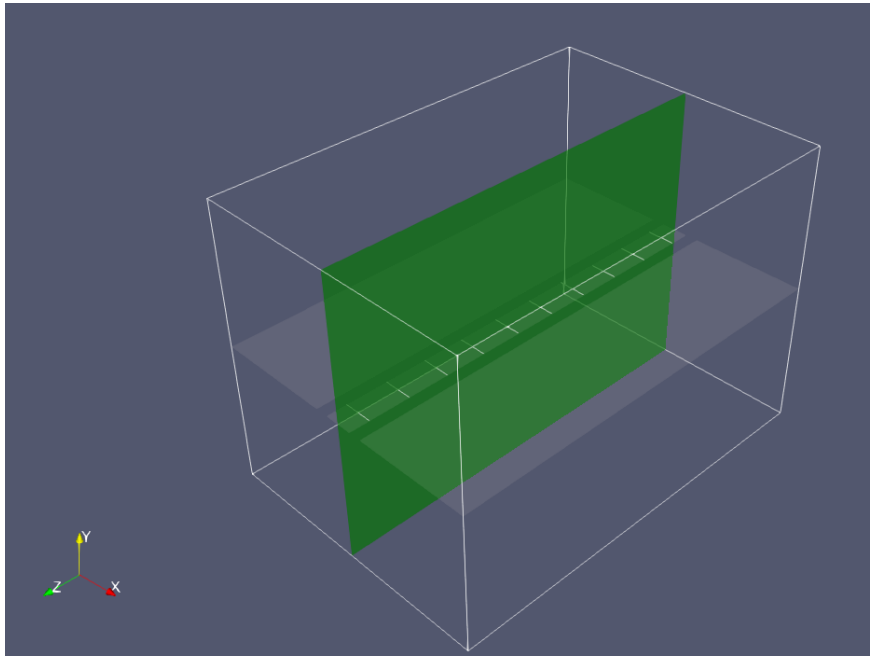
	Magnitude	Efield in X	Efield in Y	Efield in Z
 Mode 0 – Eigenfrequency: 14.9e+6 Hz				

Simulations done in MFEM (R. Anderson et.al. Computers & Mathematics with Applications, 81, 42-74, 2021)
and plotted with Paraview (Ahrens, James, Geveci, Berk, Law, Charles, *ParaView: An End-User Tool for Large Data Visualization*, Visualization Handbook, Elsevier, 2005, ISBN-13: 9780123875822)

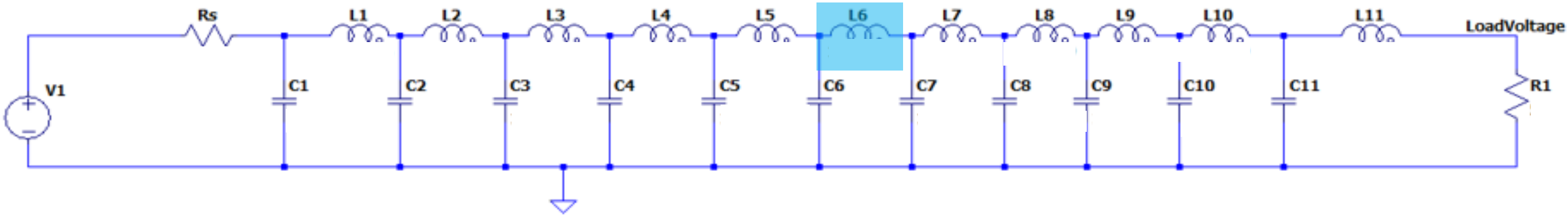








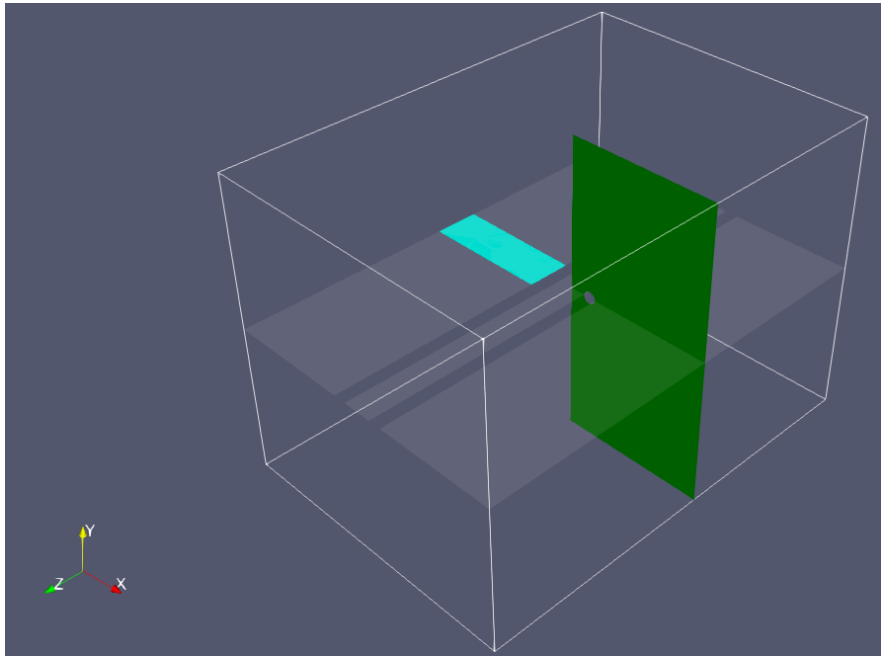
$$\text{Capacitance} = \frac{Q}{V} \rightarrow \frac{\iint \epsilon \boldsymbol{E} \cdot d\boldsymbol{S}/L}{\oint \boldsymbol{E} \cdot d\boldsymbol{\ell}}$$

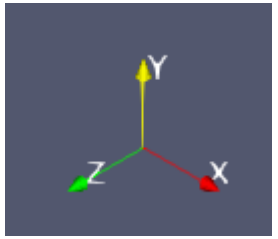


$$\text{Mutual Inductance} = \frac{\Phi_m}{I}$$

$$\rightarrow \frac{\iint \boldsymbol{B} \cdot d\boldsymbol{S}/L}{\oint \boldsymbol{B} \cdot d\boldsymbol{\ell}} \rightarrow \frac{\iint \boldsymbol{B} \cdot d\boldsymbol{S}/L}{i\omega\mu_0\epsilon \iint \boldsymbol{E} \cdot d\boldsymbol{A}}$$

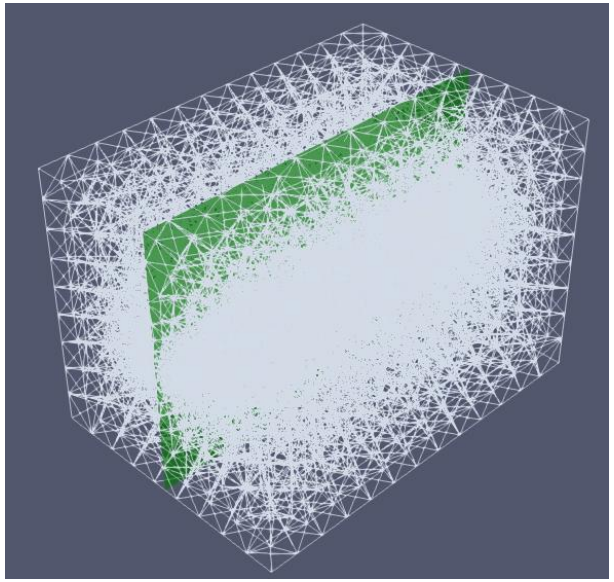
$$\boldsymbol{B} = \frac{-j}{\omega} \nabla \times \boldsymbol{E}$$

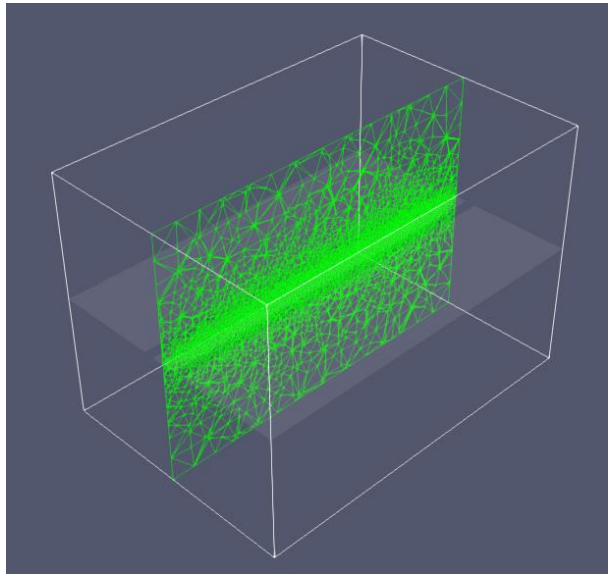


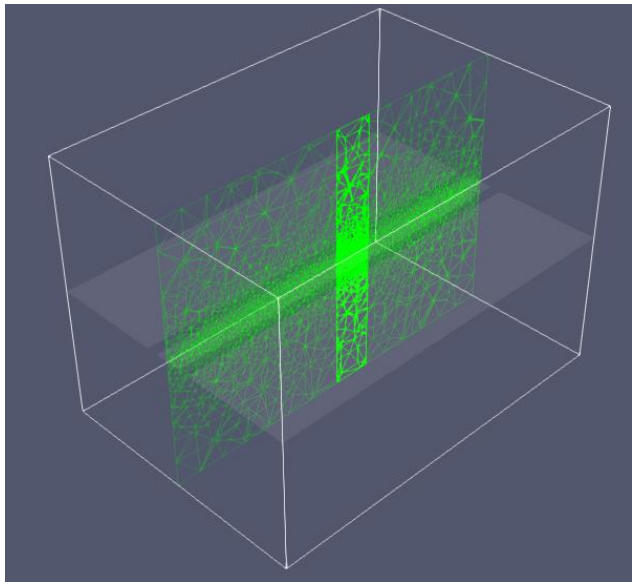


Integration Attempts

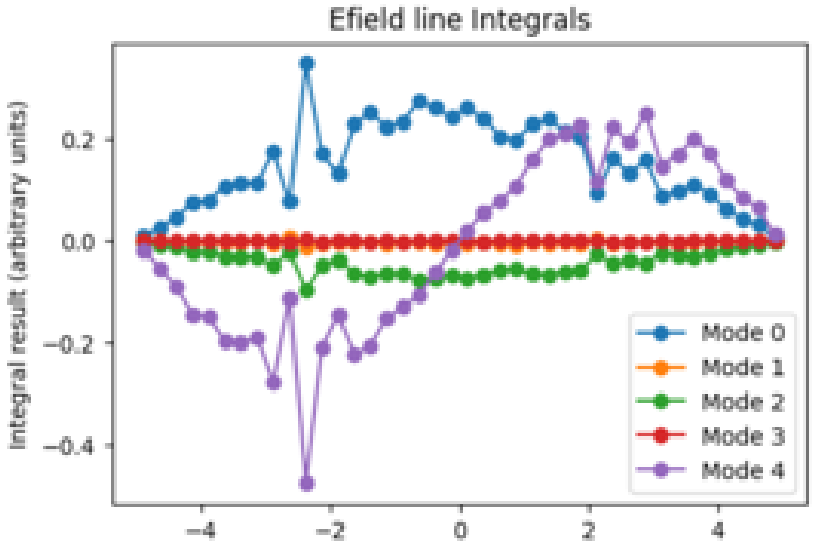
- Monte Carlo integration
  - Takes around 15 minutes per integral with 10,000 points on me
- Quadrature integration (my implementation)
  - Takes about 2 minutes per integral
- (Potential alternative) intrules_cut methods provided by MFEM

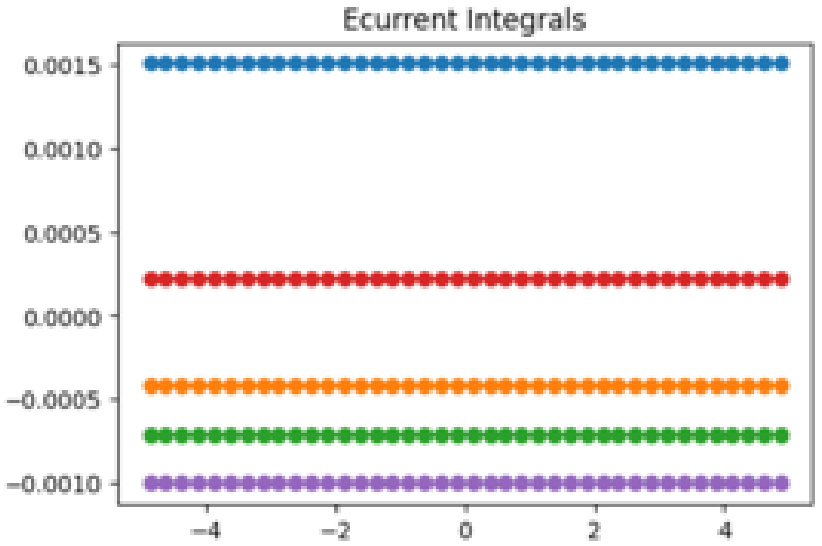


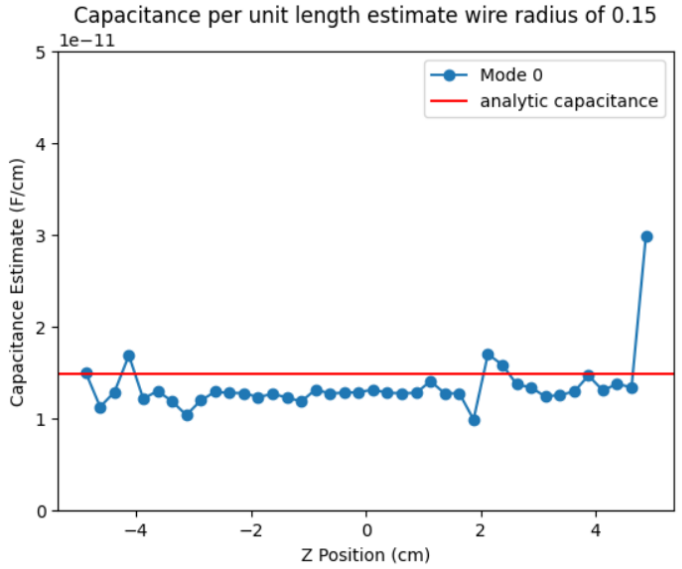




Results – Capacitance







$$\text{Capacitance} = \frac{Q}{V} \rightarrow \frac{\iint \epsilon \boldsymbol{E} \cdot d\boldsymbol{S}/L}{\oint \boldsymbol{E} \cdot d\boldsymbol{\ell}}$$

Analytic Capacitance: 2.531944e-11

Results – Inductance

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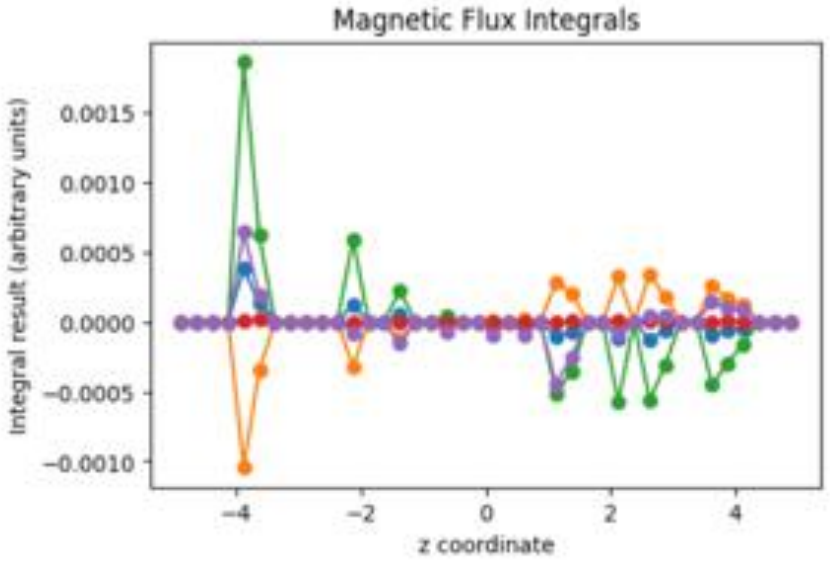

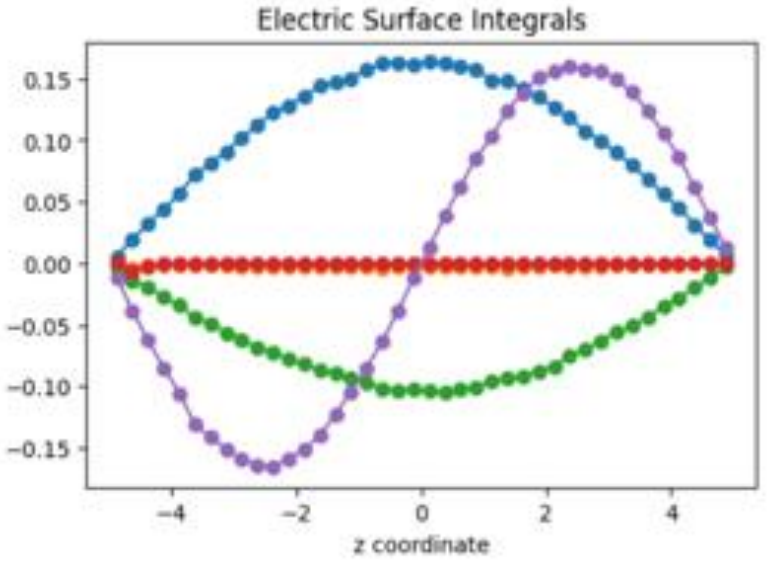

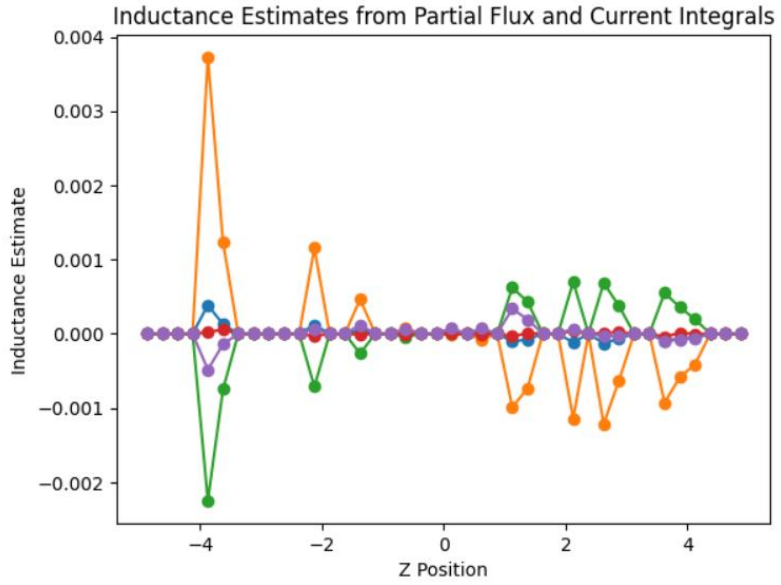

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```
Analytic Inductance: 5.394449e-07
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Dielectric

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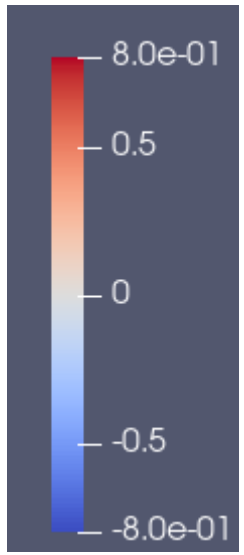
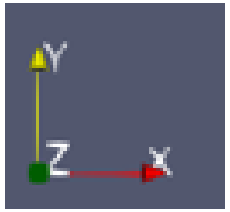
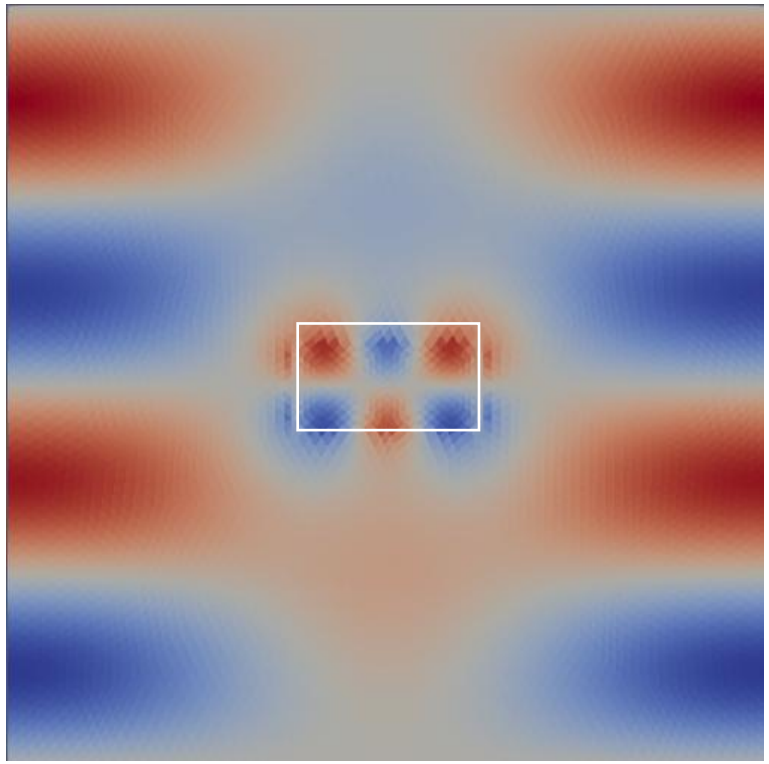
$$\nabla \times \nabla \times E = k^2 \epsilon E$$

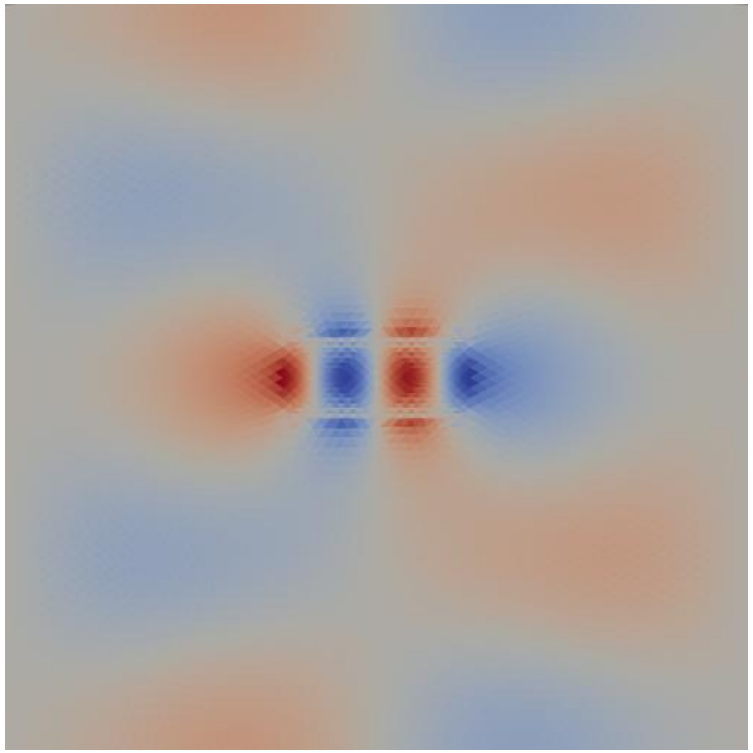
X component

Y component









Thank-you

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