



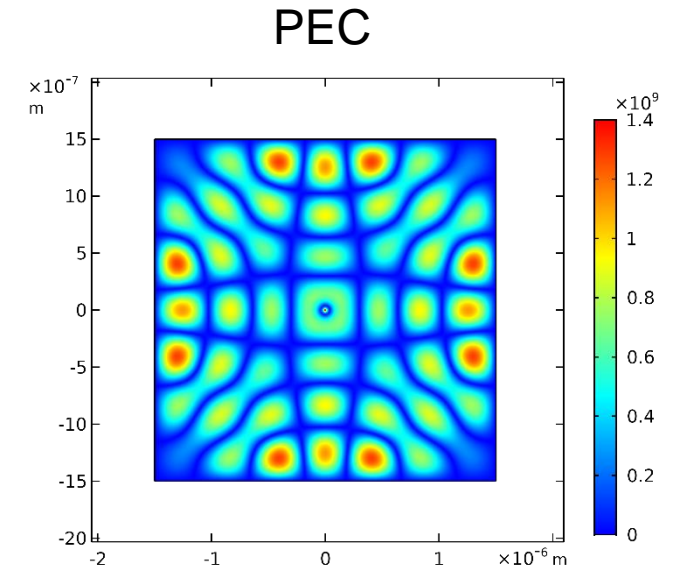
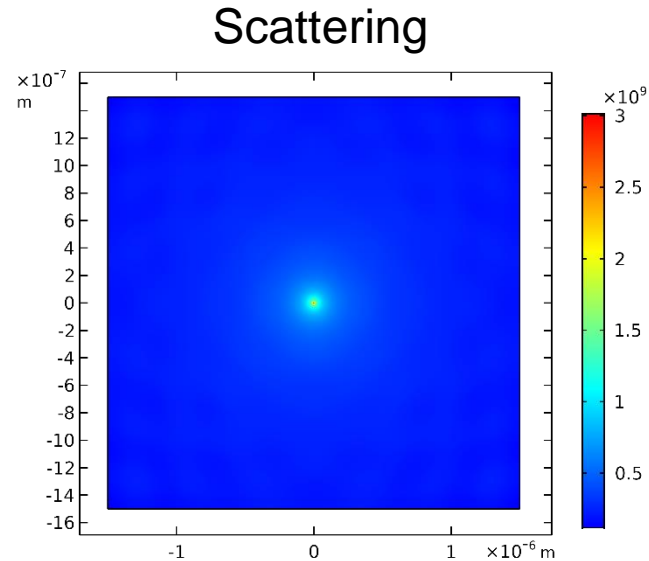
P&S COMSOL® Design Tool

Week 2: EM Introduction & Introduction to COMSOL

Manuel Kohli, Raphael Schwanninger

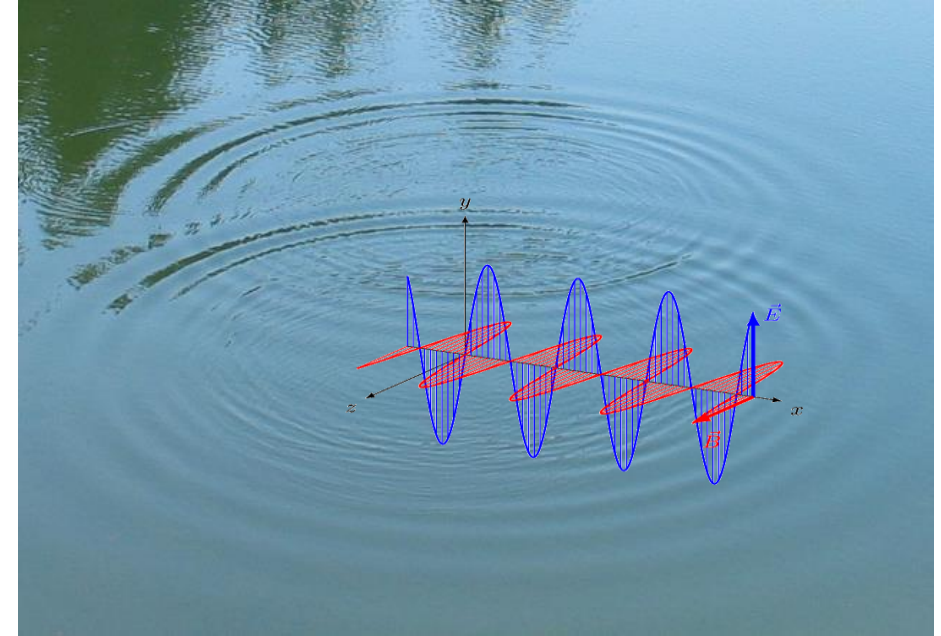
Recap

- Last Time
 - Introduction to COMSOL
 - Point Source model
 - Scattering Boundary Conditions
 - Perfect Electric Conduction (PEC)
- Today
 - More on Boundary Conditions
 - Perfect Electric Conductor (PEC)
 - Perfect Magnetic Conductor (PMC)
 - Scattering Boundary Condition
 - Periodic Boundaries Condition (PBC)
 - Perfectly Matched Layer (PML)



Motivation

- Wave behavior in nature
- But electromagnetic waves are (usually) invisible
- → COMSOL visualizes them!
- → Intuitive approach to understand mathematics
- Mathematics will be treated extensively in EM lectures



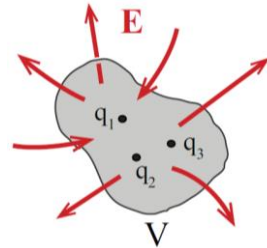
Electromagnetics: Maxwell's Equations

- Physical phenomena and laws

Gauss's law:

$$\oint_{\partial V} \mathbf{D} \, d\mathbf{A} = \int_V \rho \, dV$$

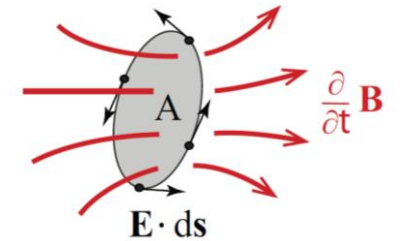
Electric displacement Field \mathbf{D}
(Free) charge density ρ



Faraday's law:

$$\oint_{\partial A} \mathbf{E} \, ds = - \frac{\partial}{\partial t} \int_A \mathbf{B} \, dA$$

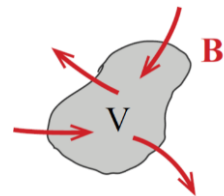
Electric Field \mathbf{H}



Gauss's law (Magnetism):

$$\oint_{\partial V} \mathbf{B} \, d\mathbf{A} = 0$$

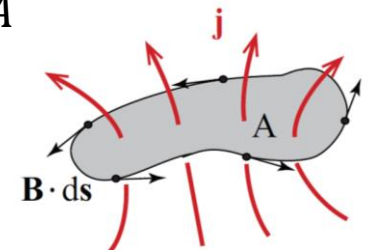
Magnetic Flux Density \mathbf{B}



Ampère's law:

$$\oint_{\partial A} \mathbf{H} \, dl = \int_A \left(\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{A}$$

(Free) current density \mathbf{J}
Magnetic Field \mathbf{H}



Electromagnetics: Maxwell's Equations



- Not Really
- One needs a model that captures the impact of fields on the material

- Electric Case Polarization P

$$D = \varepsilon_0 E + P(E) \approx \varepsilon_0 E + \varepsilon_0 \chi_E^{(1)} E$$

- Magnetic Case Magnetization M

$$B = \mu_0 H + M(H) \approx \mu_0 H + \mu_0 \chi_H^{(1)}$$

$$\varepsilon_r = 1 + \chi_E^{(1)}$$

$$\mu_r = 1 + \chi_M^{(1)}$$

Nonlinear Optics: 227-0655-00L

Electromagnetics: Materials Relations

- In order to analyze an EM problem we need to define the **material properties** involved
- Materials are defined by their **refractive index n** which is defined as

- $n = \sqrt{\mu_r \epsilon_r}$, for vacuum $n = 1$

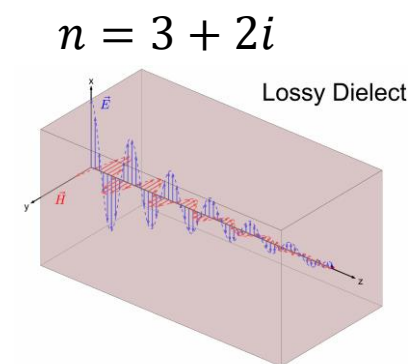
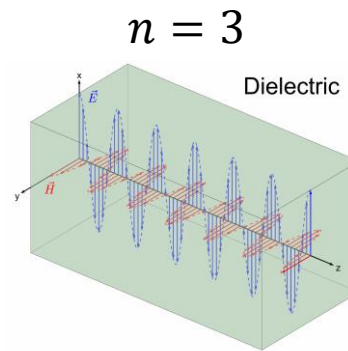
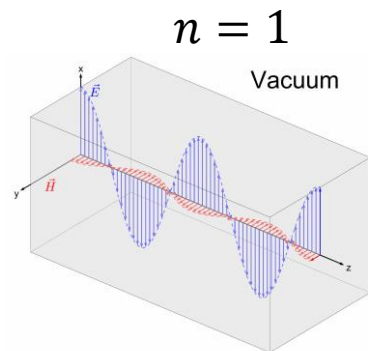
- n is a complex number $n = n' + ik$

Influences wavelength

Influences losses

$$\epsilon_r = 1 + \chi_E^{(1)}$$

$$\mu_r = 1 + \chi_M^{(1)}$$



Electromagnetics: Maxwell's Equations

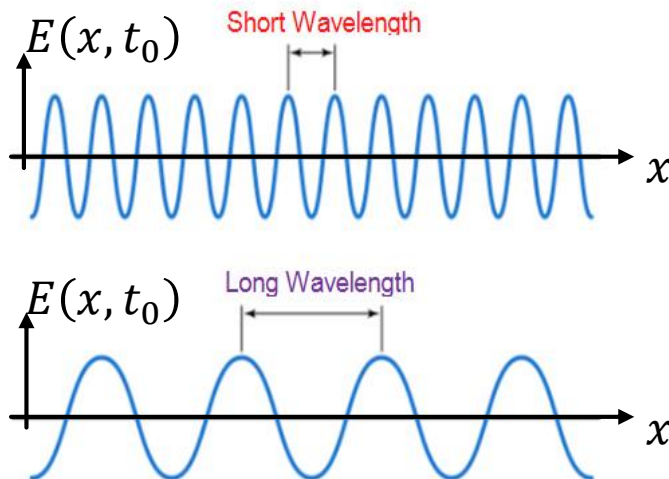
- Wave Equation from Maxwell's Equations
 - Homogenous, Isotropic, linear Material,
 - No Sources

$$\frac{\partial^2 E_z}{dx^2} - \frac{1}{c^2} \frac{\partial^2 E_z}{dt^2} = 0$$

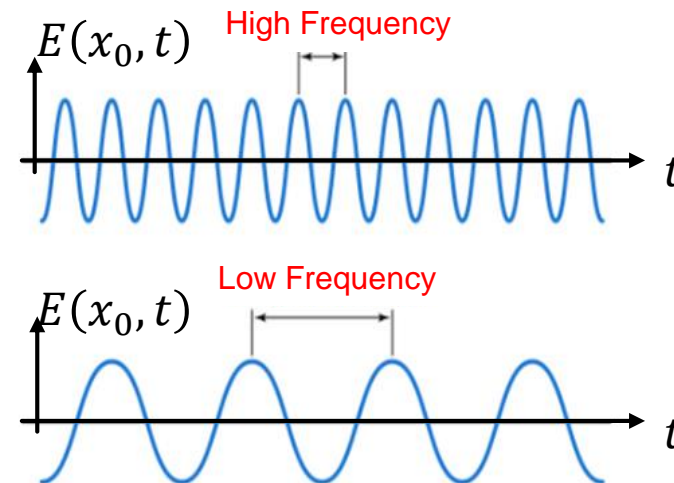
- Solution

$$E_z(x, t) = F(x - ct) + G(x + ct)$$

Fixed time



Fixed Location



Electromagnetics: Wavelength and Frequency

- Plane wave Solution:

$$E_z(x, t) = E_0 e^{-i\omega t} e^{-ikx}$$

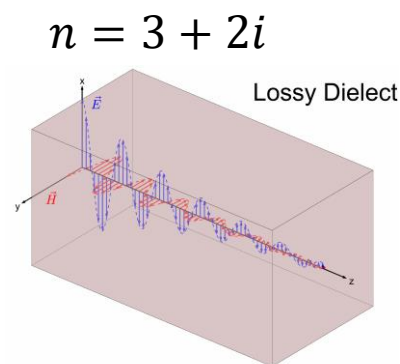
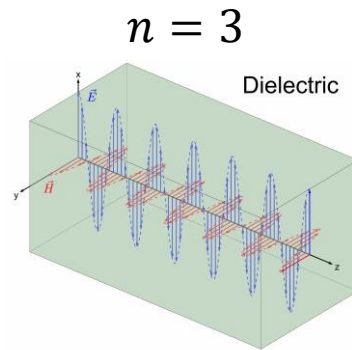
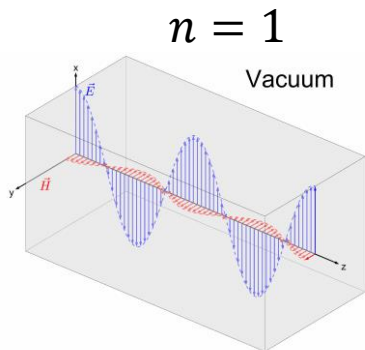
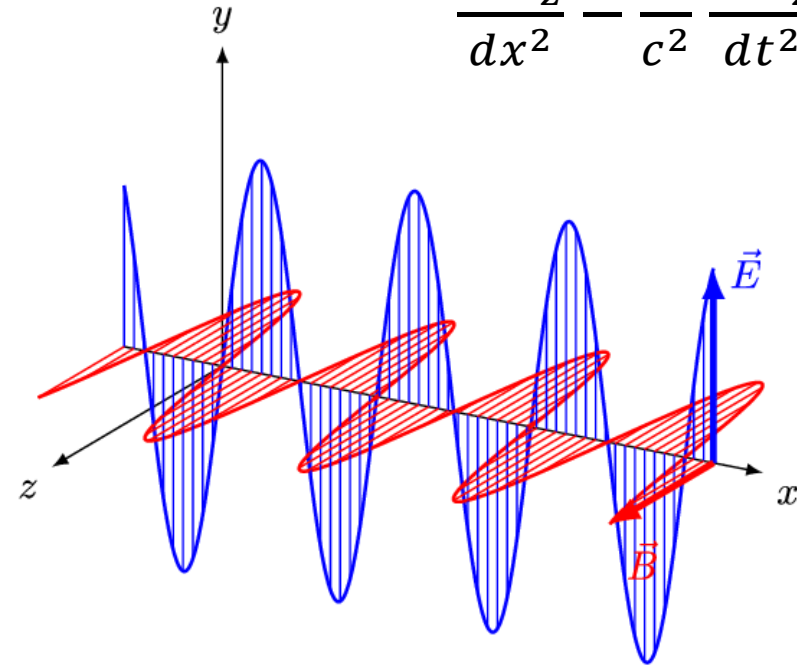
- Proof:

$$-k^2 e^{-i\omega t} e^{-ikx} + \frac{\omega^2}{c^2} e^{-i\omega t} e^{-ikx} = 0$$

- With

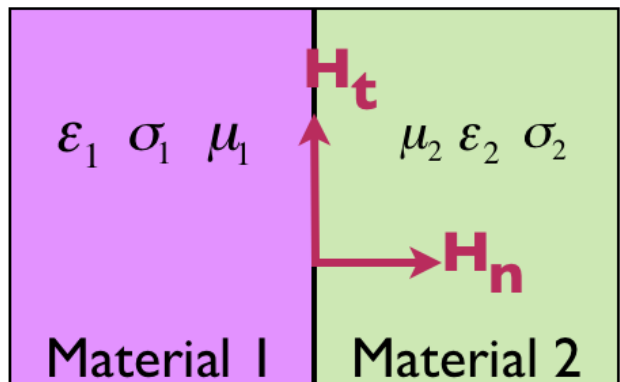
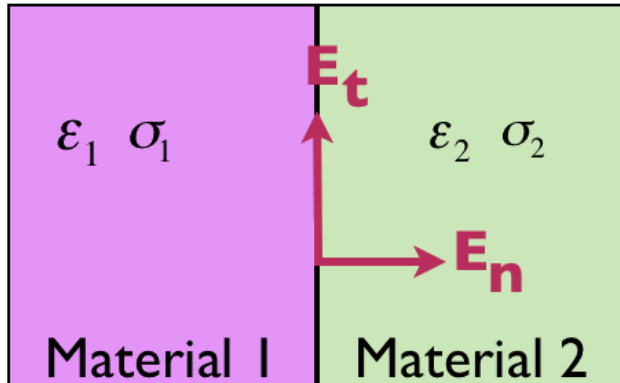
$$k^2 = \frac{\omega^2}{c^2} = \frac{\omega^2}{c_0^2} n^2 \quad e^{-i\frac{\omega}{c_0} nx}$$

$$\frac{\partial^2 E_z}{dx^2} - \frac{1}{c^2} \frac{\partial^2 E_z}{dt^2} = 0$$



Boundary Conditions

- Maxwell's Boundary Conditions



Boundary Conditions

$$E_{t,1} - E_{t,2} = 0$$

$$\epsilon_1 E_{n,1} - \epsilon_2 E_{n,2} = \rho_f \quad (\text{surface charge density at the interface})$$

$$H_{t,1} - H_{t,2} = J_s \quad (\text{surface current density at the interface})$$

$$\mu_1 H_{n,1} - \mu_2 H_{n,2} = 0$$

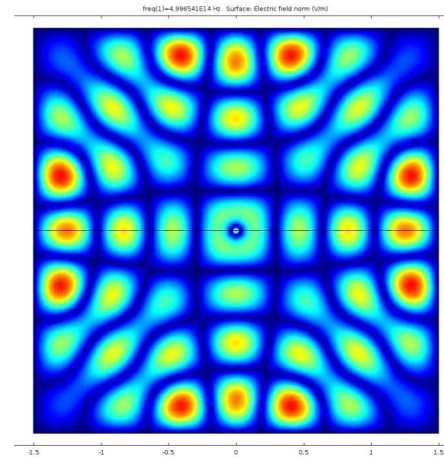
227-0160-00L: Fundamentals of Physical Modeling and Simulations

227-2037-00L: Physical Modelling and Simulation

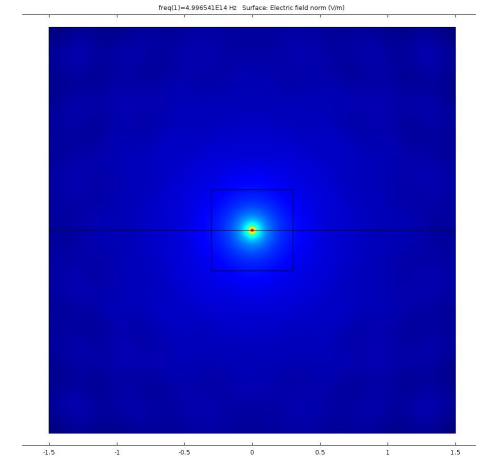
227-0110-00 G : Electromagnetic Waves: Materials, Effects, and Antennas:

COMSOL: Boundary Conditions

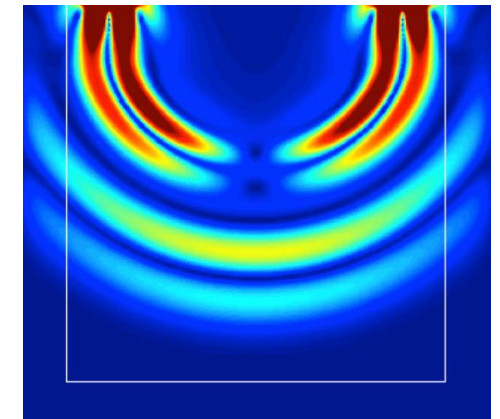
- Purpose of boundary conditions → define simulation domain
- Types of boundary conditions in COMSOL
 - Perfect Electric Conductor (PEC)
 - Perfect Magnetic Conductor (PMC)
 - Scattering Boundary Condition
 - Periodic Boundaries Condition (PBC)
 - Perfectly Matched Layer (PML)



PEC Boundaries



Scattering Boundaries



PML Boundaries

COMSOL: Boundary Conditions

Perfect Electric Conductor (PEC)

Properties

- Equivalent to infinite electric conductivity
- $\lim_{\sigma \rightarrow \infty} j = \lim_{\sigma \rightarrow \infty} \sigma E = \infty \Rightarrow E = 0$: No Electric fields inside
- $E = 0$: Constant magnetic field inside

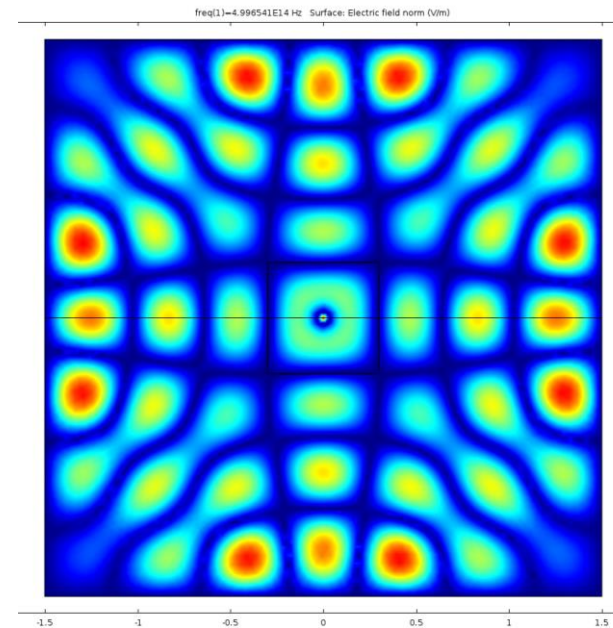
$$\oint_{\partial A} \mathbf{E} \, ds = -\frac{\partial}{\partial t} \int_A \mathbf{B} \, dA$$

Examples

- Microwave planar structures
- Metallic substrates
- Short circuit interface
- To implement some certain symmetry

$$E_{t,1} - E_{t,2} = 0$$

$$\Rightarrow E_{t,1} = 0$$

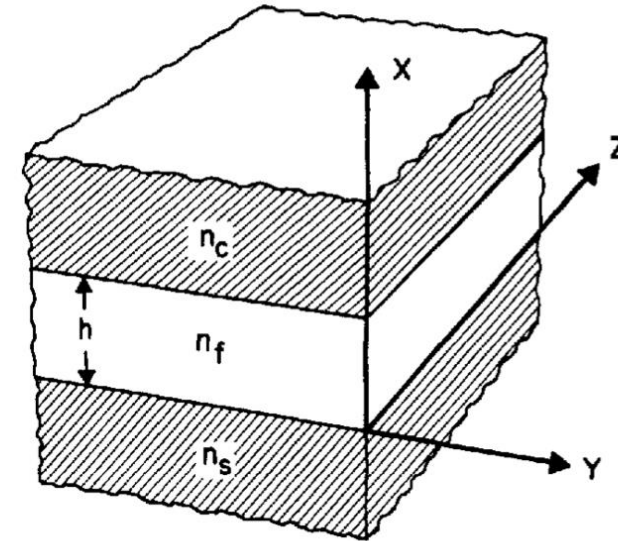


COMSOL: Boundary Conditions

- **Perfect Magnetic Conductor (PMC)**
 - Properties
 - Equivalent to infinite magnetic conductivity (large μ)
 - $\lim_{\mu \rightarrow \infty} B = \lim_{\mu \rightarrow \infty} \mu H = \infty \Rightarrow H = 0$.
- Examples
 - To account for certain symmetry
 - Interface between dielectric and air
 - Open circuit interface

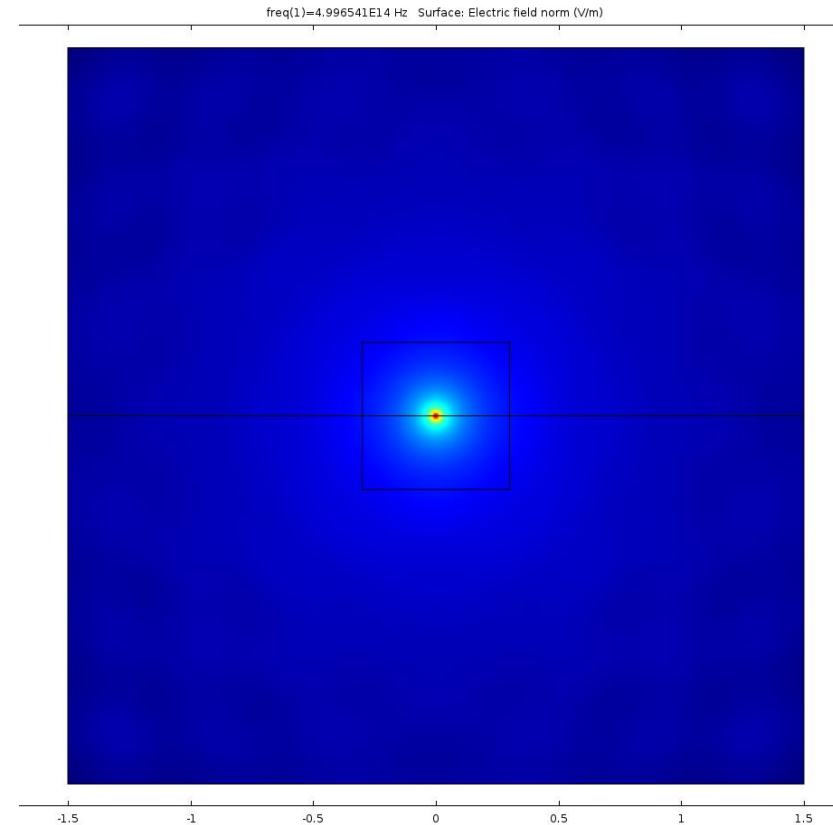
$$\mu_1 H_{n,1} - \mu_2 H_{n,2} = 0$$

$$\Rightarrow H_{n,1} = 0$$



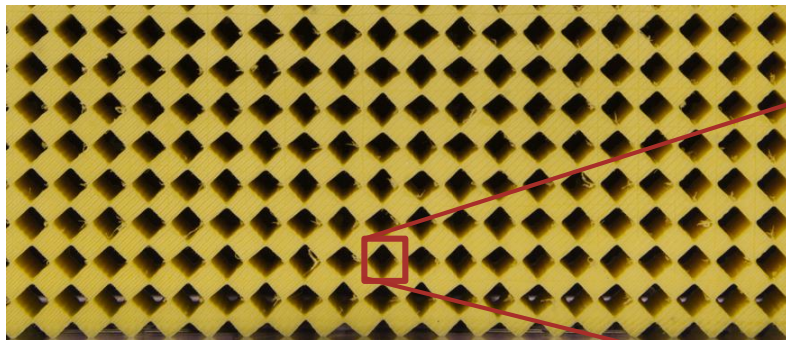
COMSOL: Boundary Conditions

- **Scattering Boundary Condition**
 - Properties
 - Electric field is absorbed \rightarrow no reflection
 - Examples
 - To simulate an “infinite” domain
 - As we did last time with the point source

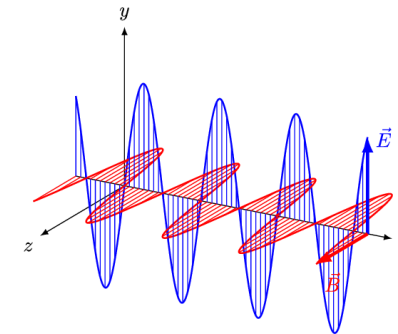
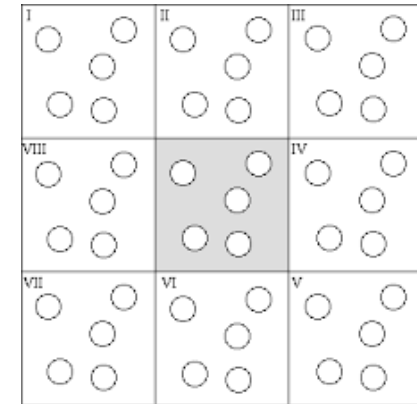
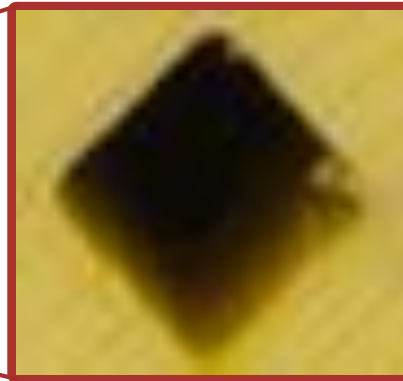


COMSOL: Boundary Conditions

- **Periodic Boundary Condition**
 - For repeating structures
 - Use a unit cell for the analysis
 - Simulates systems expanding infinitely in 1D/2D



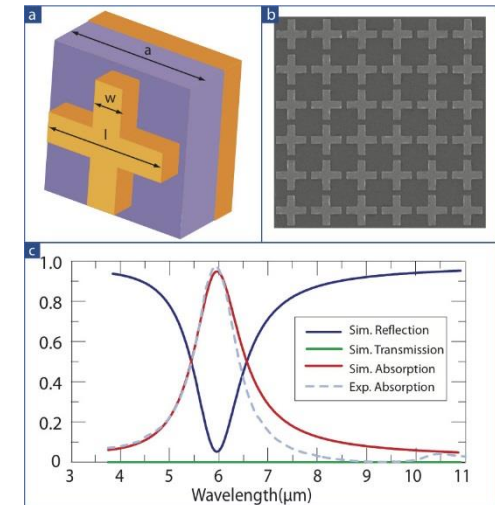
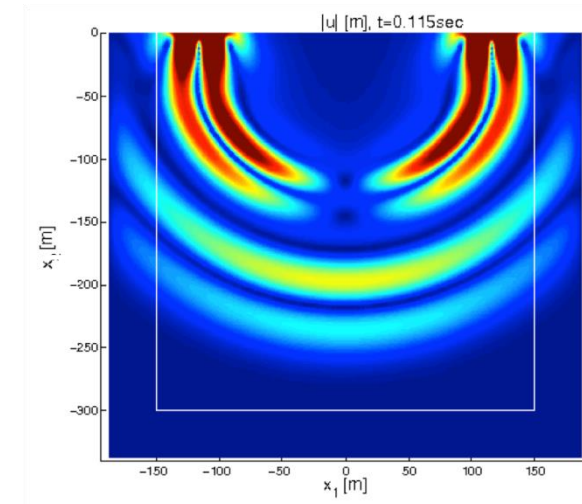
Periodic Boundaries



COMSOL: Boundary Conditions

- **Perfectly Matched Layer (PML)**
 - Scattering Boundary
 - Properties
 - Absorbing boundary
 - Truncates EM space in numerical simulations.
 - Possible to simulate open boundary problems.
 - Reduce scattered/reflected waves.

- **Examples**
 - Antennas
 - Reflectors
 - Absorbing structures
 - Metamaterials



Real life absorber

Starting COMSOL

- Every Student has access to Linux Server

Connection to Linux Server

1) Download and install Cisco Anyconnect: <https://ethz.ch/content/dam/ethz/special-interest/hest/isg-hest-dam/documents/pdf/vpn-de.pdf>

Available for MS,MAC & Linux

2) Connect to ETH network using Ciso Anyconnect

3) Connect to Linux Server

- Linux & Mac: using terminal type **«ssh username@itet-ief-l0.ethz.ch -X»** (l0 = L null)
- Windows, Linux, Max: using any remote desktop with xserver capability (e.g. Remmina)

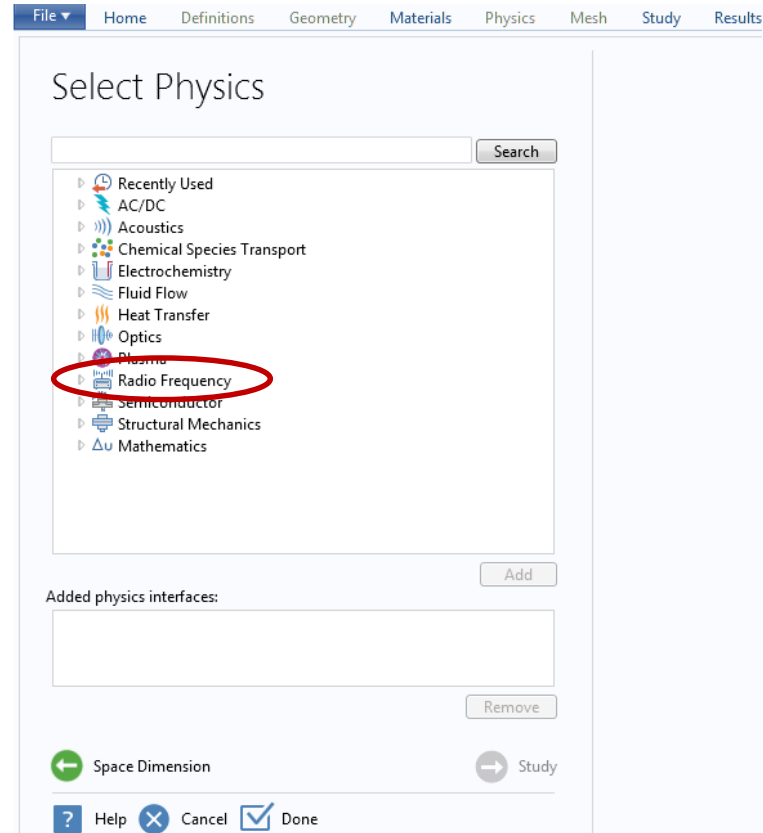
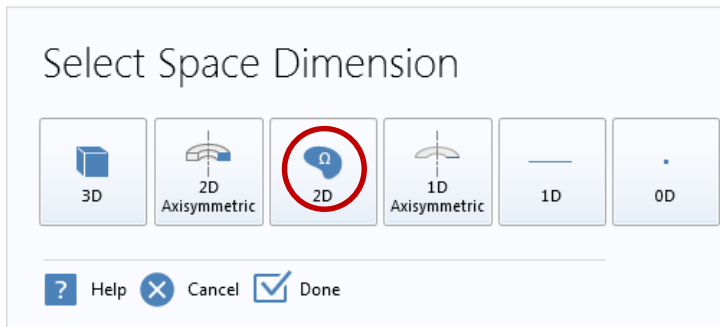
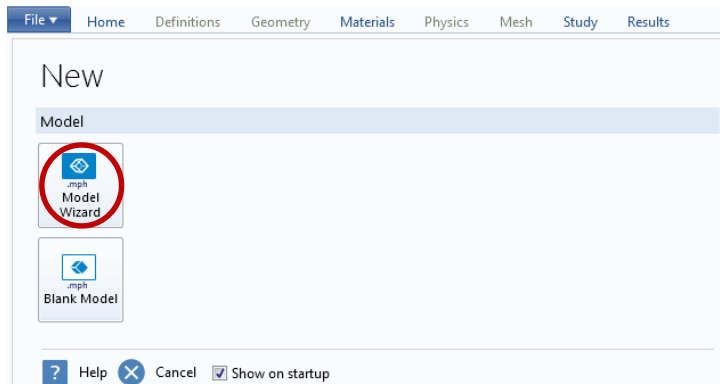
4) Enter Username and Password

5) Start COMSOL

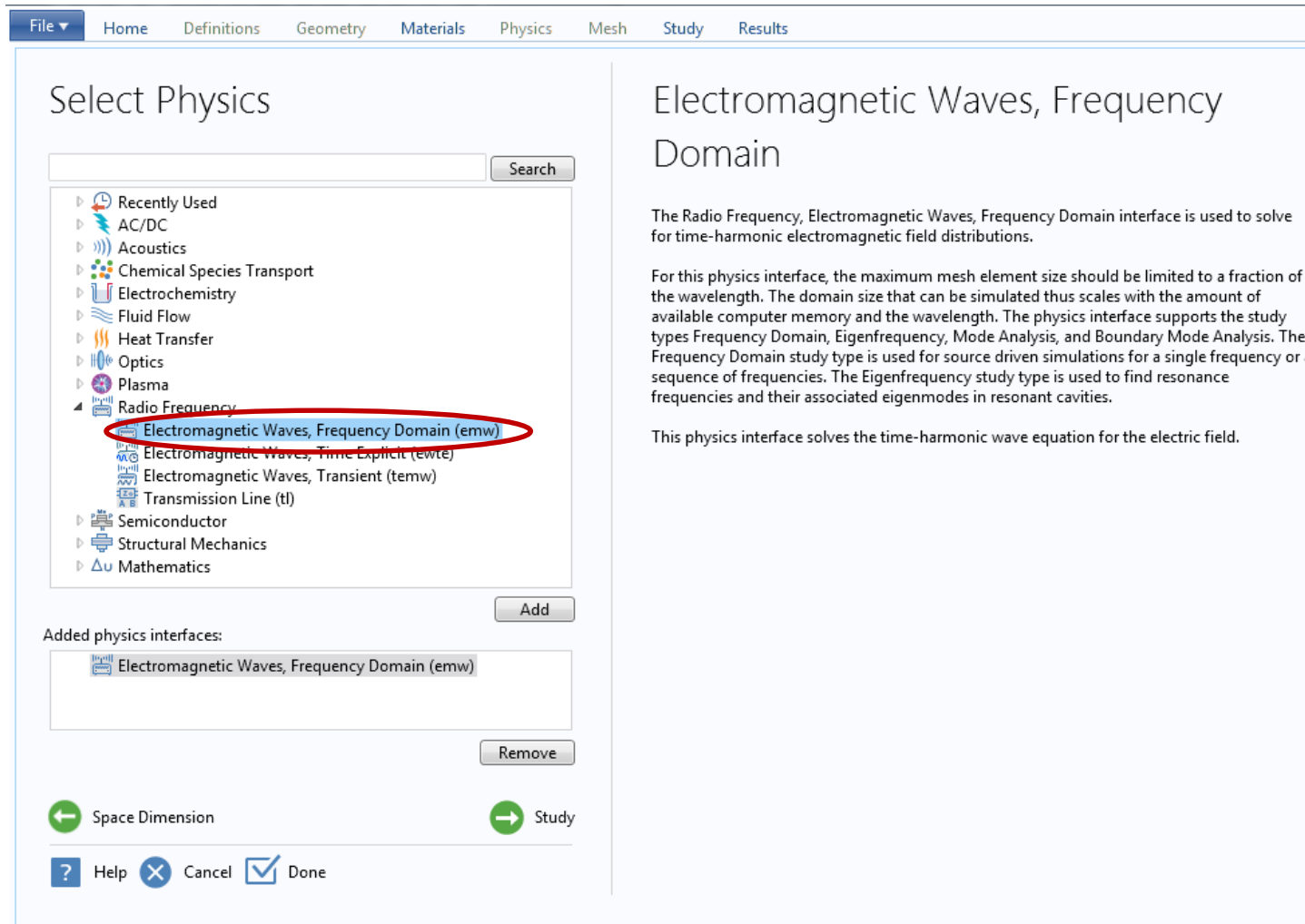
type: «comsol &» into the terminal

COMSOL: Last Time

Command to start Comsol: **comsol**



COMSOL: Last Time



The screenshot shows the 'Select Physics' dialog box in COMSOL. The 'Radio Frequency' category is expanded, and 'Electromagnetic Waves, Frequency Domain (emw)' is selected and circled in red. The 'Added physics interfaces' section shows 'Electromagnetic Waves, Frequency Domain (emw)' has been added. The 'Study' button is highlighted in green.

Select Physics

Search

- Recently Used
- AC/DC
- Acoustics
- Chemical Species Transport
- Electrochemistry
- Fluid Flow
- Heat Transfer
- Optics
- Plasma
- Radio Frequency
 - Electromagnetic Waves, Frequency Domain (emw)**
 - Electromagnetic Waves, Time Explicit (temte)
 - Electromagnetic Waves, Transient (temw)
 - Transmission Line (tl)
- Semiconductor
- Structural Mechanics
- Mathematics

Add

Added physics interfaces:

- Electromagnetic Waves, Frequency Domain (emw)

Remove

← Space Dimension → Study

? Help X Cancel ✓ Done

Electromagnetic Waves, Frequency Domain

The Radio Frequency, Electromagnetic Waves, Frequency Domain interface is used to solve for time-harmonic electromagnetic field distributions.

For this physics interface, the maximum mesh element size should be limited to a fraction of the wavelength. The domain size that can be simulated thus scales with the amount of available computer memory and the wavelength. The physics interface supports the study types Frequency Domain, Eigenfrequency, Mode Analysis, and Boundary Mode Analysis. The Frequency Domain study type is used for source driven simulations for a single frequency or a sequence of frequencies. The Eigenfrequency study type is used to find resonance frequencies and their associated eigenmodes in resonant cavities.

This physics interface solves the time-harmonic wave equation for the electric field.

COMSOL: Last Time

The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The ribbon below the menu bar contains various tool icons for Application Builder, Model, Definitions, Geometry, Materials, Physics, Mesh, and Study.

The **Model Builder** panel on the left shows a tree view of the model structure for "Untitled.mph (root)":

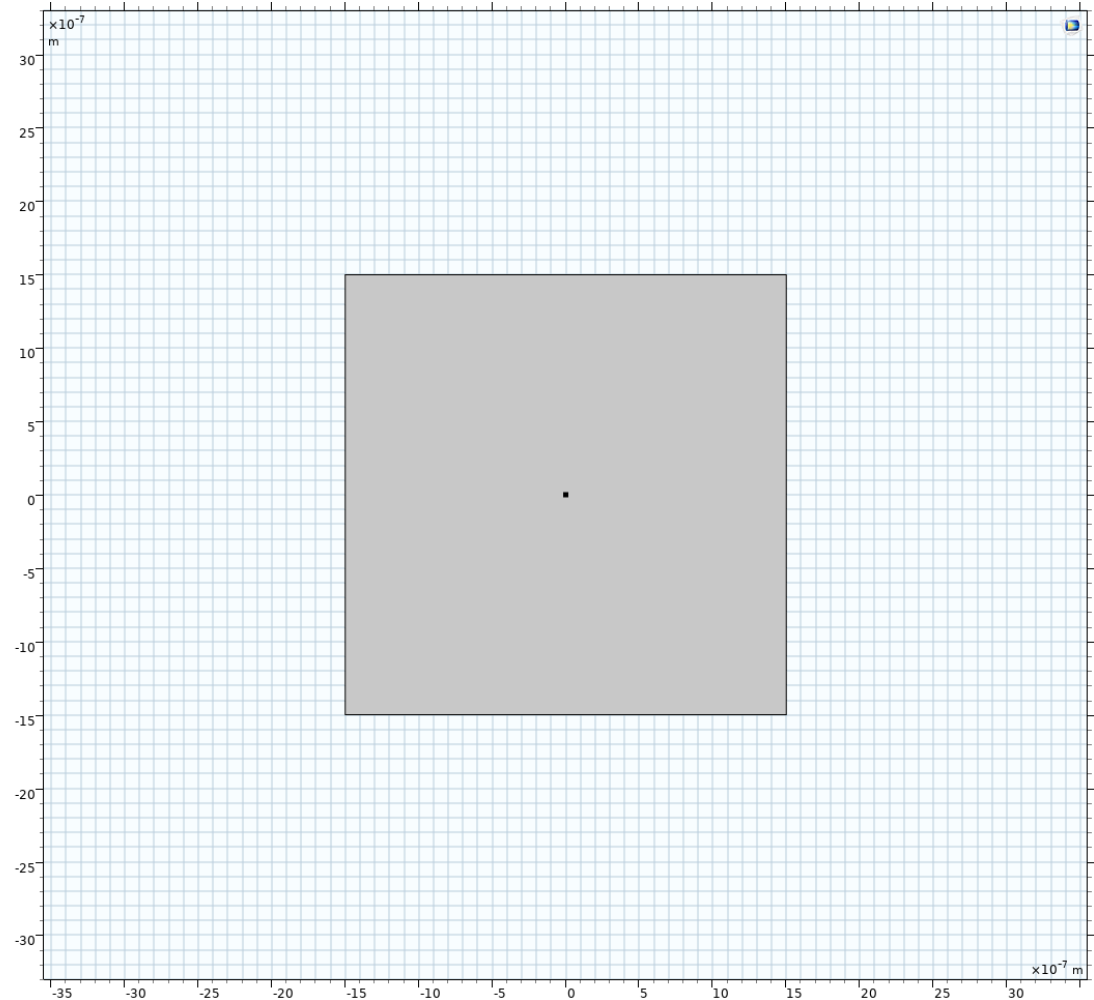
- Global Definitions
- Materials
- Component 1 (comp1)
 - Definitions
 - Geometry 1 (circled in red)
 - Materials (circled in green)
 - Electromagnetic Waves, Frequency Domain (emw) (circled in blue)
 - Wave Equation, Electric 1
 - Perfect Electric Conductor 1
 - Initial Values 1
 - Equation View
 - Mesh 1 (circled in blue)
 - Study 1 (circled in pink)
 - Step 1: Eigenfrequency
 - Solver Configurations
 - Job Configurations
 - Results

The **Settings** panel on the right shows the configuration for the selected **Geometry 1** object:

- Label: Geometry 1
- Units
 - Scale values when changing units:
 - Length unit: m
 - Angular unit: Degrees
- Advanced
 - Default relative repair tolerance: 1E-6
 - Automatic rebuild:

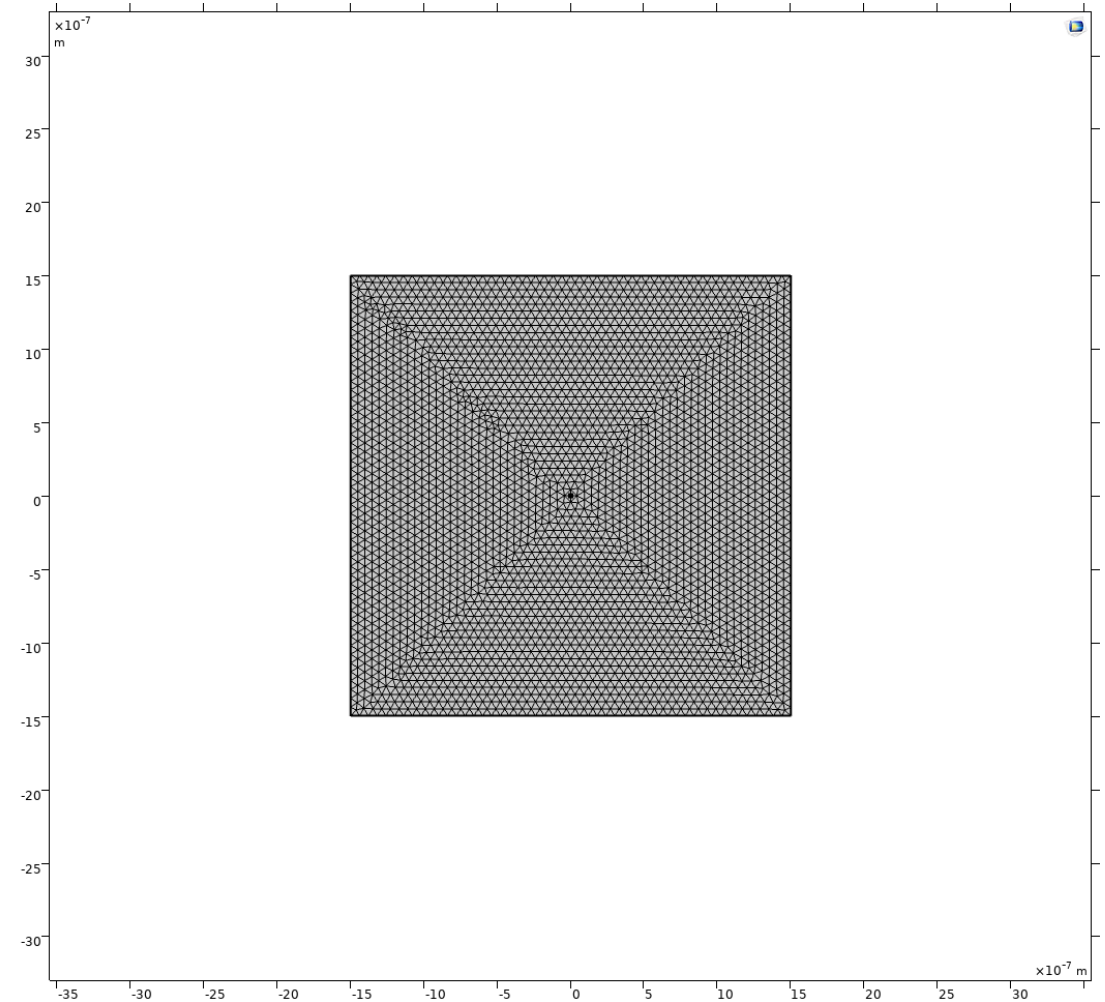
COMSOL: Last Time

- Define simulation domain
- Build geometry

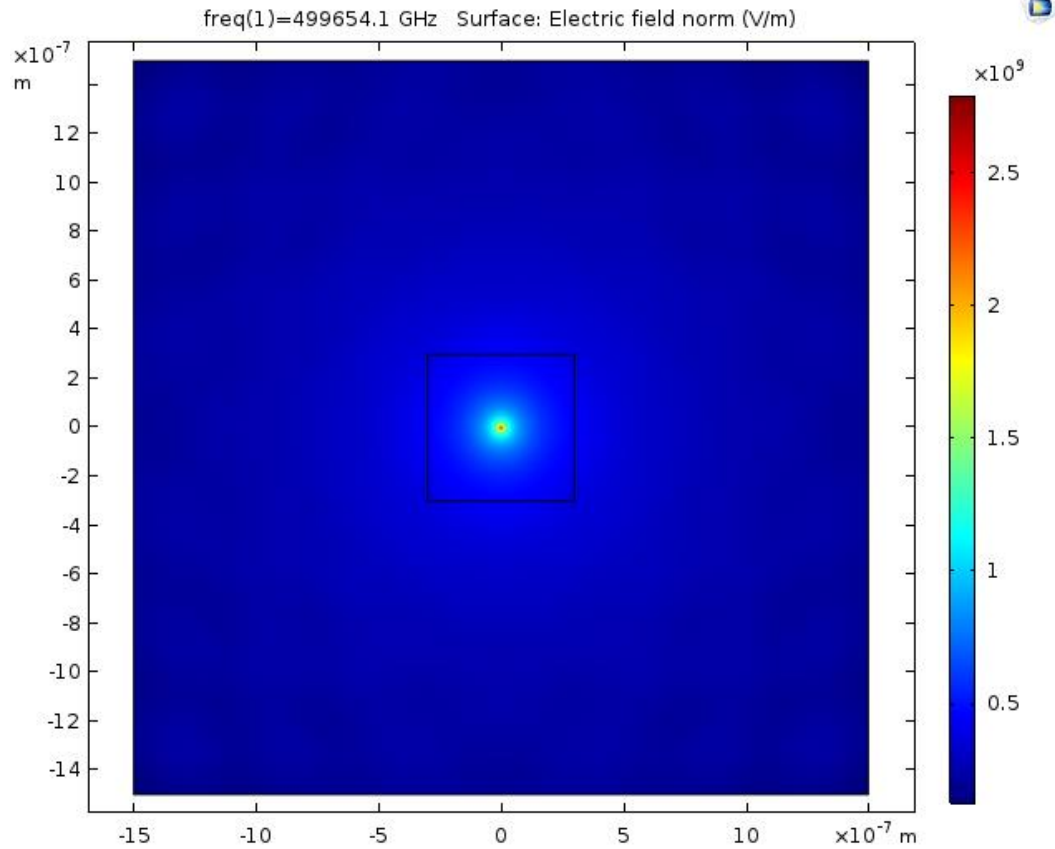


COMSOL: Last Time

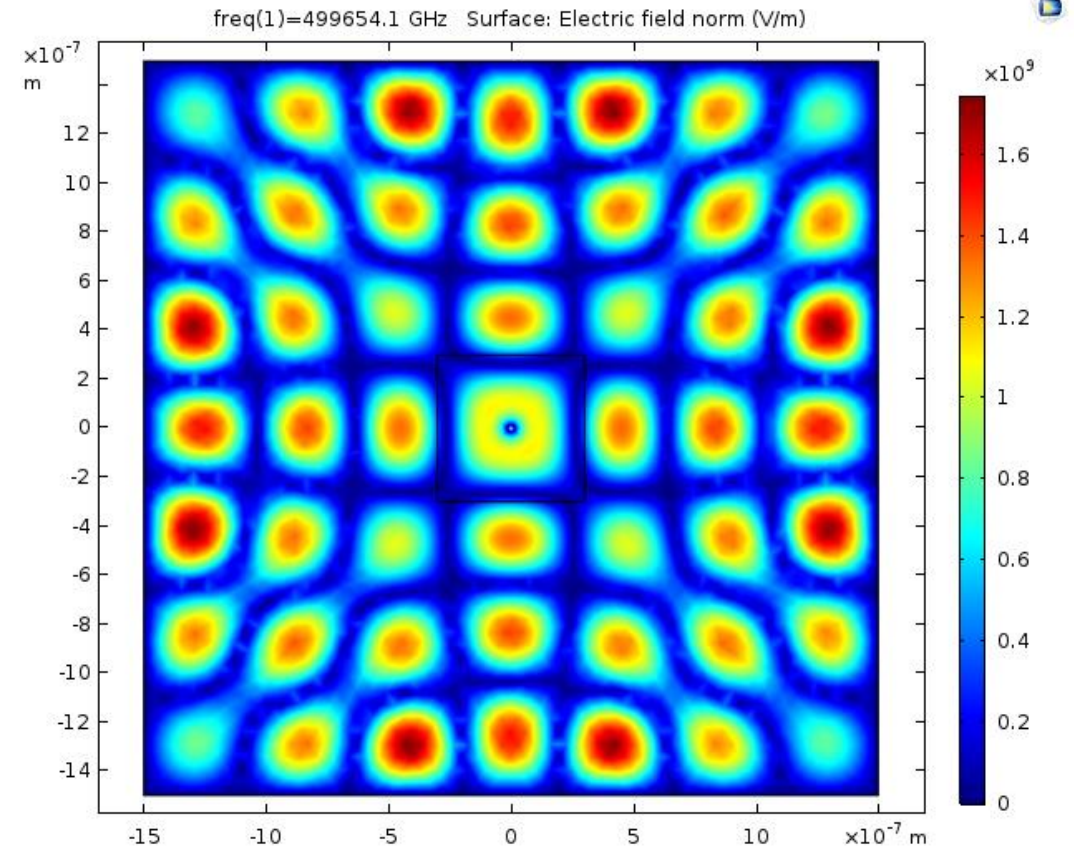
- Discretization of simulation domain
 - Build mesh
- Mesh size determines accuracy of solution
 - Too large mesh \Rightarrow wrong results
- Accuracy vs. simulation time
 - **Today:** Optimization by manual refinement



COMSOL: Last Time



Scattering Boundaries



PEC Boundaries

COMSOL: Today

- Mirror effect by using boundary conditions
- Double Source

