HFSS OVERVIEW

User perspective on computational electromagnetics

Motivation | The basic problem | Demos

Who Am I?

- School at The Ohio State University
  - BS Physics, BS ECE, MS ECE
  - Currently UCSB Physics PhD student
- Engr. at Lake Shore Cryotronics
  - **Microwave EM/satellite hardware**
  - **Terahertz physics/metamaterials**
  - Numerical micromagnetics
  - Analog design
  - GaN semiconductor devices

WHY STUDY CEM?

- Impact scale
  - Estimated ~$5e9 industry value
  - HFSS R18.1 cost companies ~70e3/seat
  - RCS simulations of a real M1 Abrams can take a month on a supercomputer
- Learn now!
  - Involved math/physics are deep & profound
  - Leverage lots of hours of research to help your project

*Global Simulation & Analysis Software Market, By Product Type (Finite Element Analysis, Computational Fluid Dynamics, etc.), By End Use Industry (Automotive, Aerospace & Defense, etc.), By Region Competition Forecast and Opportunities, 2012 – 2022; Apr. 2017

Computational Electromagnetics

Time Harmonic Form

$$\begin{cases} \nabla \times \mathbf{E} = -\jmath\omega\mu_0 \boxed{\overline{\overline{\mu}}_r}\mathbf{H} \\ \nabla \times \mathbf{H} = \jmath\omega\epsilon_0 \boxed{\overline{\overline{\epsilon}}_r}\mathbf{E} + \sigma\mathbf{E} + \mathbf{J}^{\mathbf{imp}} \end{cases} \text{in } \Omega$$

$$\begin{cases} \nabla \times \mathbf{E} = -\jmath\omega\mu_0 \mathbf{H} \\ \nabla \times \mathbf{H} = \jmath\omega\epsilon_0 \mathbf{E} \end{cases} \text{in } \mathcal{R}^3 \backslash \Omega$$

$$\boxed{\lim_{|\mathbf{x}|\to\infty} |\,\mathbf{x}\,| \left\{ \nabla \times \mathbf{E} + \jmath k \mathbf{E} \right\} = 0}$$

Time Varying Form

$$\begin{cases} \nabla \times \mathbf{E} = -\mu_0 \dfrac{\partial}{\partial t} \overline{\overline{\mu}}_r \mathbf{H} \\ \nabla \times \mathbf{H} = \epsilon_0 \dfrac{\partial}{\partial t} \overline{\overline{\epsilon}}_r \mathbf{E} + \sigma\mathbf{E} + \mathbf{J}^{\mathbf{imp}} \end{cases} \text{in } \Omega$$

$$\begin{cases} \nabla \times \mathbf{E} = -\mu_0 \dfrac{\partial}{\partial t} \mathbf{H} \\ \nabla \times \mathbf{H} = \epsilon_0 \dfrac{\partial}{\partial t} \mathbf{E} \end{cases} \text{in } \mathcal{R}^3 \backslash \Omega$$

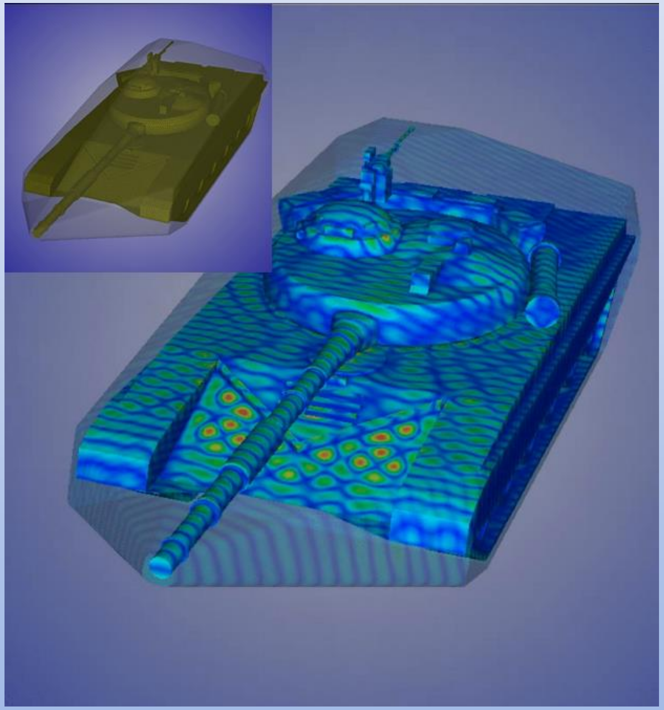
$$\lim_{|\mathbf{x}|\to\infty} |\,\mathbf{x}\,| \left\{ \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial}{\partial t} \mathbf{E} \right\} = 0$$

Complex-valued, spatially-varying tensors

Uniqueness of Maxwell's equations in non-lossy regions?

SAMPLE PROBLEMS

- Antenna design
- Radar cross sections
- Realistic transmission line impedances
- Balun and adapter design
- Metamaterials and periodic systems
- Scattering & electrically rough interfaces
- Optics and optical fibers
- Electromagnetic interference/compatibility
- … and many more!



JF Lee, Class Notes for ECE 5510, The Ohio State University, Dept. of Electrical and Computer Engineering, AU2017

Three ways to do CEM

Finite Difference Time Domain

- "So easy that even a physicist can do it"
- Low accuracy, especially with multiple length scales
- $\sigma(\omega_{max}^6 L^5)$

Finite Element

- Complex, somewhat difficult to understand
- High accuracy
- Computationally expensive

Method of Moments [MoM]

- Very difficult to understand
- High accuracy
- Computationally easier than FEM in some cases

JF Lee, Class Notes for ECE 5510, The Ohio State University, Dept. of Electrical and Computer Engineering, AU2017

Solution philosophy

"You should *always* know the answer to problem before you solve it"

-Ben Munk

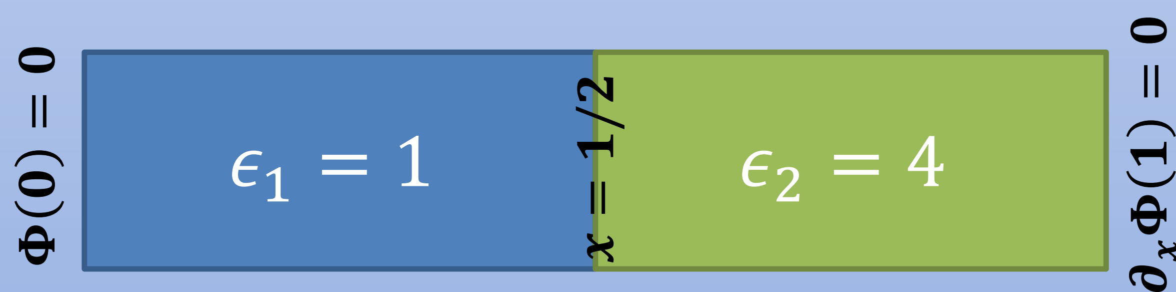
- The brother of the venerable JF Lee speaks of students/engineers who just plug their problem in and blindly believe the answer!
- You still have to know the basic programming, engineering, physics and the math to get any meaning behind your results
- Bottom line: **don't believe HFSS just because it runs on a computer!**

TOY FEM EXAMPLE [1]

- Poisson's eqn: Sturm-Liouville operator in 1D subject to some BCs

$$\mathcal{L}(\Phi) \doteq -\, \partial_x \epsilon_r \partial_x \Phi = \frac{\rho}{\epsilon_0} = 1 \ \text{ with } \epsilon_r = \begin{Bmatrix} \epsilon_1 & 0 < x < \frac{1}{2} \\ \epsilon_2 & \frac{1}{2} \leq x < 1 \end{Bmatrix}$$

- Physical meaning: static dielectric interface between ϵ_1 and ϵ_2
- How can we solve this?



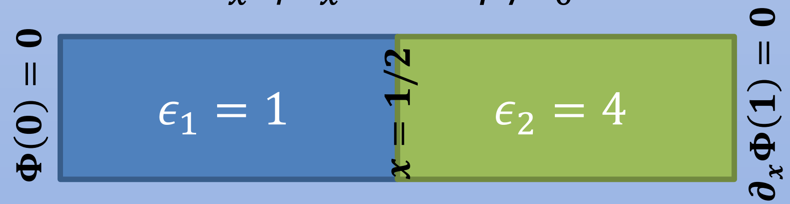
BEN MUNK APPROACH TO THE TOY MODEL

- Integrate twice and apply boundary conditions

$$\Phi(x) = \begin{cases} -\dfrac{x^2}{2} + x & 0 \le x < \dfrac{1}{2} \\ -\dfrac{x^2}{8} + \dfrac{x}{4} + \dfrac{9}{32} & \dfrac{1}{2} \le x < 1 \end{cases}$$

- Physical meaning: static dielectric interface between ϵ_1 and ϵ_2
- BCs: should go to zero at x = 0 and gradient should vanish at x = 1 [OK]

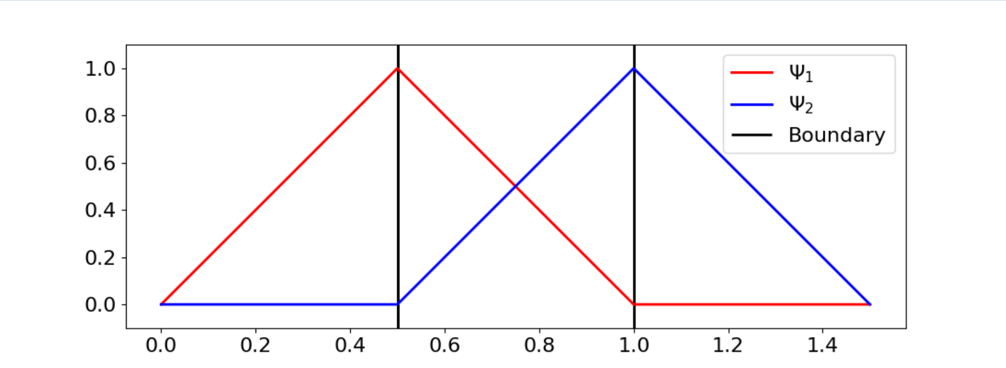
$$\partial_x \epsilon_r \partial_x \Phi = -\rho/\epsilon_0$$



TOY FEM EXAMPLE [2]

- Expand in **trial** basis functions

$$\Phi(x) \approx \sum_{m=1}^{M} a_m \psi_m(x)$$



- Taking only two terms: one per region with a different dielectric

$$\Phi(x) \approx \psi_1(x)a_1 + \psi_2(x)a_2 = [\psi_1(x) \quad \psi_2(x)] \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

TOY FEM EXAMPLE [3]

- Use **Galerkin's method** to solve for the expansion coefficients that variationally minimize the residue

- Collapse the operator equation/BCs into a matrix problem

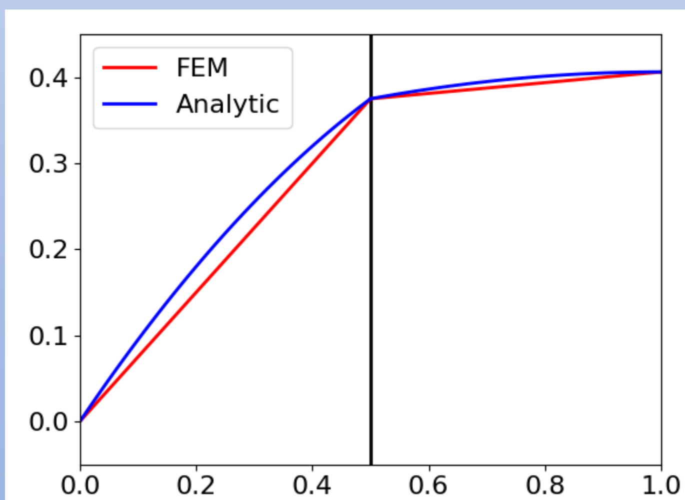
$$a_1 \int_0^1 \epsilon_r (\partial_x \phi_1)^2 dx + a_2 \int_0^1 \epsilon_r (\partial_x \phi_2)^2 dx = \int_0^1 \psi_1 dx$$
$$a_1 \int_0^1 \epsilon_r (\partial_x \phi_1)^2 dx + a_2 \int_0^1 \epsilon_r (\partial_x \phi_2)^2 dx = \int_0^1 \psi_1 dx$$

- For us:

$$\begin{bmatrix} 10 & -8 \\ -8 & 8 \end{bmatrix} \begin{bmatrix} \mathrm{a}_1 \\ \mathrm{a}_2 \end{bmatrix} = \begin{bmatrix} 1/2 \\ 1/4 \end{bmatrix} = \widehat{M}|\mathrm{a}> = |b> \quad \Rightarrow \quad a_1 = \frac{3}{8} \mid a_2 = \frac{13}{32}$$

TAKEAWAYS

- Guaranteed to have **minimum residue** under Galerkin weighting
- Based on selection of basis (trial) functions – **meshing**
- **More meshing, more accurate, more computationally expensive**
- Depends on matrix math – vulnerable to **condition number**



$$\begin{bmatrix} 10 & -8 \\ -8 & 8 \end{bmatrix} \rightarrow \begin{bmatrix} 9+\sqrt{65} & 0 \\ 0 & 9-\sqrt{65} \end{bmatrix} \approx \begin{bmatrix} 17 & 0 \\ 0 & 1 \end{bmatrix}$$

Condition number: 17/1 = 17

What if this were $\begin{bmatrix} 1e-16 & 0 \\ 0 & 1 \end{bmatrix}$?

Would you trust matrix operations to not lose precision?

REAL WORLD EXAMPLES!

- HFSS = High Frequency Structure Simulator
- Pioneered by Jin-Fa Lee, sold to Ansys (currently on version ~R19)
- Has many features I don't know/understand – you are encouraged to explore all of its features!
- Examples:
  - [My example] Microstrip transmission line
  - [Your turn] Shorted transmission line

Follow along screenshots

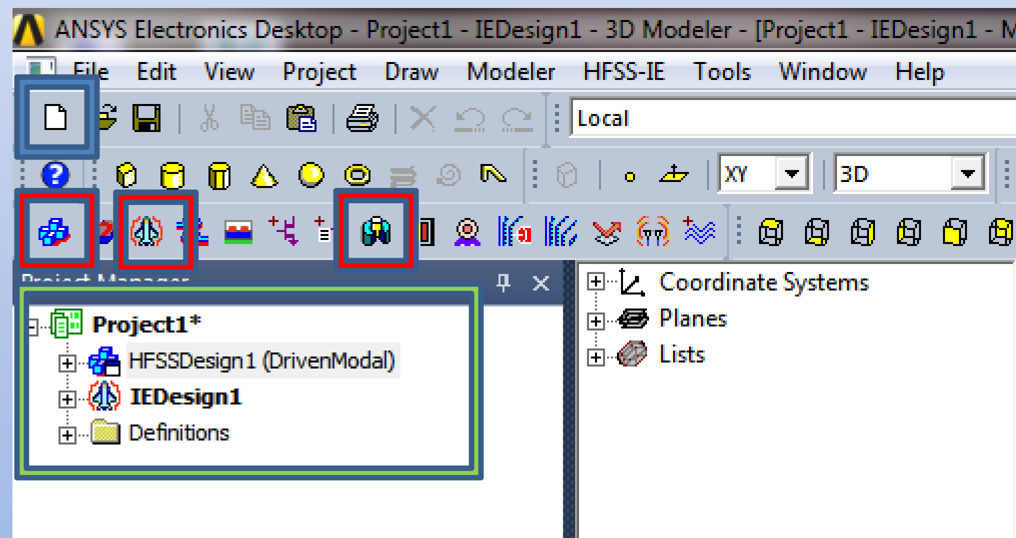
MICROSTRIP TRANSMISSION LINE

Getting Started

BLUE: Insert new project

RED: Insert (L to R)
HFSS FEM | HFSS MoM | Maxwell

GREEN: Select your design here



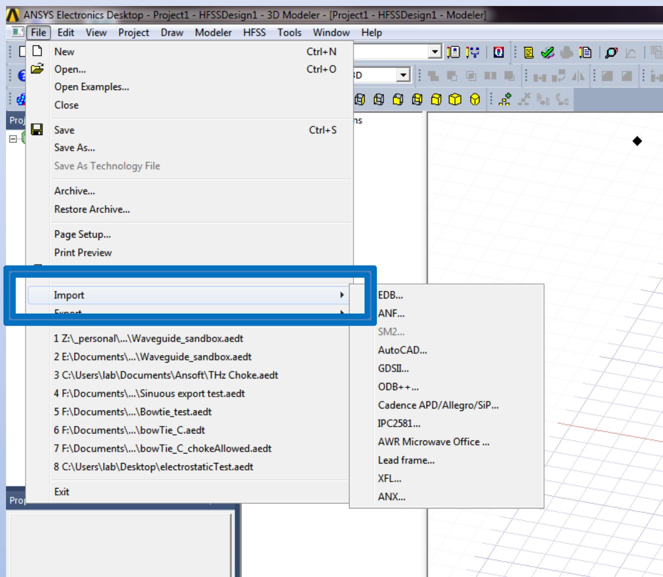
Ben Munk Considerations

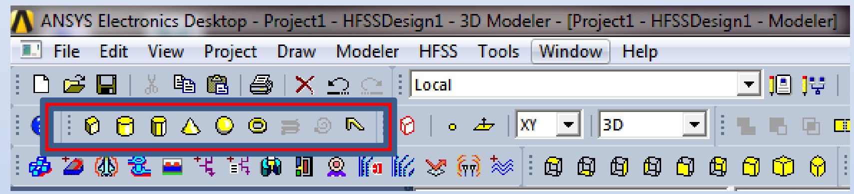
- What do we expect? Simulation from 5 GHz – 15 GHz, L~ 10 mm
- For $\epsilon_r \approx 9$, quasi-TEM mode Fabry-Perot oscillations every…

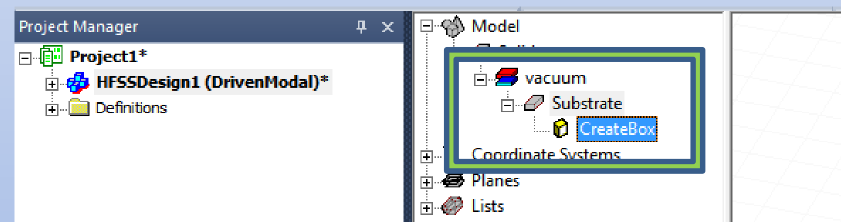
$$\frac{\epsilon_r + 1}{2}\frac{c_{vacuum}}{L} \approx 6\ GHz$$

- High transmission coefficients, low reflection coefficients
- Electric field/magnetic field/Poynting's vector riding down the TRL
- Anything else?

MAKE YOUR DESIGN [1]





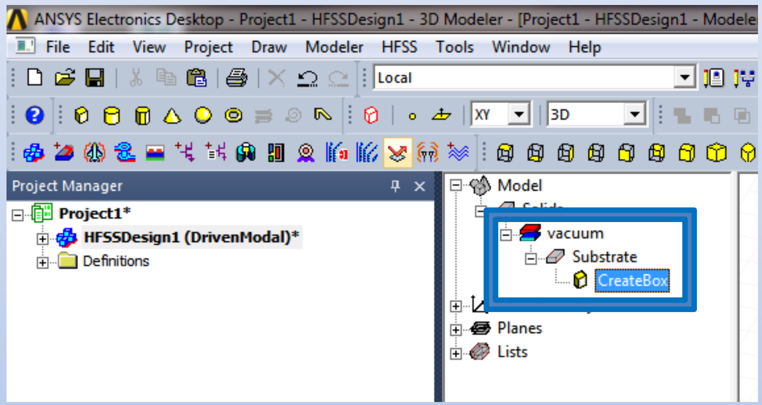


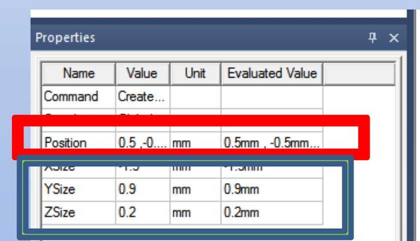
BLUE: Import file from other SW

RED: Insert basic geometric shapes, can also extrude 2D objects to 3D

GREEN: Select your design here

MAKE YOUR DESIGN [2]



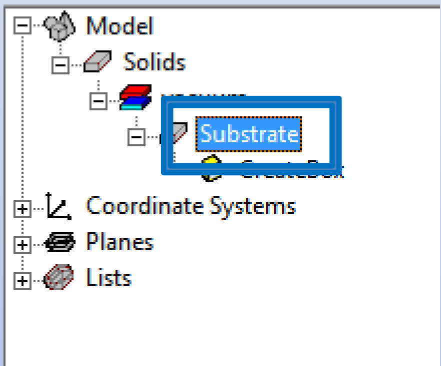


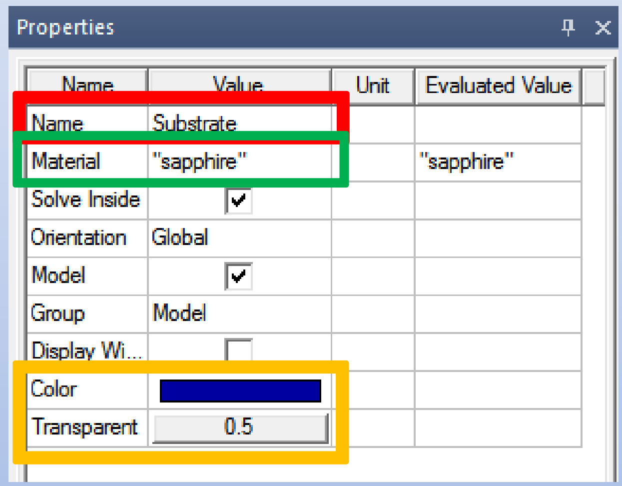
BLUE: To edit geometric parameters of the box, click here

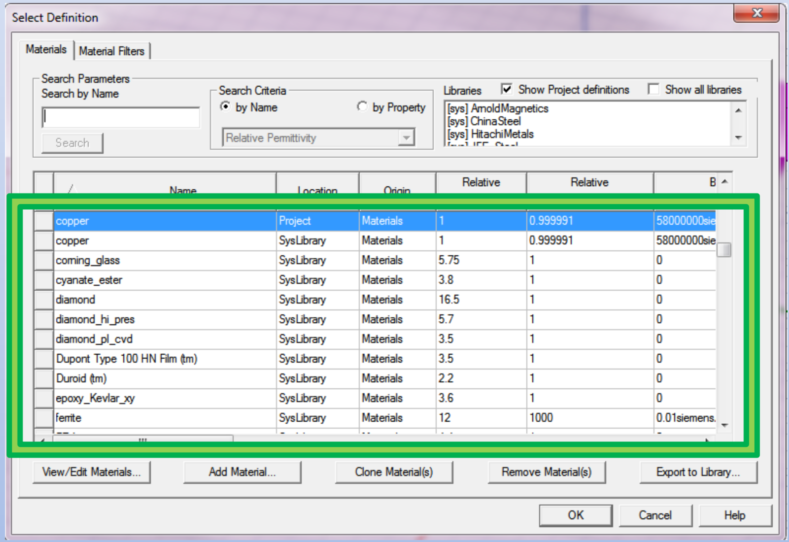
RED: origin of one of the corners [X,Y,Z]

GREEN: Dimensions depending on the geometric shape, can be negative or variables

MAKE YOUR DESIGN [3]







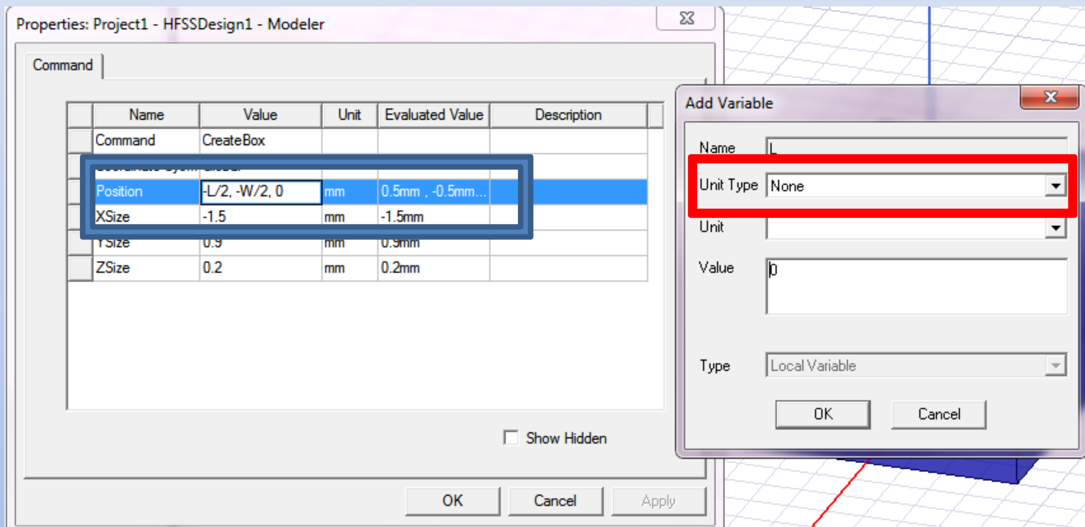
BLUE: To edit EM properties of the box, click here

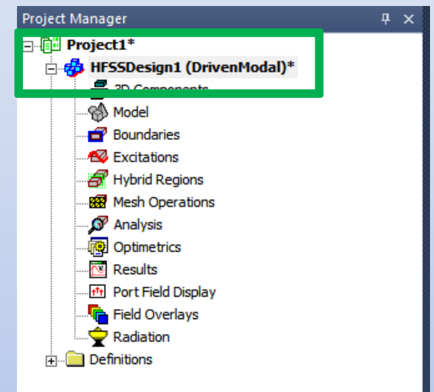
RED: *always* rename parts of the model to be physically relevant

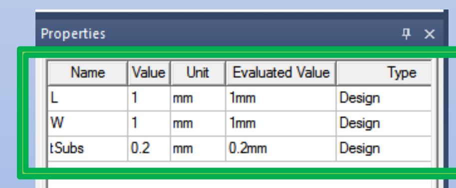
GREEN: Click here to change the material

ORANGE: Color-code and 50% transparency always helps me track me track the model

Parametrizing the Design





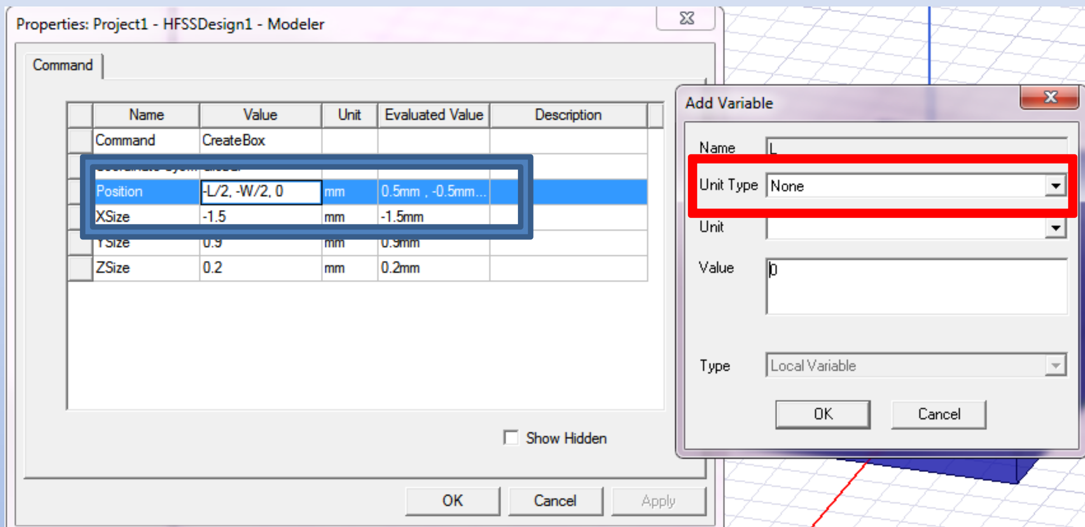


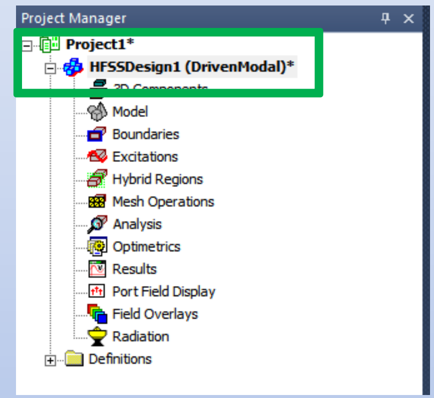
BLUE: good to make the design symmetric about the origin, if possible

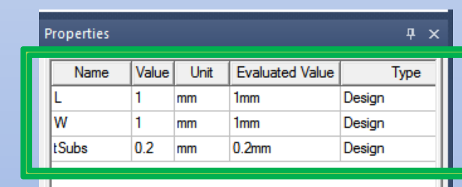
RED: always add units to parameters (they can be expressions of other parameters too)

GREEN: Change parameters from this menu

PARAMETRIZING THE DESIGN







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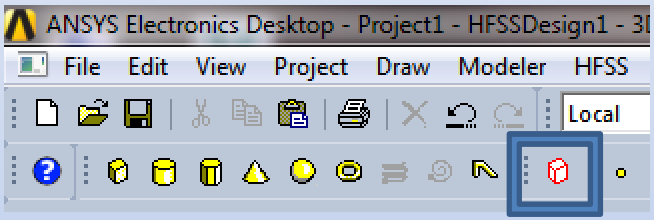
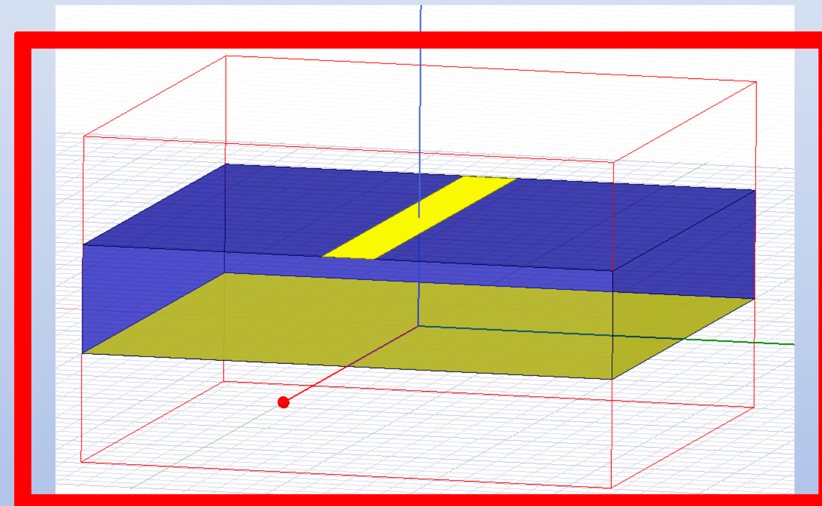
RED: always add units to parameters (they can be expressions of other parameters too)

GREEN: Change parameters from this menu

Simulation Boundary Conditions [1]



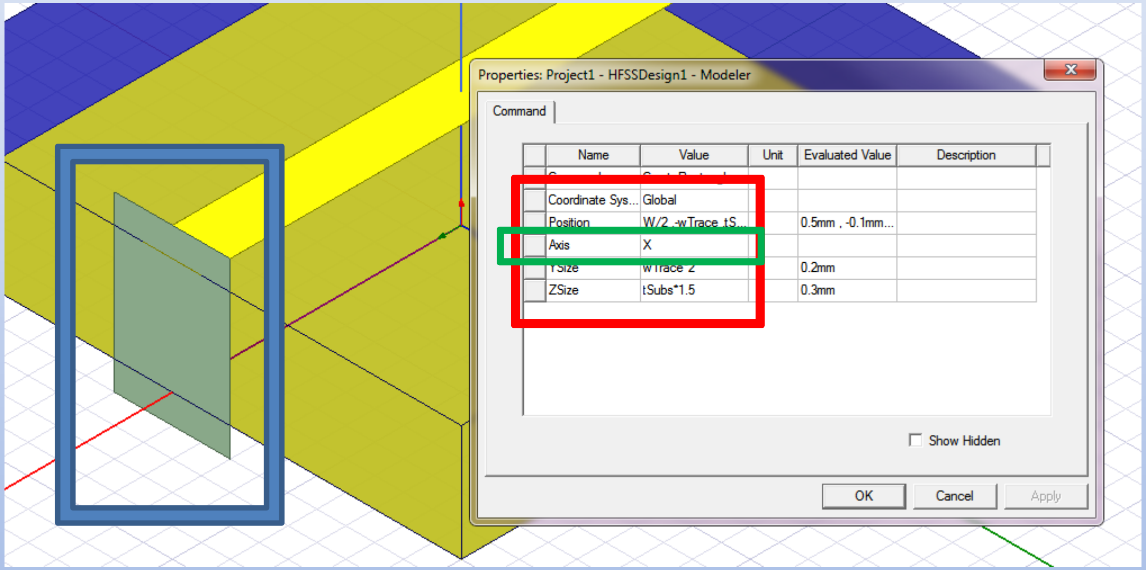


BLUE: Add a radiation box around the design. For TRLs, I pad 100% in $\pm$Z. Generally want $> \frac{\lambda}{4}$ padding from radiating edges. Be sure to change the bounday condition to “rad”

RED: check the radiation box to see if it looks right, then hide it (it looks annoying!)

GREEN: Change object visibility, incl. the radiation boundary

Simulation Boundary Conditions [2]



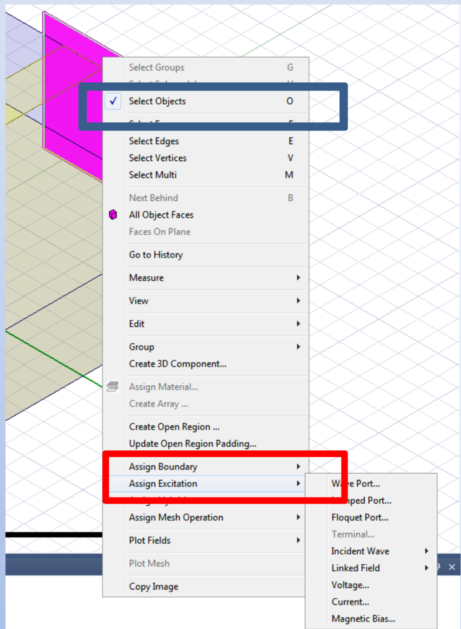
BLUE: Add a plane for excitation. Copy and paste it to make the second one

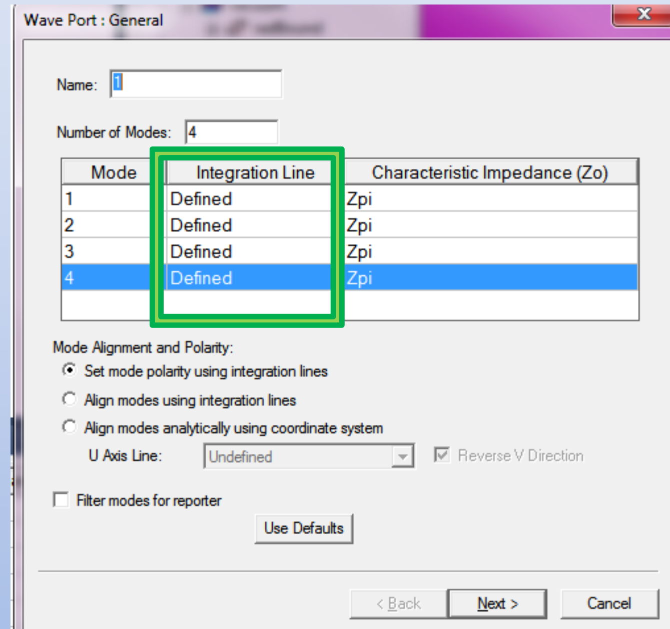
RED: take advantage of your parametrization

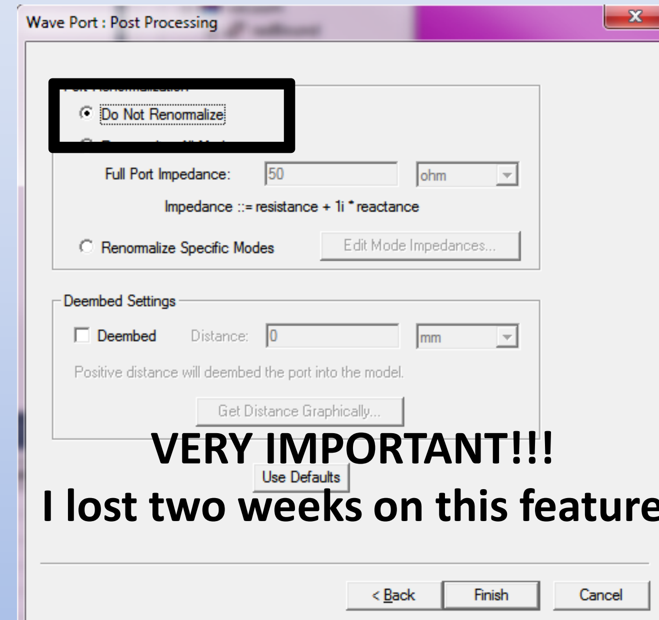
GREEN: Alter the axis as needed (defaults to Z, not good for us!)

UC SANTA BARBARA PHYSICS THE WORLD GETS CHANGED HERE.

SIMULATION BOUNDARY CONDITIONS [3]







VERY IMPORTANT!!!

I lost two weeks on this feature

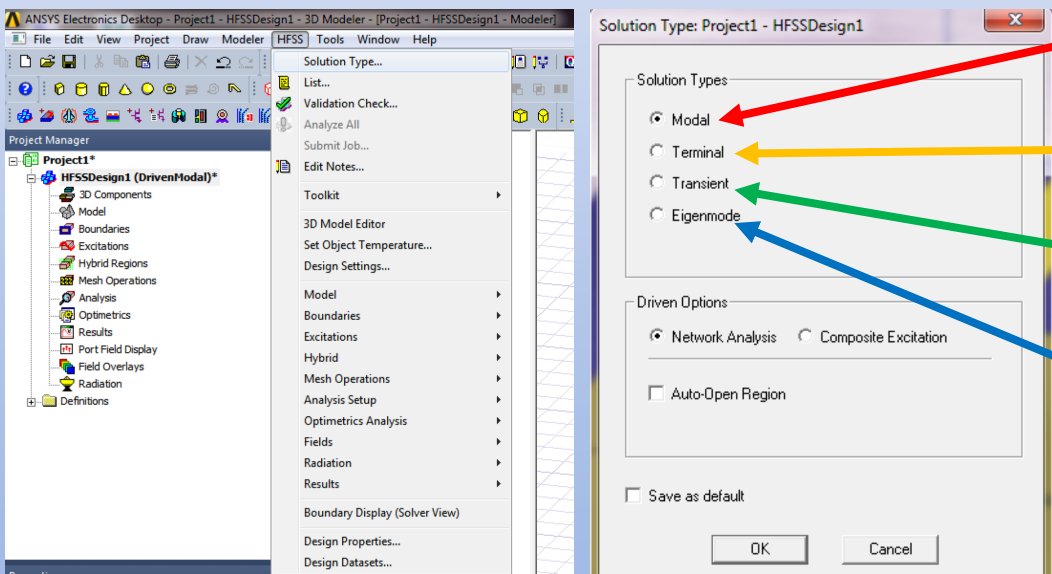
BLUE: Select the appropriate object or face (>>F to select a face)

RED: assigned boundary values or a make a port

GREEN: defines the field integration pathway

Note: wave ports excite a wave mode on a surface and lumped port excites a node or a single point. Try to replicate the physics as you can

Preparing the simulation [1]



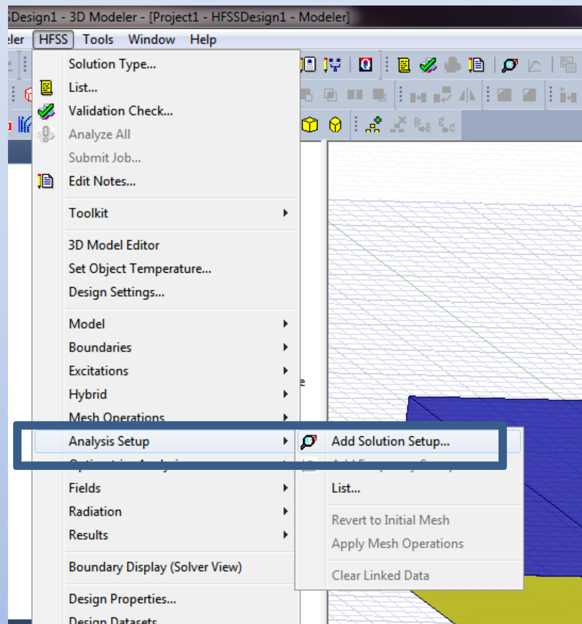
Transmission Lines

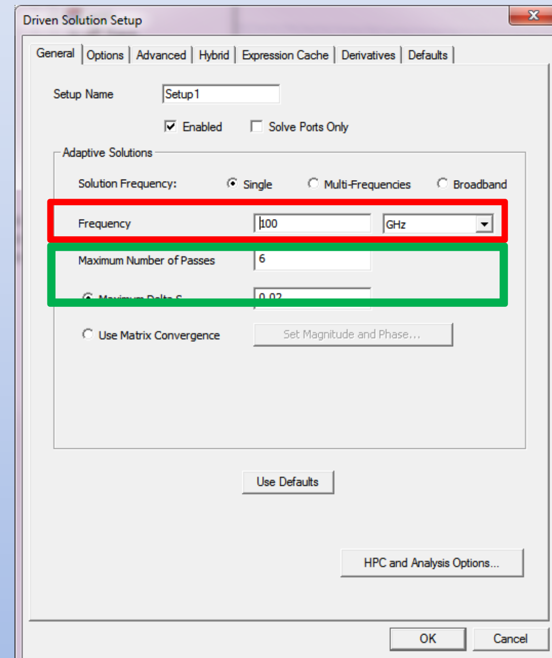
Antennas

Just like the name sounds

Resonators and metamaterials

Making a Simulation



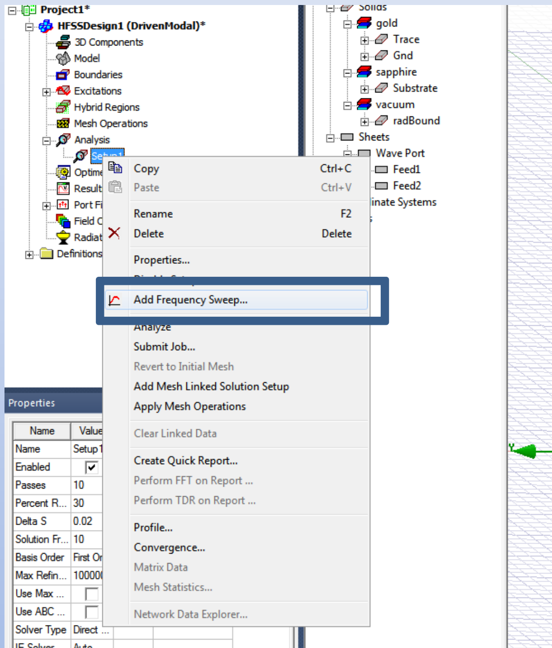


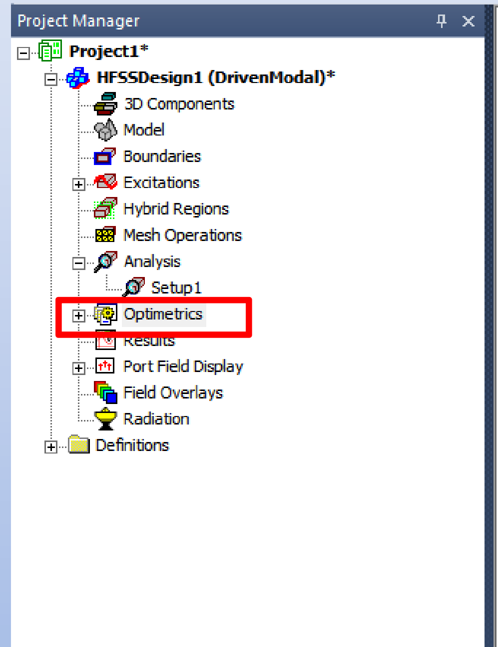
BLUE: Prepare a simulation

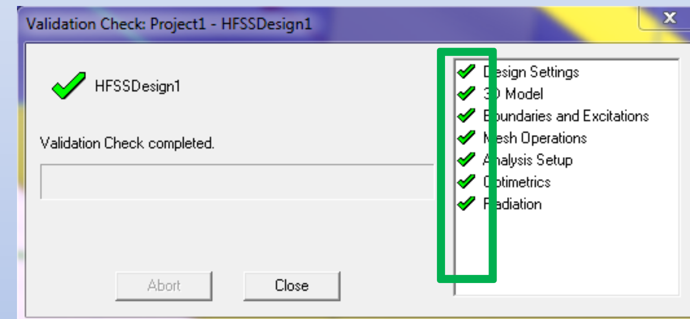
RED: frequency used in adaptive meshing solutions

GREEN: adaptive meshing success criterion, lower is better but usually takes longer

ADD A FREQUENCY OR PARAMETRIC SWEEP





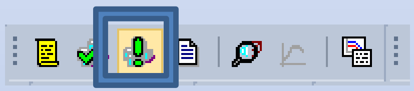


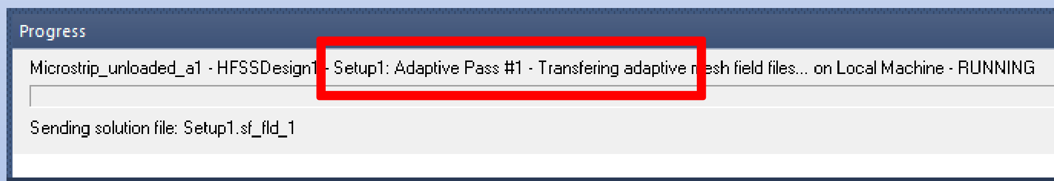
BLUE: sweep the frequency based on the center frequency mesh

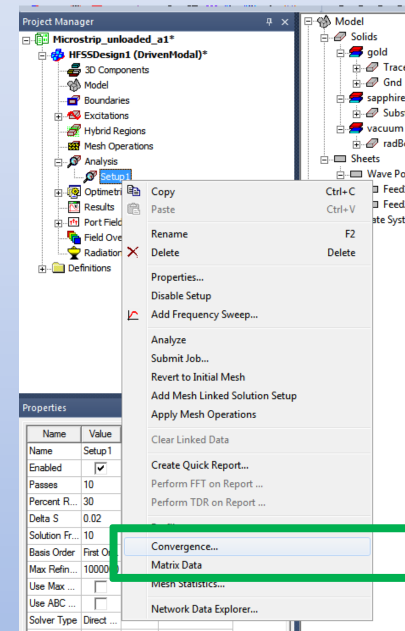
RED: parametric sweep/optimizations… where a lot of the of the engineering is!

GREEN: button used to check to make sure you're ready to simulate

WHILE IT RUNS





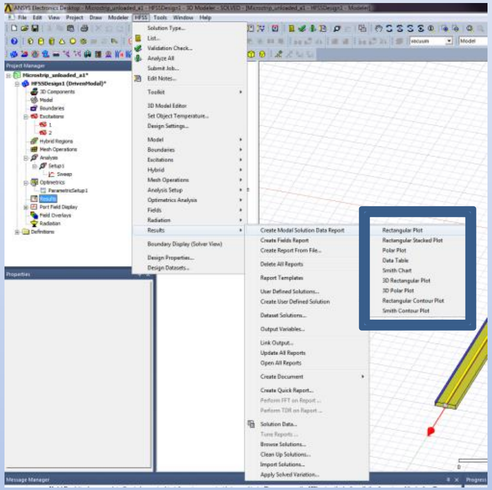


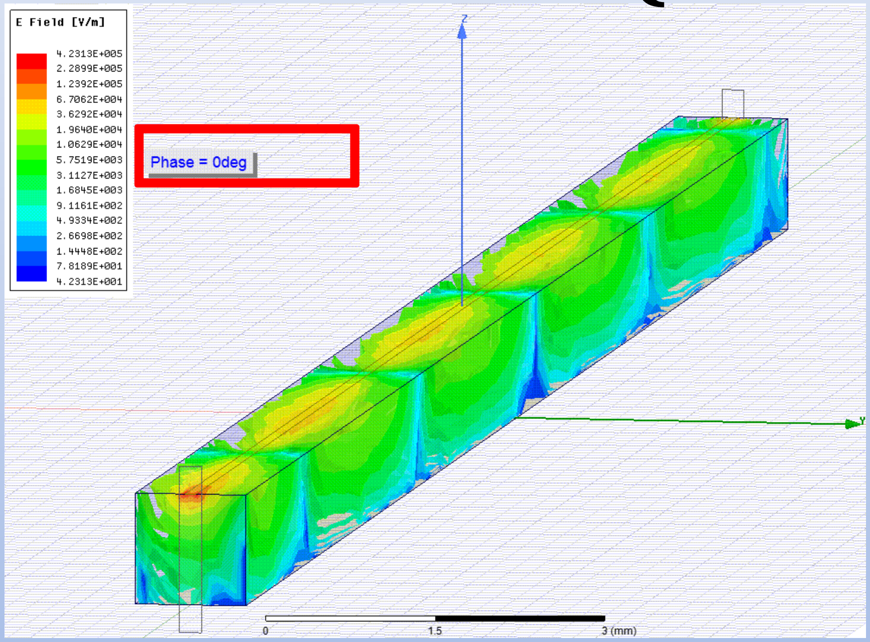
BLUE: Simulate command

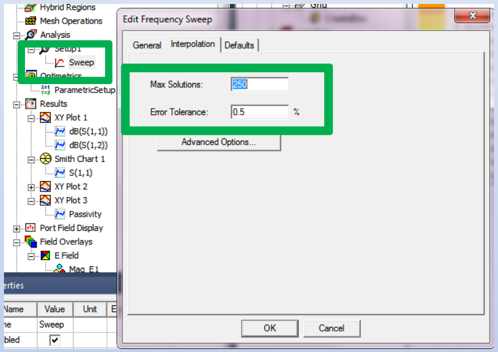
RED: status bar, simulation can be cancelled as needed on the RHS of this bar

GREEN: Check s matrix convergence/mesh statistics… etc. here. **ALWAYS CHECK THIS!**

Interpret the results (Ben Munk!)





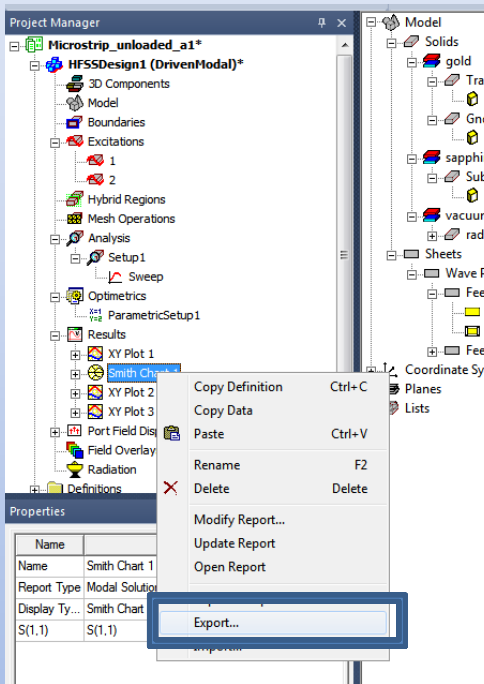


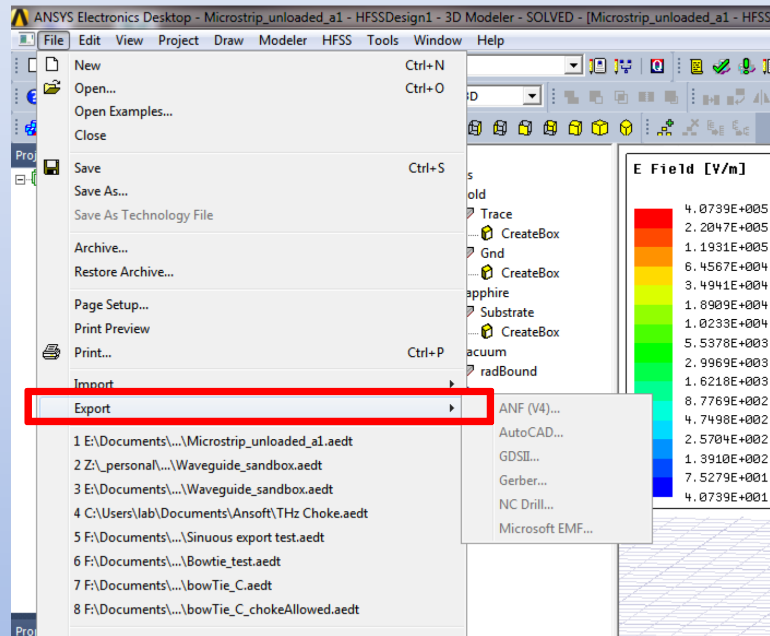
BLUE: Insert 1 of a number of types of plots and select your desired output

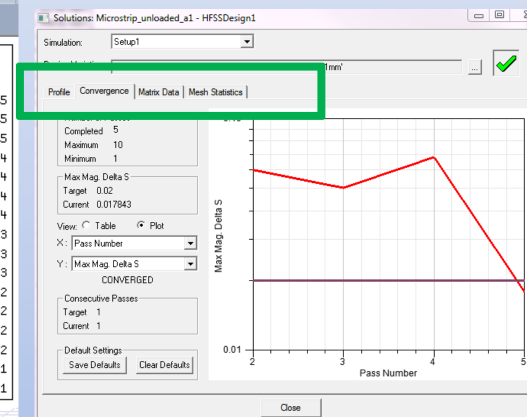
RED: can animate fields as needed

GREEN: If the passivity is bad, decrease ΔS or the tolerated residue

Export results







BLUE: Export CSV files of your data for prettier plotting

RED: status bar, simulation can be cancelled as needed on the RHS of this bar

GREEN: Save the convergence and some mesh statistics for the record

Exercise – study a short

- Use the previous design files
- Ben Munk considerations?
  - Standing wave instead of a propagating wave
  - High reflection coefficient
  - Low loss: trace should "hug" the Smith Chart border
- Modify the structure for one port
  - Suggestion: delete feed2 and add a gold short to ground
  - Measure S11
- Try for a couple different substrate thicknesses (parametric step)
- Try for very thin gold (100 nm) versus tall gold (100 microns)
- Try for narrow versus thick feed ports

TRY REPRODUCING SOMETHING LIKE THIS