ETH zürich

P&S COMSOL® Design Tool

Week 2: EM Introduction & Introduction to COMSOL

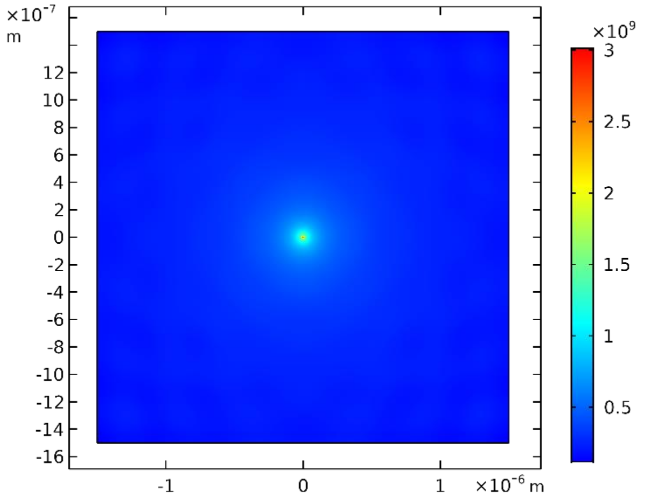
Manuel Kohli, Raphael Schwanninger

Recap

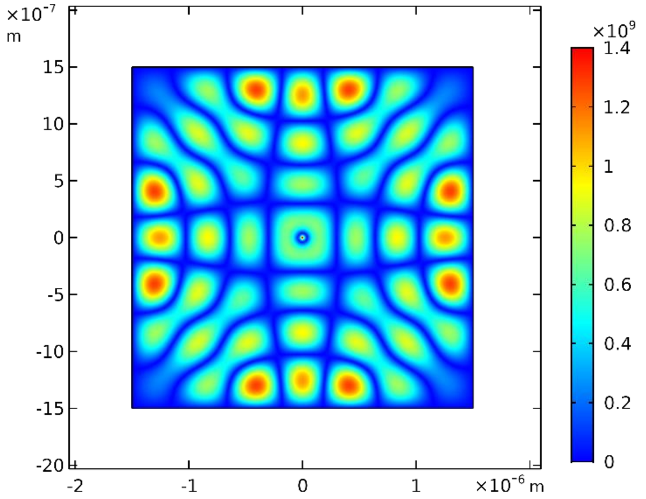
- Last Time
  - Introduction to COMSOL
  - Point Source model
    - Scattering Boundary Conditions
    - Perfect Electric Conduction (PEC)

- Today
  - More on Boundary Conditions
    - Perfect Electric Conductor (PEC)
    - Perfect Magnetic Conductor (PMC)
    - Scattering Boundary Condition
    - Periodic Boundaries Condition (PBC)
    - Perfectly Matched Layer (PML)

Scattering

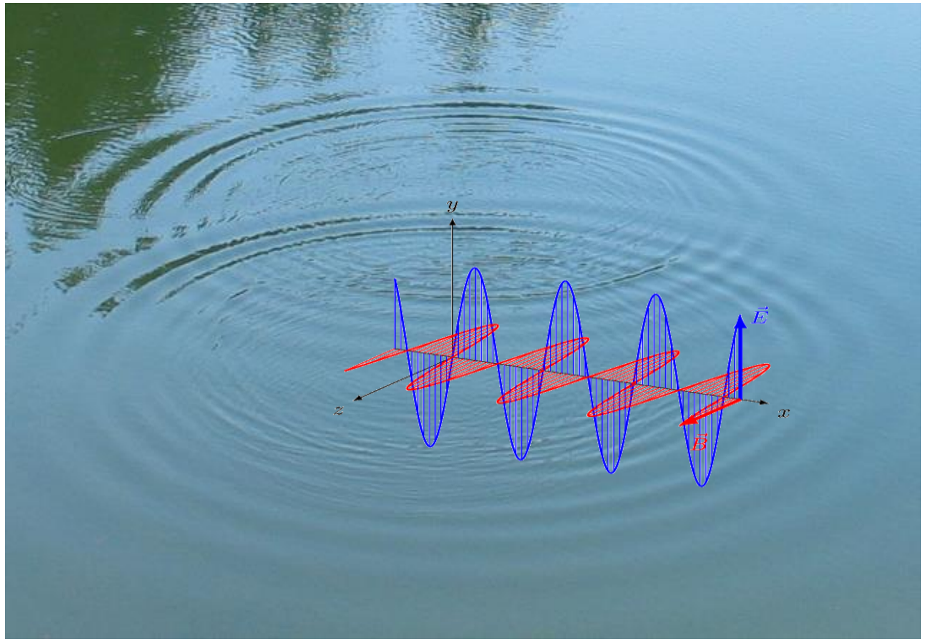


PEC



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

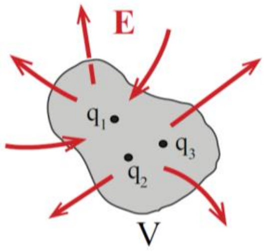


Electromagnetics: Maxwell's Equations

- Physical phenomena and laws

Gauss's law:

$$\oint_{\partial V} D\, dA = \int_V \rho dV$$

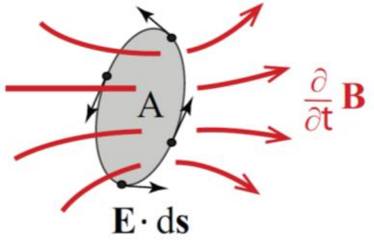


Electric displacement Field D

(Free) charge density ρ

Faraday's law:

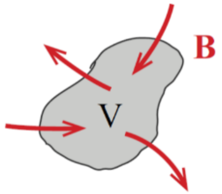
$$\oint_{\partial A} E\, ds = -\frac{\partial}{\partial t}\int_A B\, dA$$



Electric Field H

Gauss's law (Magnetism):

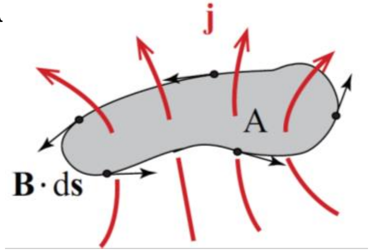
$$\oint_{\partial V} B\, dA = 0$$



Magnetic Flux Density B

Ampère's law:

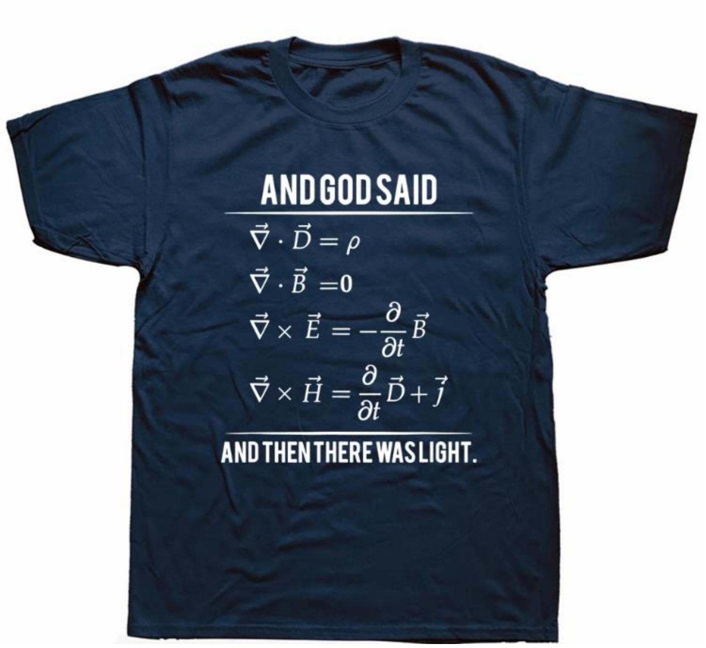
$$\oint_{\partial A} H\, dl = \int_A \left(J + \frac{\partial D}{\partial t}\right) dA$$



(Free) current density J

Magnetic Field 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

Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Electromagnetics: Materials Relations

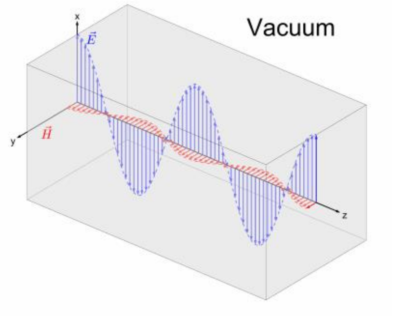
- In order to analyze an EM problem we need to define the **material properties** involved
- Materials are defined by their **refractive index $\boldsymbol{n}$** which is defined as
  - $\boldsymbol{n} = \sqrt{\boldsymbol{\mu_r \varepsilon_r}}$, for vacuum $n = 1$
  - n is a complex number $n = n' + ik$

Influences wavelength

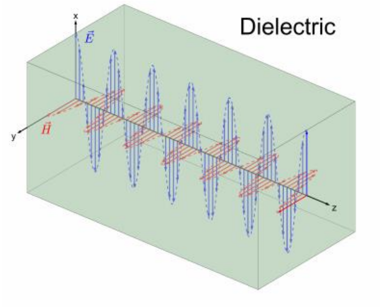
Influences losses

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

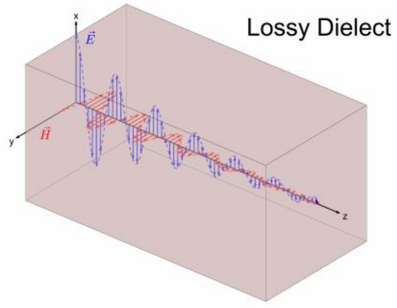
$n = 1$



$n = 3$



$n = 3 + 2i$



Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Electromagnetics: Maxwell's Equations

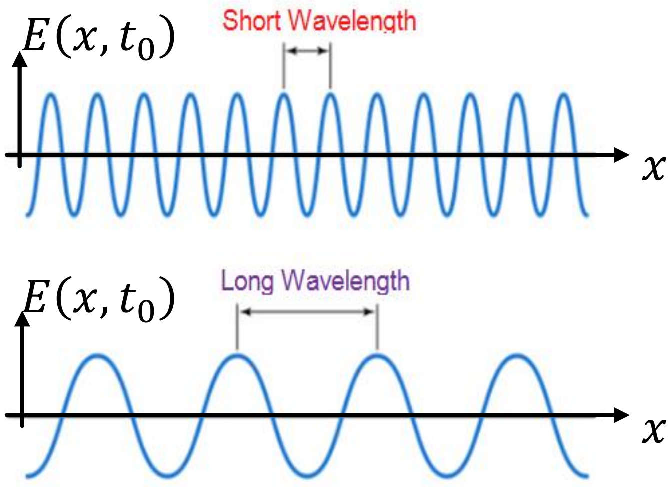
- Wave Equation from Maxwell's Equations
  - Homogenous, Isotropic, linear Material,
  - No Sources

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

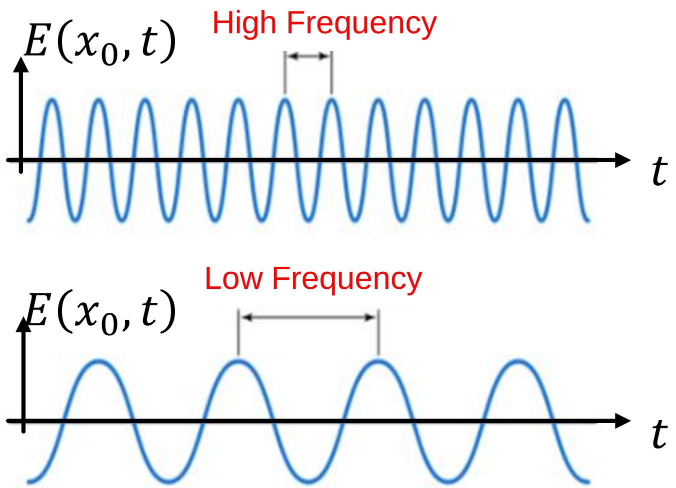
- Solution

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

<u>Fixed time</u>



<u>Fixed Location</u>



Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

Electromagnetics: Wavelength and Frequency

- Plane wave Solution:

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

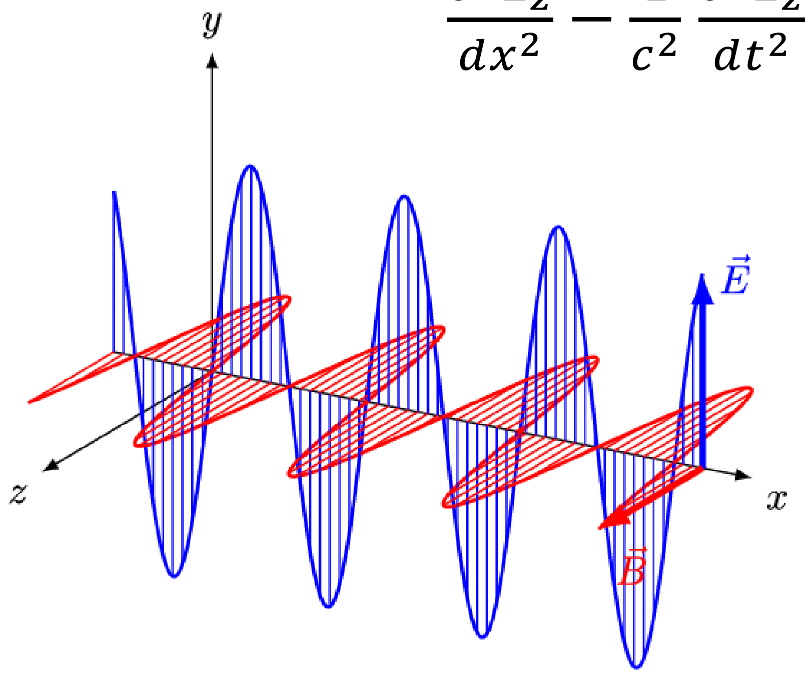
- Proof:

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

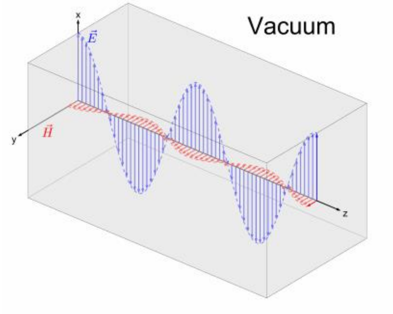
- With

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

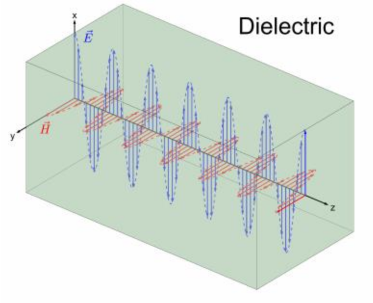
$$\frac{\partial^2 E_z}{dx^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{dt^2} = 0$$



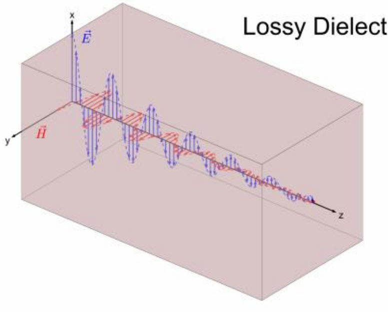
$n = 1$



$n = 3$

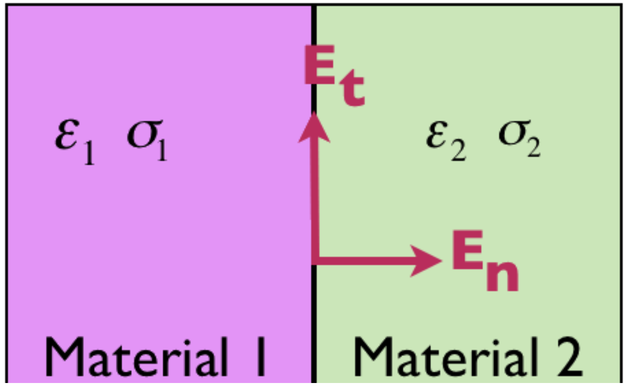


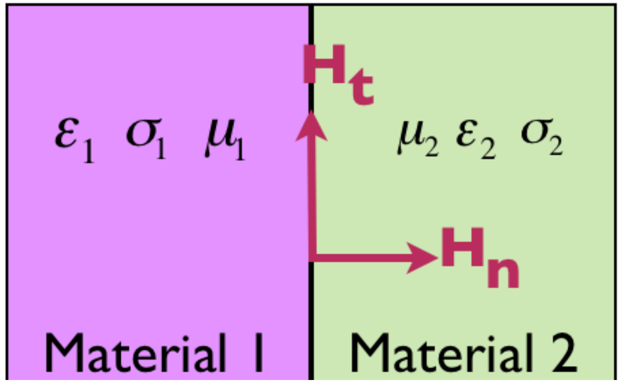
$n = 3 + 2i$



Boundary Conditions

- Maxwell's Boundary Conditions





Boundary Conditions

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

$\varepsilon_1 E_{n,1} - \varepsilon_2 E_{n,2} = \rho_f$ (surface charge density at the interface)

$H_{t,1} - H_{t,2} = J_s$ (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

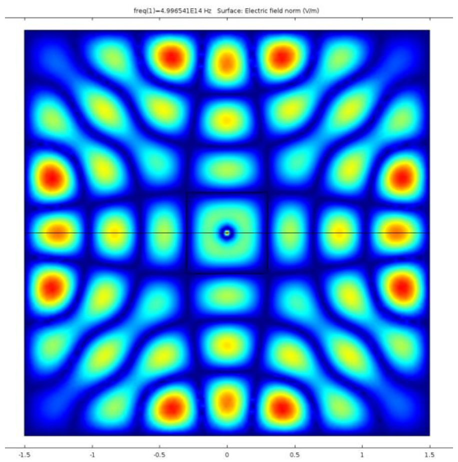
227-2037-00L: Physical Modelling and Simulation

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

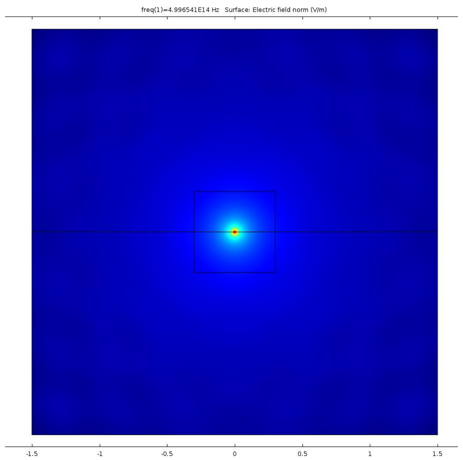
COMSOL: Boundary Conditions

- Purpose of boundary conditions → define simulation domain

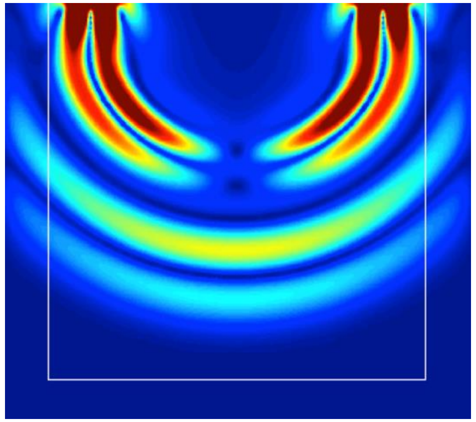
- Types of boundary conditions in COMSOL
  - Perfect Electric Conductor (PEC)
  - Perfect Magnetic Conductor (PMC)
  - Scattering Boundary Condition
  - Periodic Boundaries Condition (PBC)
  - Perfectly Matched Layer (PML)



PEC Boundaries



Scattering Boundaries



PML Boundaries

Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

COMSOL: Boundary Conditions

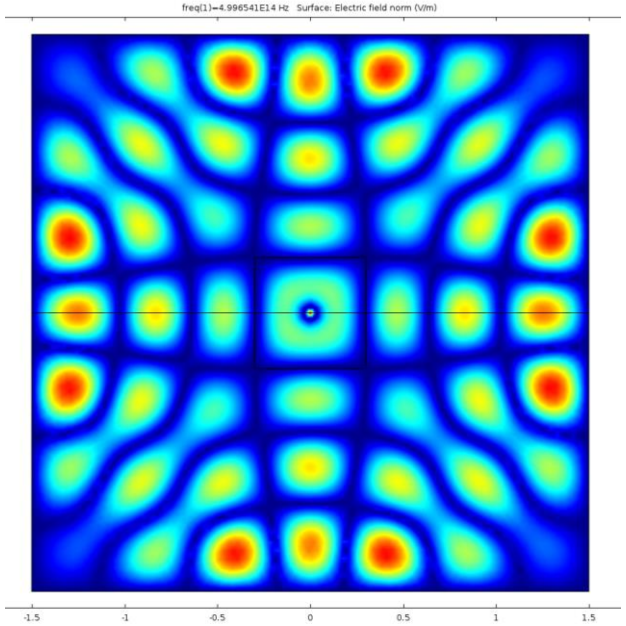
- **Perfect Electric Conductor (PEC)**
  - Properties
    - Equivalent to infinite electric conductivity
    - $\lim_{\sigma\to\infty} j = \lim_{\sigma\to\infty} \sigma E = \infty$ => $E = 0$: No Electric fields inside
    - $E = 0$: Constant magnetic field inside

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

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

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

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



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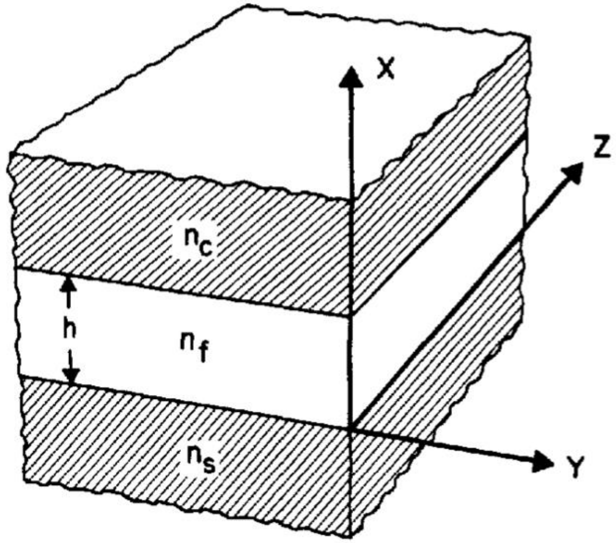
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

COMSOL: Boundary Conditions

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

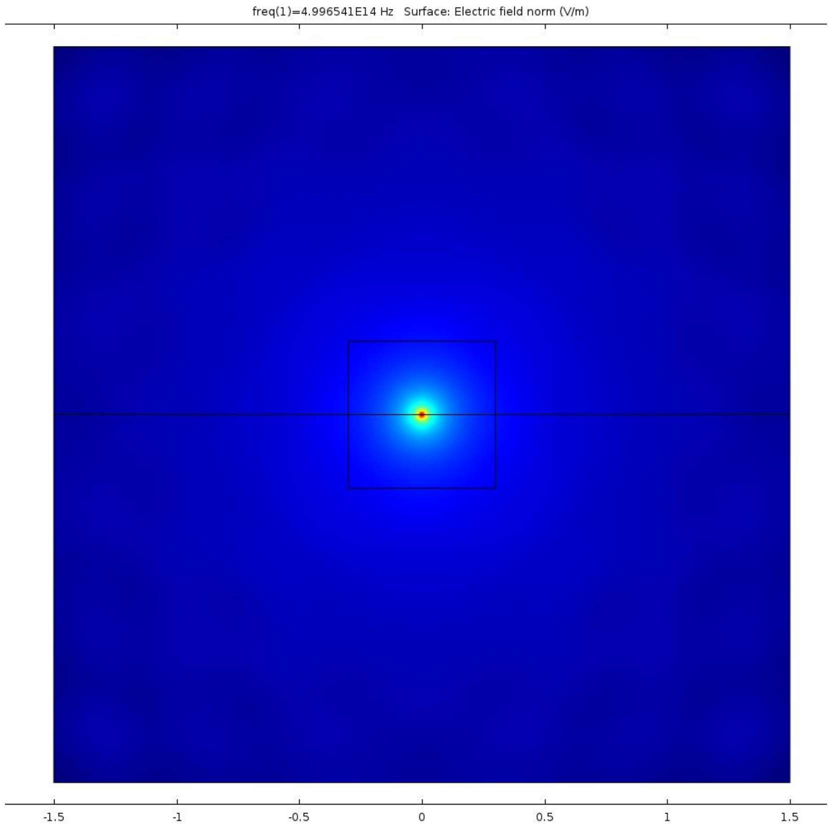
$$\mu_1 H_{n,1} - \mu_2 H_{n,2} = 0$$

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



COMSOL: Boundary Conditions

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



Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
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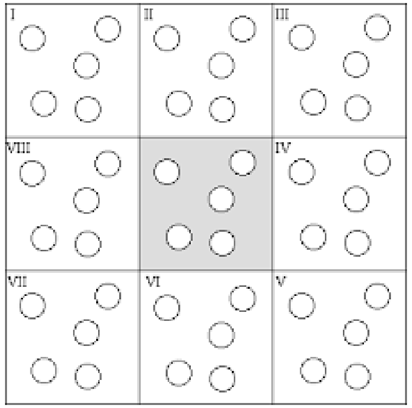
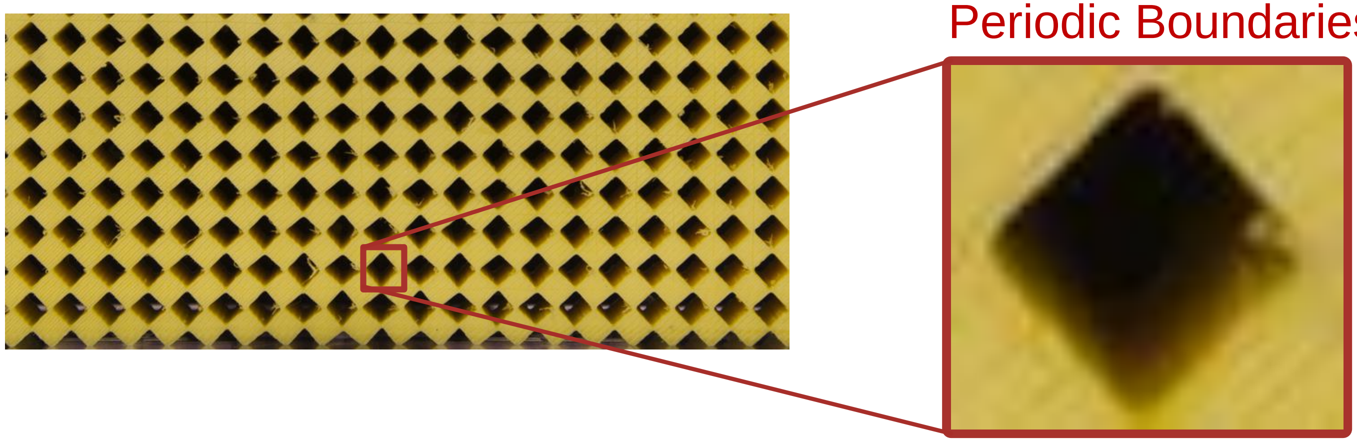
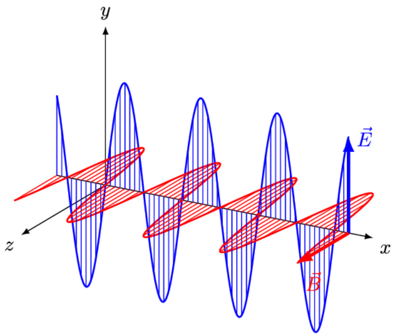
COMSOL: Boundary Conditions

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



Periodic Boundaries



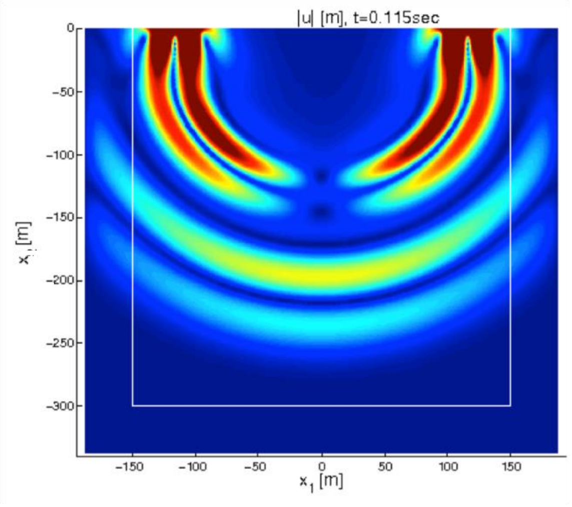


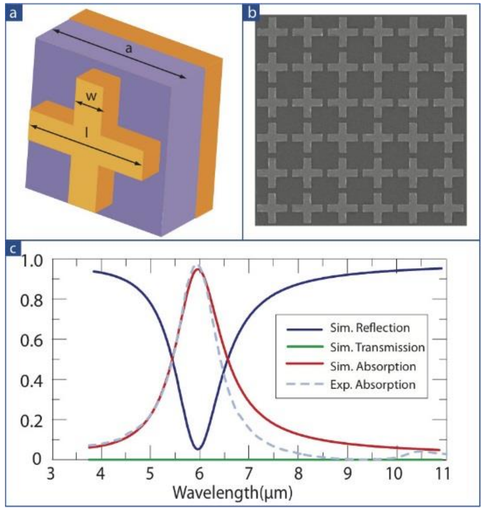
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

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

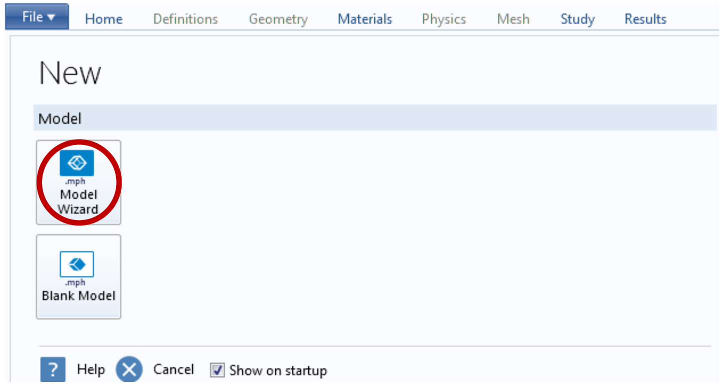
3) Connect to Linux Server
   - Linux & Mac: using terminal type **«ssh username@itet-ief-l0.ethz.ch -X»** (l0 = L null)
   - Windows, Linux, Max: using any remote desktop with xserver capability (e.g. Remmina)

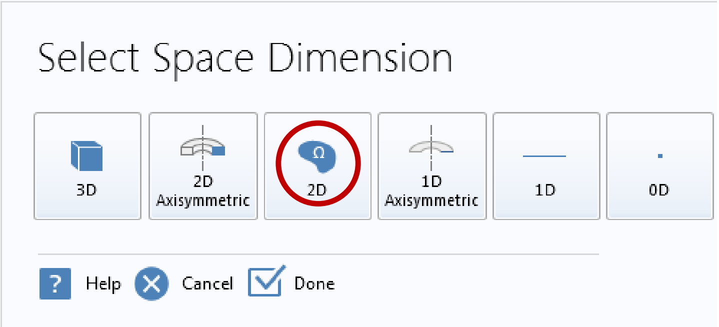
4) Enter Username and Password

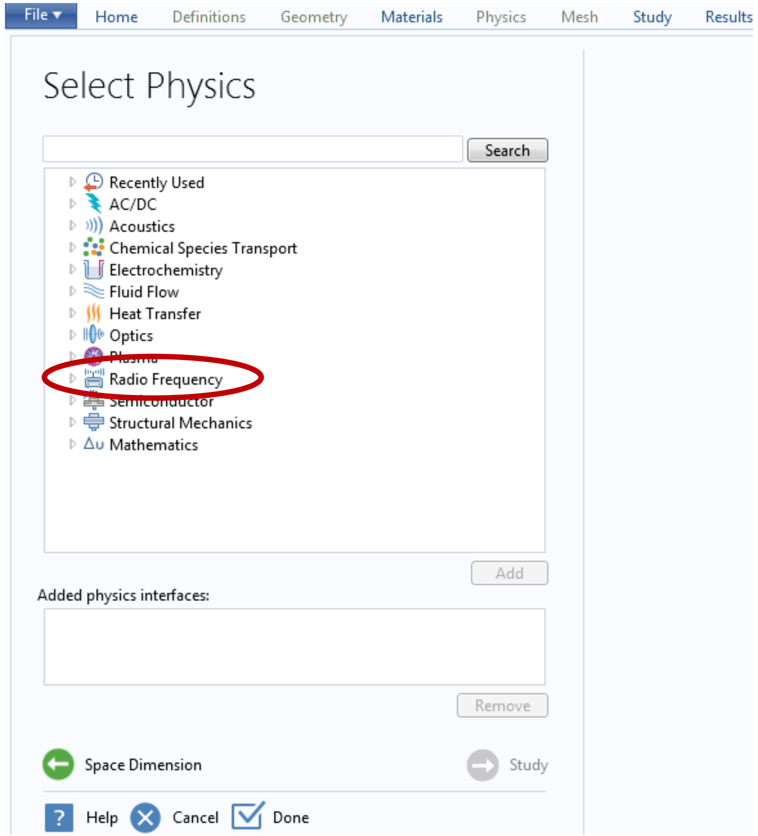
5) Start COMSOL
type: «comsol &» into the terminal

COMSOL: Last Time

Command to start Comsol: comsol







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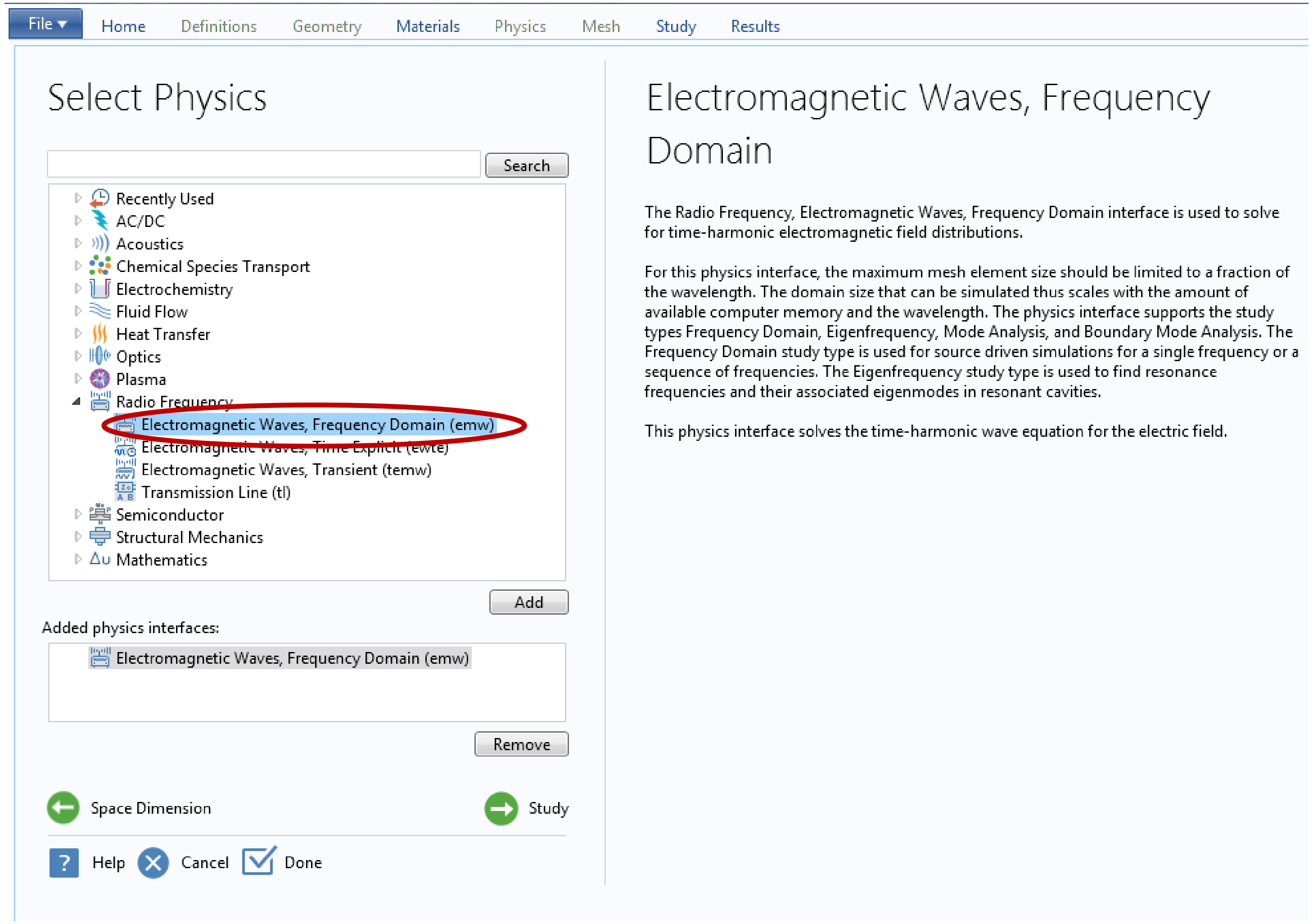
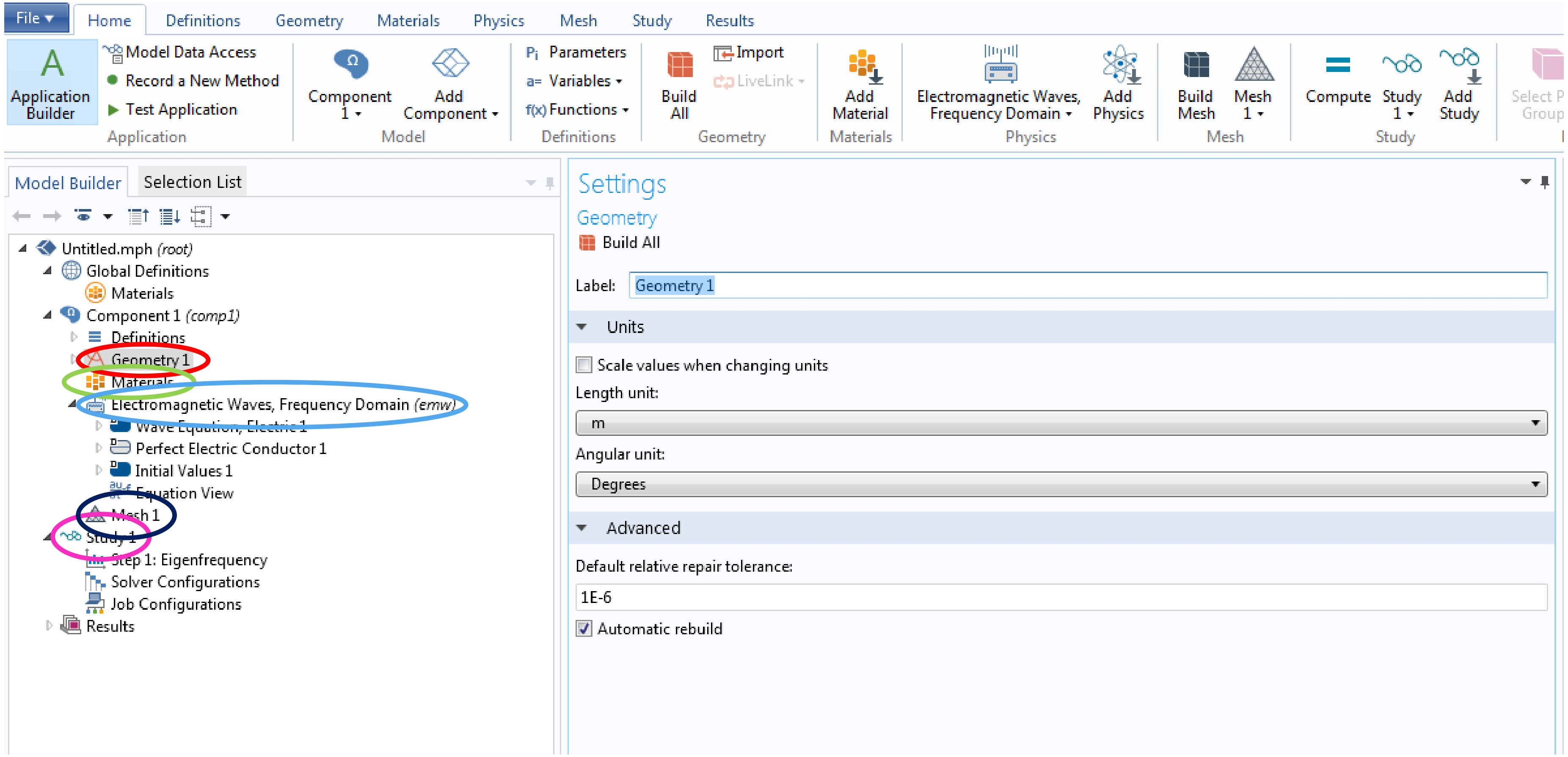
COMSOL: Last Time

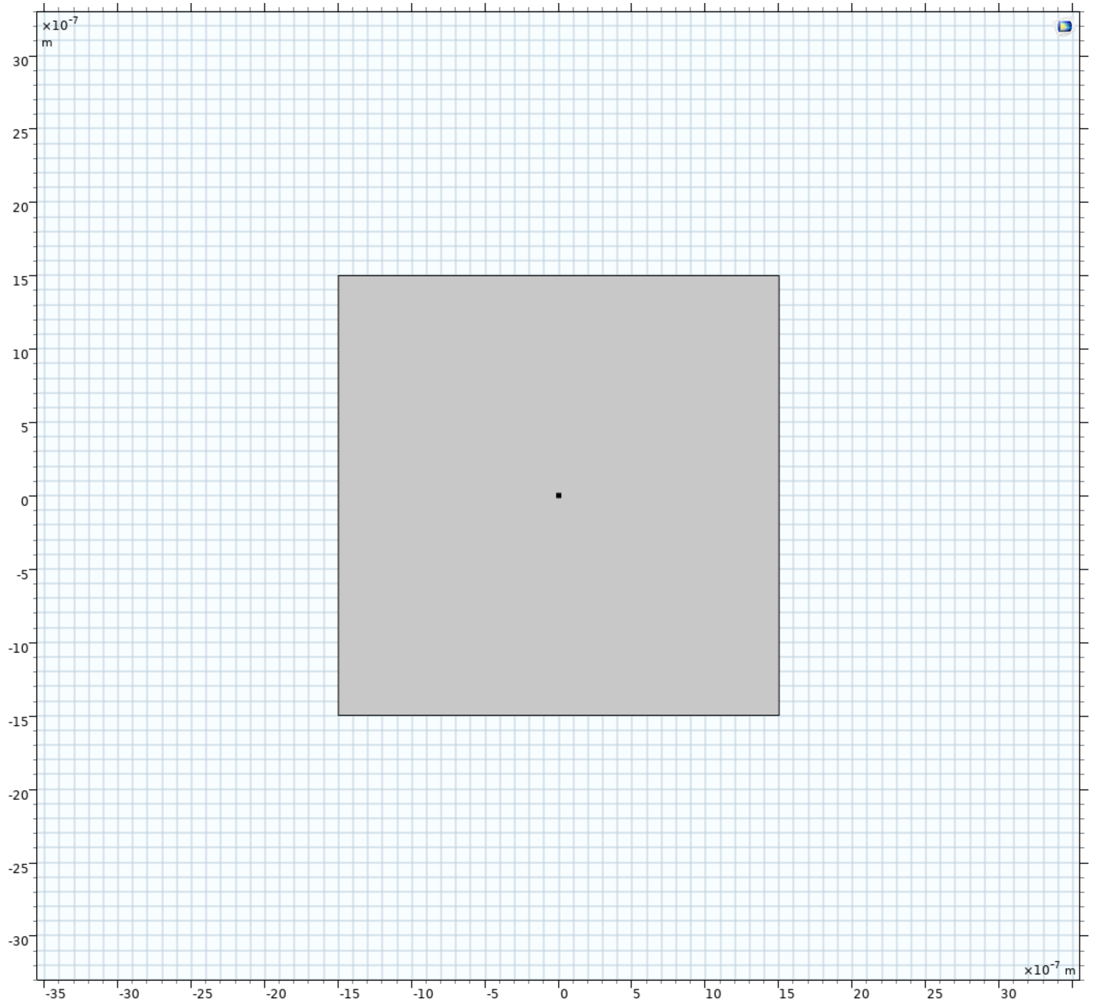


COMSOL: Last Time



COMSOL: Last Time

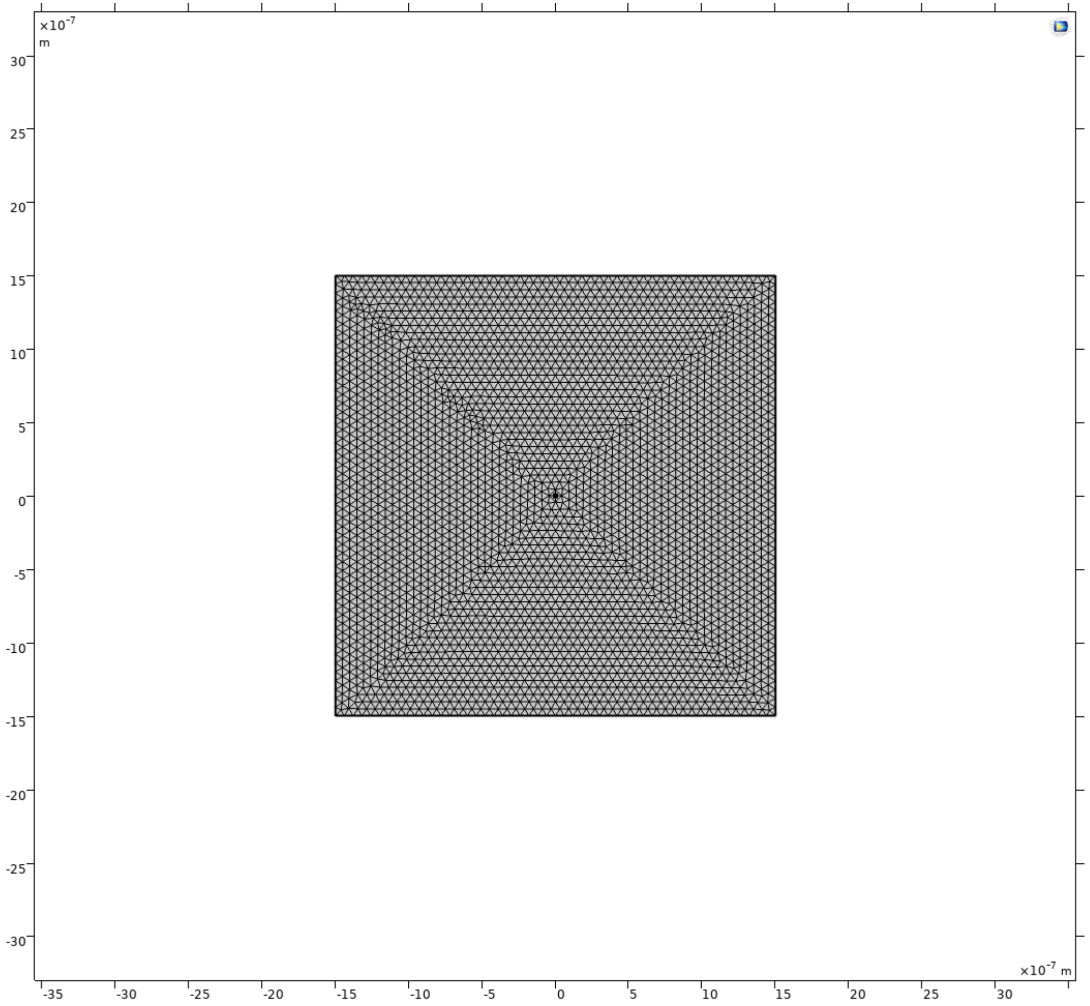
- Define simulation domain
- Build geometry



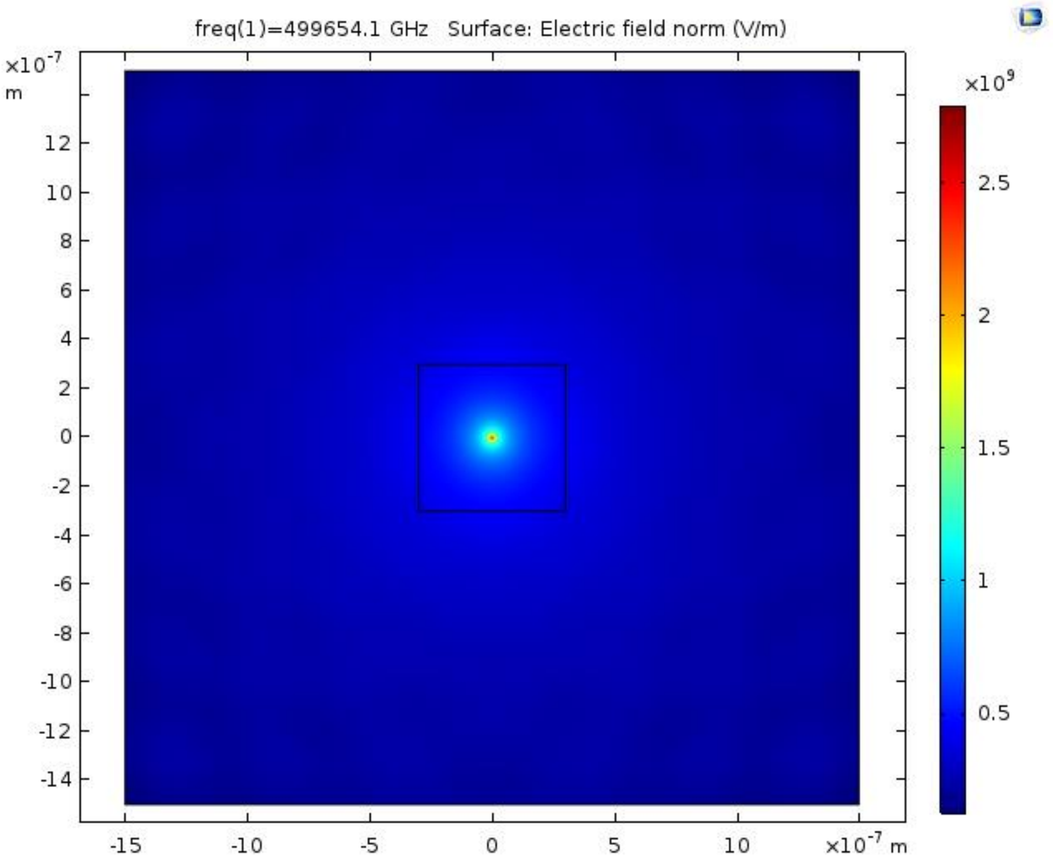
Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

COMSOL: Last Time

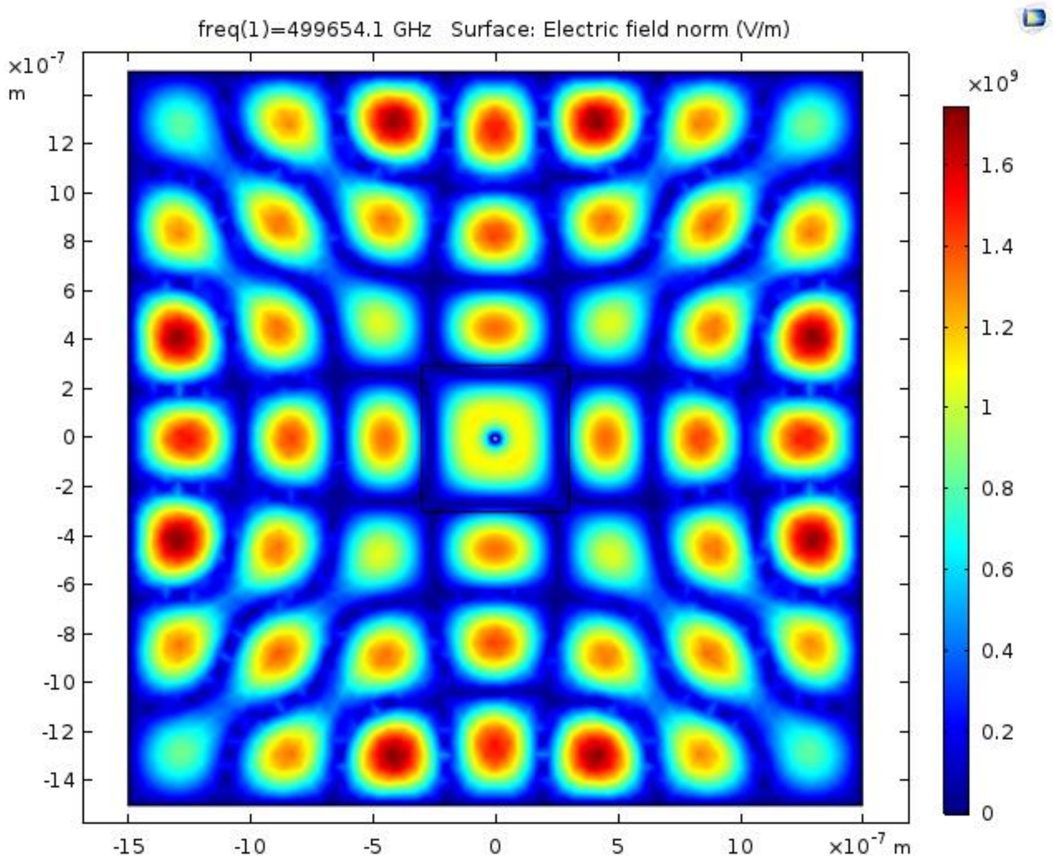
- Discretization of simulation domain
  - Build mesh
- Mesh size determines accuracy of solution
  - Too large mesh ⇒ wrong results
- Accuracy vs. simulation time
  - **Today**: Optimization by manual refinement



COMSOL: Last Time



Scattering Boundaries



PEC Boundaries

Manuel Kohli – manuel.kohli@ief.ee.ethz.ch
Raphael Schwanninger – raphael.schwanninger@ief.ee.ethz.ch

COMSOL: Today

- Mirror effect by using boundary conditions
- Double Source