ETH zürich

P&S COMSOL® Design Tool

Week 2: EM Introduction & Introduction to COMSOL

Manuel Kohli, Raphael Schwanninger

Content

- Recap

- Electromagnetics Introduction
  - Wavelength and Frequency
  - Spectrum
  - Maxwell's Equations
  - Wave Equation
  - Material Relations
  - Boundary Conditions

- COMSOL
  - Last Time
  - Today

Learning Objectives

- In this course, we aim to teach you the process of optical component design
- You will learn to:

… **develop** a component idea into a specific design problem

… **create** the correct simulation environment (model the photonic device)

… **analyze** simulation results and **interpret** different physical effects involved

… **evaluate** the design according to initial specifications and recommend improved solution

… **summarize** the results and report them

Semester Outline

- Simulation concept
  - EM review
  - 2D EM simulation
- Intro to COMSOL tools
  - Wave optics
  - Mode solver
  - Boundary mode solver

6 weeks

- Project
  - Presentation
  - Report

6 weeks
Final presentation: Monday, 29.05.2023
Report : Monday, 05.06.2023

If there is a conflict, please let us know early

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Practical Information – Administrative

- Time: Mondays from **13:15h** to **~15:00 h**
- Location: **ETZ D61.1**
- Our availability: office hours ETZ K-floor

(*Send email to schedule a meeting*)

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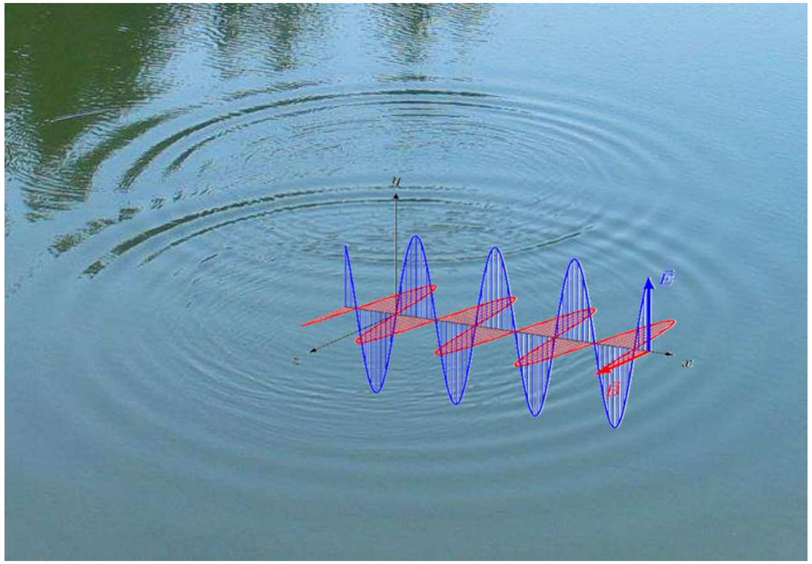
About us

- Raphael Schwanninger
  - Mid- IR Photodetectors based on colloidal quantum dot materials
  - Metamaterials for absorption enhancement schemes
    - Simulation of different detector concepts
    - Fabrication of detectors with novel materials

- Manuel Kohli
  - Ferroelectric electro-optic modulators on SiN
    - Photonic integration of different platforms
    - Design, fabrication, and measurement
    - “Optical Machine” Assembly (PIC + EIC)
  - 3D Nanofabrication for novel components

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



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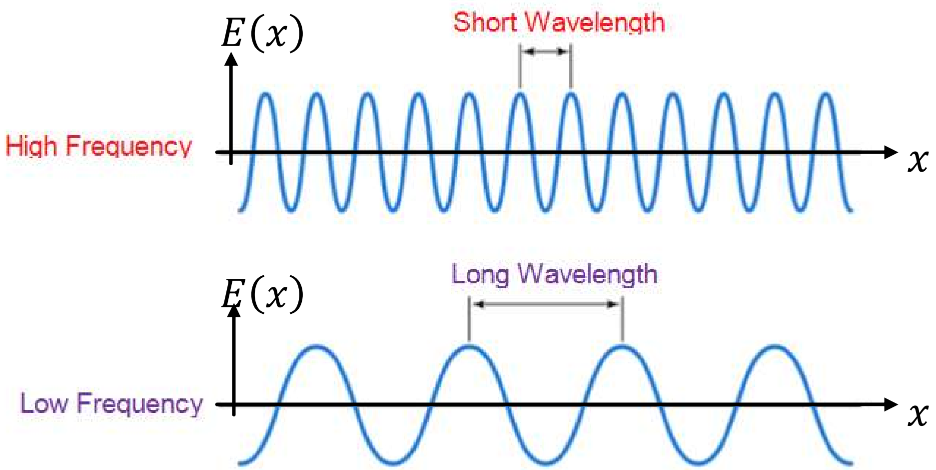
Electromagnetics: Wavelength and Frequency

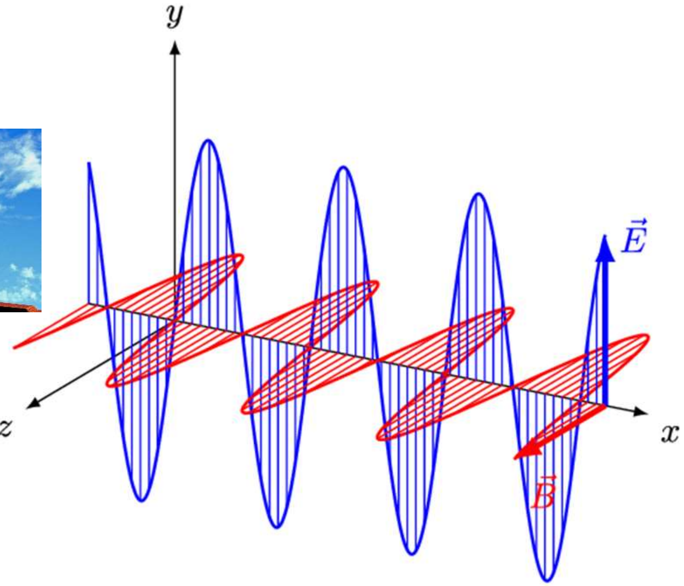
- One moment in time, electric field:



- $f = \frac{c}{\lambda}$, c is the speed of light

Let's see what happens over time:

Antenna



→ Electric field vector changes in time and space

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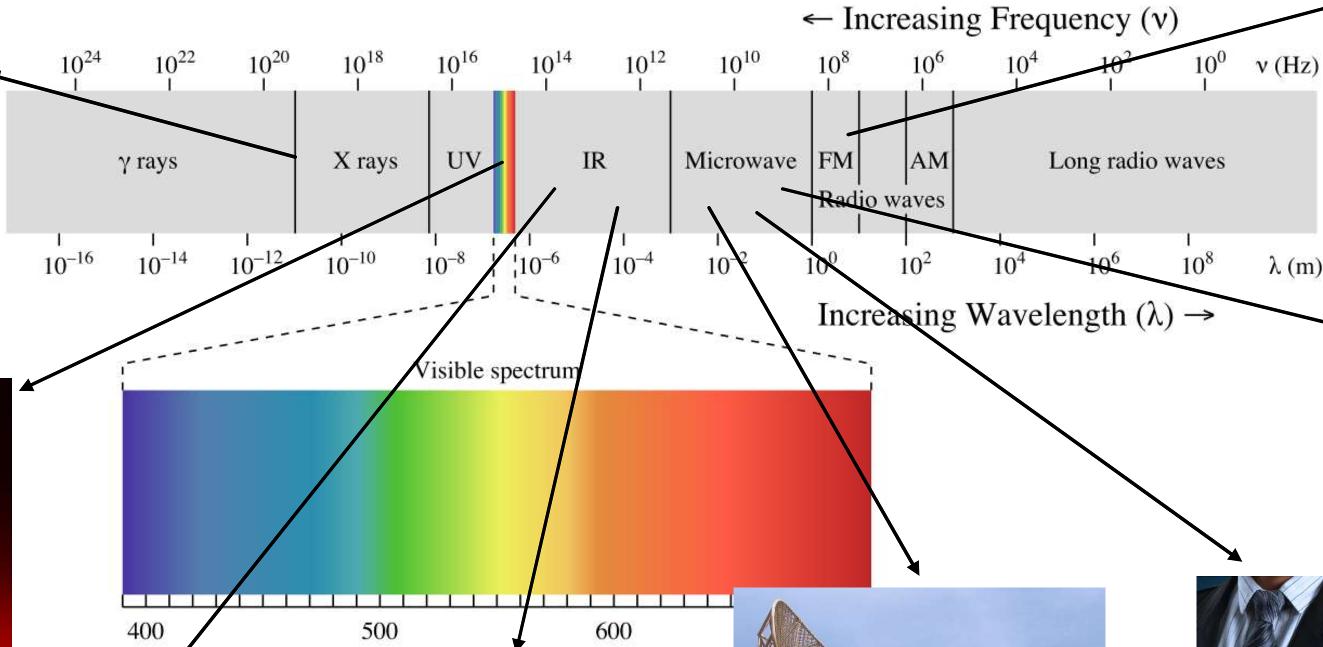
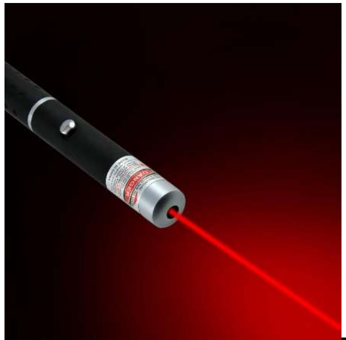
Electromagnetics in Our Daily Life

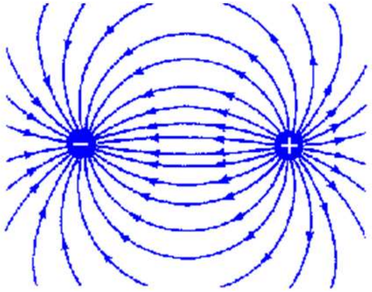




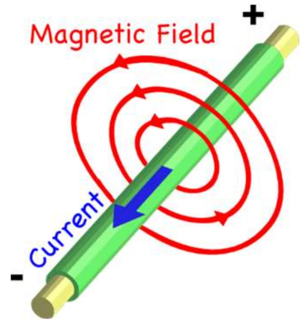
Electromagnetics: What you've seen before

- Physical phenomena and laws

Electric field between positive and negative charge



Current flows
→ magnetic field



Faraday's law of induction

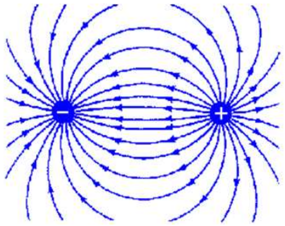
$$u(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt}\iint_A \vec{B} \cdot d\vec{A}$$

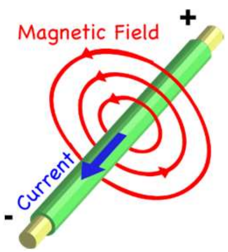
Coulomb force: $F = Eq$
Ohmic law: $U = R \cdot I$
Kirchhoff current & voltage law:

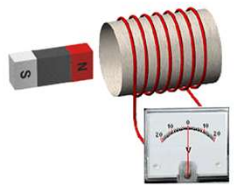
$$\sum_{node} I_i = 0, \sum_{loop} U_i = 0$$

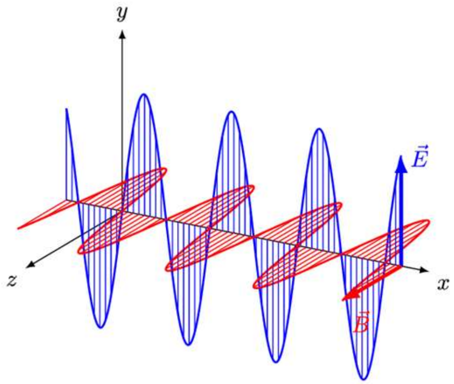
Electromagnetics: Maxwell's Equations

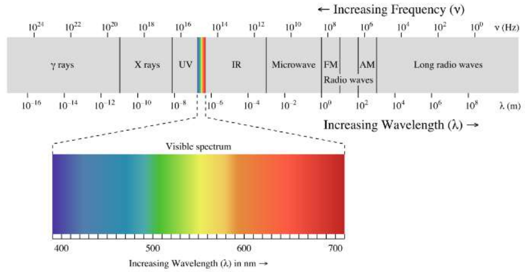
- All of these can be explained with











Only 4 equations ! → Maxwell's equations

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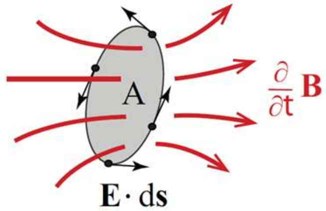
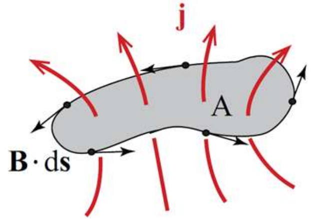
Electromagnetics: Maxwell's Equations

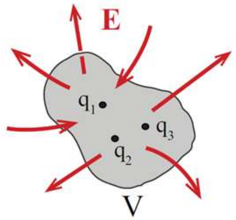


Electric field E — 1. $\oint_{\partial A} E\, ds = -\frac{\partial}{\partial t}\int_A B\, dA$ — Magnetic field B

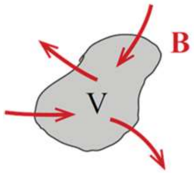


Magnetic field H — 2. $\oint_{\partial A} H\, dl = \int_A \left(J + \frac{\partial D}{\partial t}\right) dA$ — Current density J, Electric displacement Field D

Electric displacement field D — 3. $\oint_{\partial V} D\, dA = \int_V \rho dV$ — Charge density ρ



Magnetic field B — 4. $\oint_{\partial V} B\, dA = 0$



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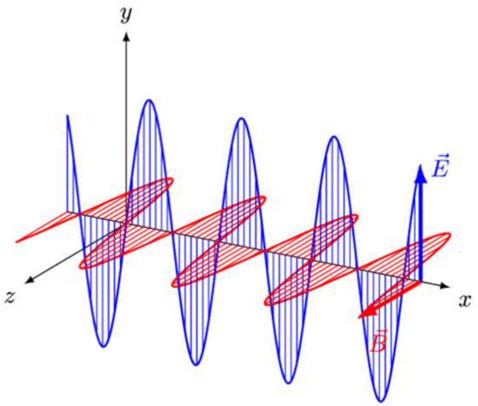
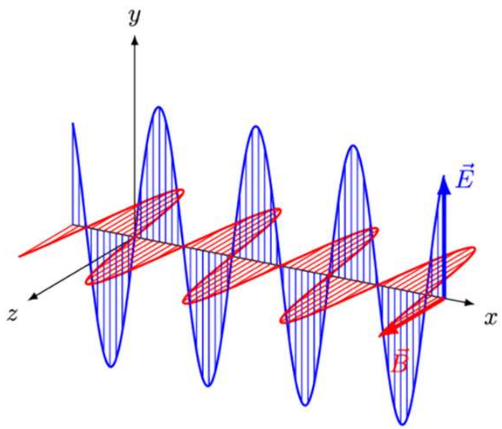
Electromagnetics: Maxwell's Equations

- Electrodynamics

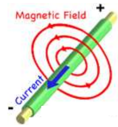


1. $\oint_{\partial A} E\, ds = -\cancel{\frac{\partial}{\partial t}\int_A B\, dA}$
2. $\oint_{\partial A} H\, ds = \int_A \left(J + \cancel{\frac{\partial D}{\partial t}}\right) dA$
3. $\oint_{\partial V} D\, dA = \int_V \rho dV$
4. $\oint_{\partial V} B\, dA = 0$

- Electrostatics (no change over time → $\frac{\partial}{\partial t} = 0$)

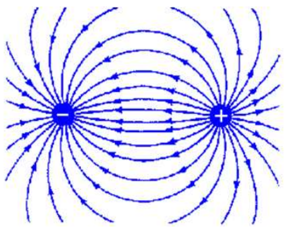


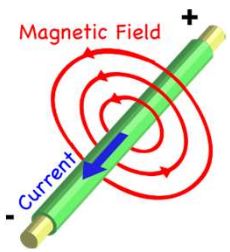
1. $\oint_{\partial A} E\, dl = 0$ (mesh rule)
2. $\oint_{\partial A} H\, dl = \int_A J\, dA = I$
3. $\oint_{\partial V} D\, dA = \int_V \rho dV$
4. $\oint_{\partial V} B\, dS = 0$

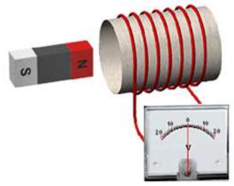


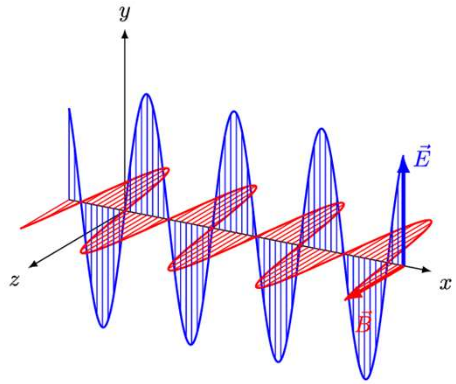
Electromagnetics: Maxwell's Equations

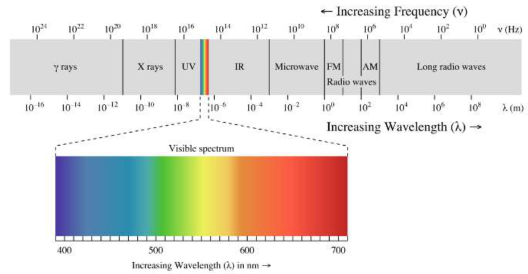
- All of these can be explained with











Only 4 equations ! → Maxwell's equations

1. $\oint_{\partial A} E\, ds = -\frac{\partial}{\partial t}\int_A B\, dA$
2. $\oint_{\partial A} H\, ds = \int_A \left(J + \frac{\partial D}{\partial t}\right) dA$
3. $\oint_{\partial V} D\, dA = \int_V \rho dV$
4. $\oint_{\partial V} B\, dA = 0$

From Maxwell's equations the wave equation can be derived:

$$\boxed{\frac{\partial^2 E_z}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} = 0}$$

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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 $n = n' + ik$

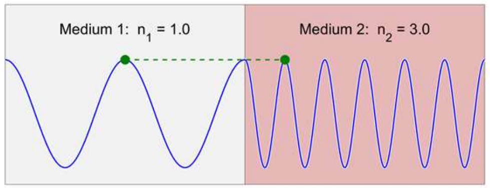
Influences wavelength

Influences losses

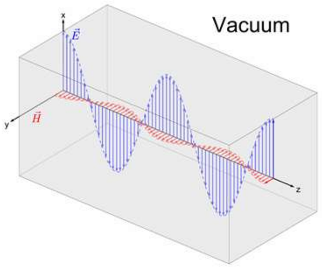
Antenna

Air

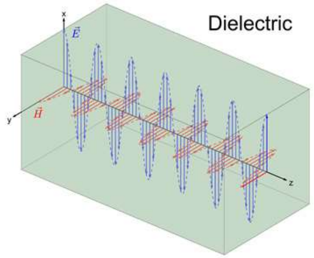
Glass



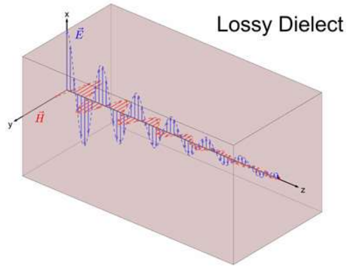
$n = 1$



$n = 3$

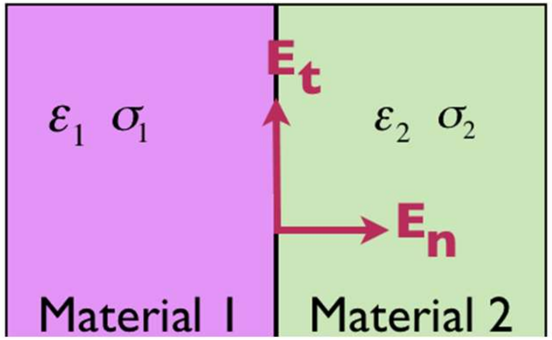


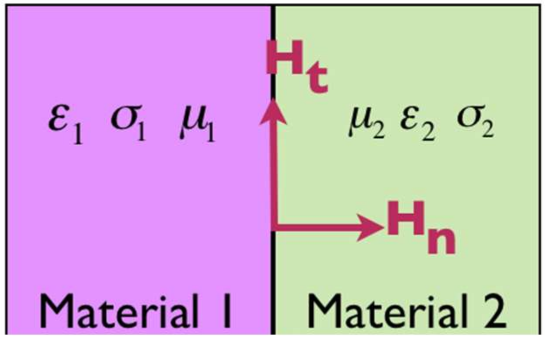
$n = 3 + 2i$



Boundary Conditions

- Maxwell's Boundary Conditions





Boundary Conditions

$E_{t,1} - E_{t,2} = 0$
$\varepsilon_1 E_{n,1} - \varepsilon_2 E_{n,2} = \sigma_f$ (surface charge density at the interface)
$H_{t,1} - H_{t,2} = J_s$ (surface current density at the interface)
$\mu_1 H_{n,1} - \mu_1 H_{n,2} = 0$

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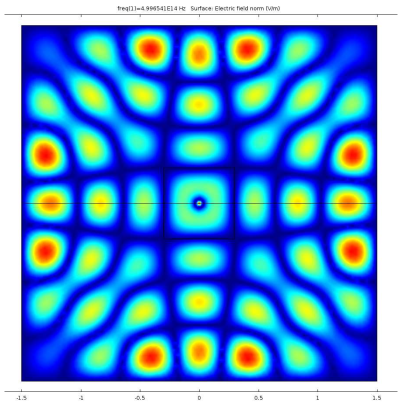
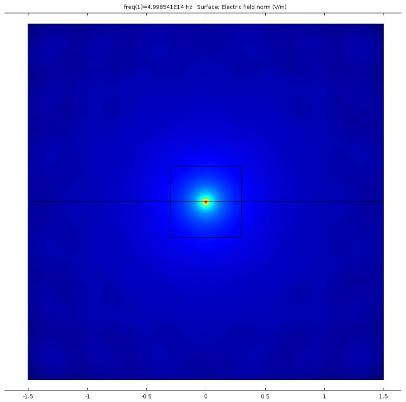
COMSOL: Boundary Conditions

- Purpose of boundary conditions → define simulation domain

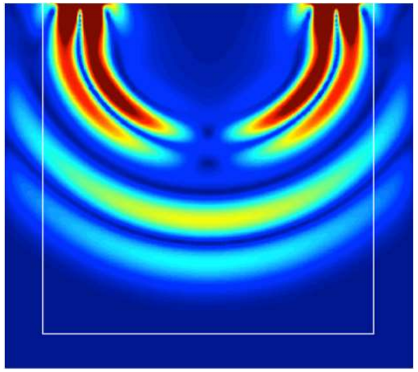
- Types of boundary conditions in COMSOL
  - Perfect Electric Conductor (PEC)
  - Perfect Magnetic Conductor (PMC)
  - Scattering Boundary Condition
  - Periodic Boundaries Condition (PBC)
  - Perfectly Matched Layer (PML)



PEC Boundaries



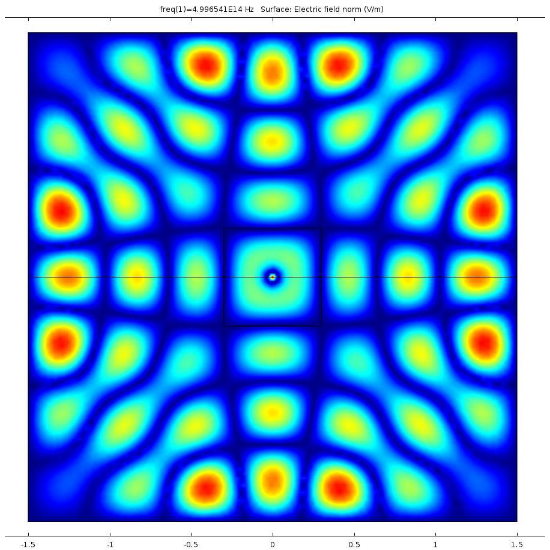
Scattering Boundaries



PML Boundaries

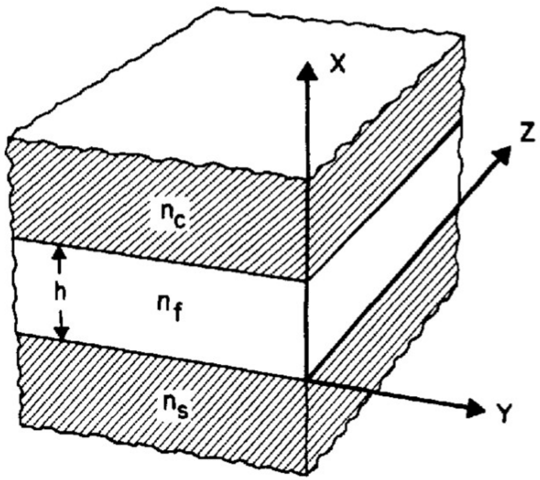
COMSOL: Boundary Conditions

- **Perfect Electric Conductor (PEC)**
  - Properties
    - Electric field cannot penetrate → reflection of electric field
    - Equivalent to infinite electric conductivity
  - Examples
    - Microwave planar structures
    - Metallic substrates
    - Short circuit interface
    - To implement some certain symmetry



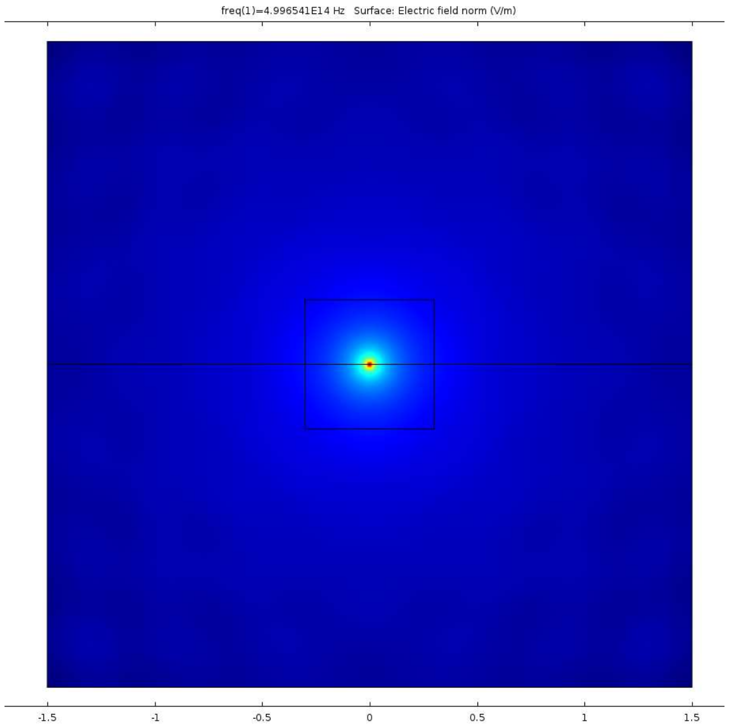
COMSOL: Boundary Conditions

- **Perfect Magnetic Conductor (PMC)**
  - Properties
    - Magnetic field cannot penetrate → reflection of magnetic field
    - Equivalent to infinite magnetic conductivity
  - Examples
    - To account for certain symmetry
    - Interface between dielectric and air
    - Open circuit interface



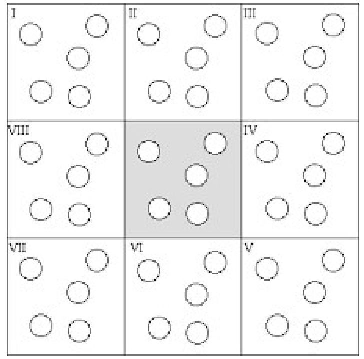
COMSOL: Boundary Conditions

- **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

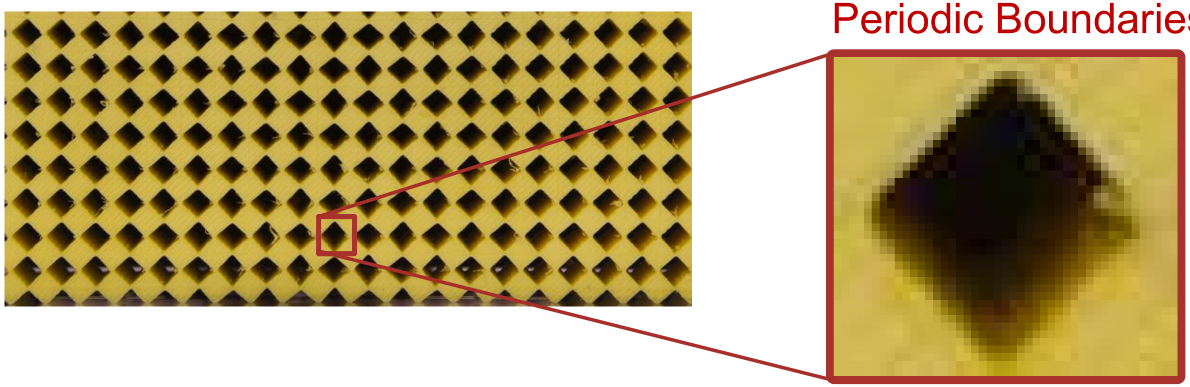


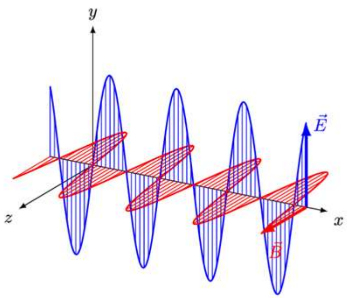
COMSOL: Boundary Conditions

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



Periodic Boundaries

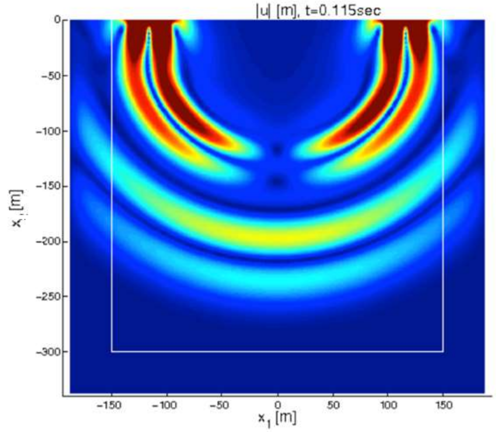


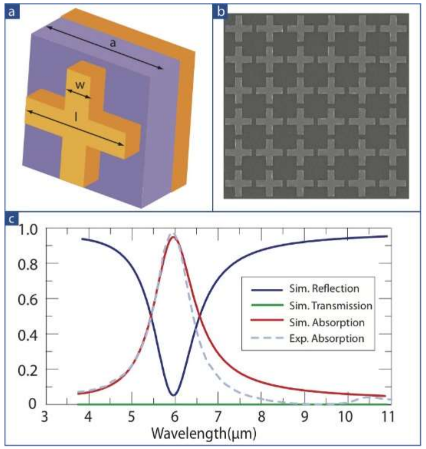


COMSOL: Boundary Conditions

- **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»
   - 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

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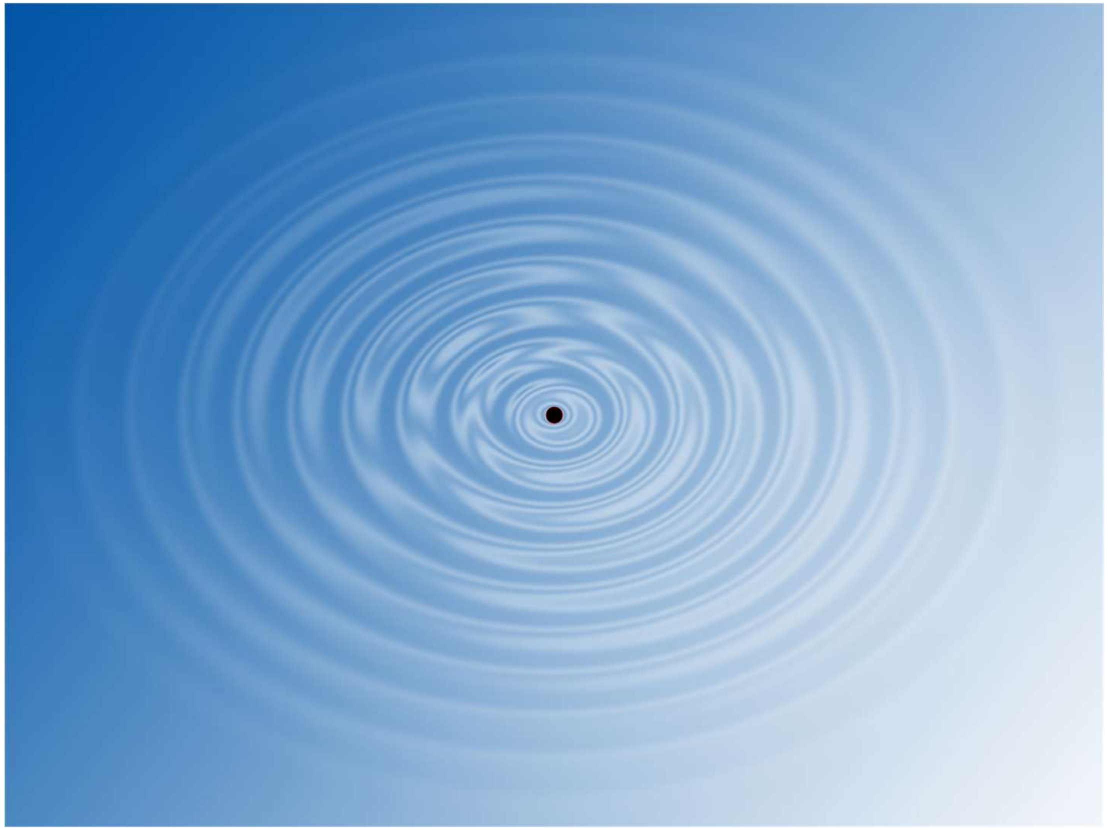
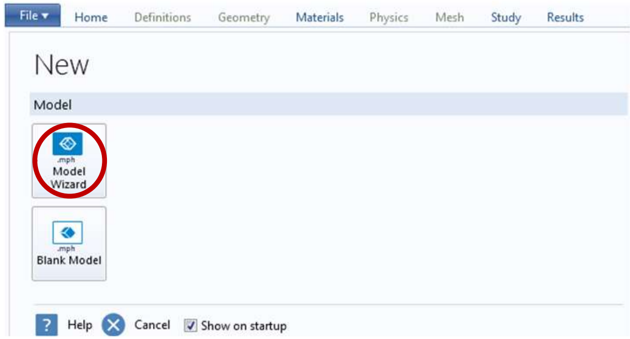
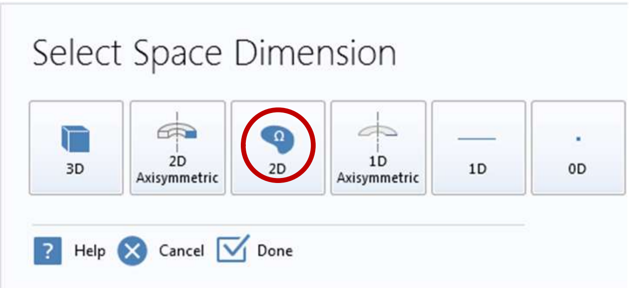
COMSOL: Last Time – Point Source Field

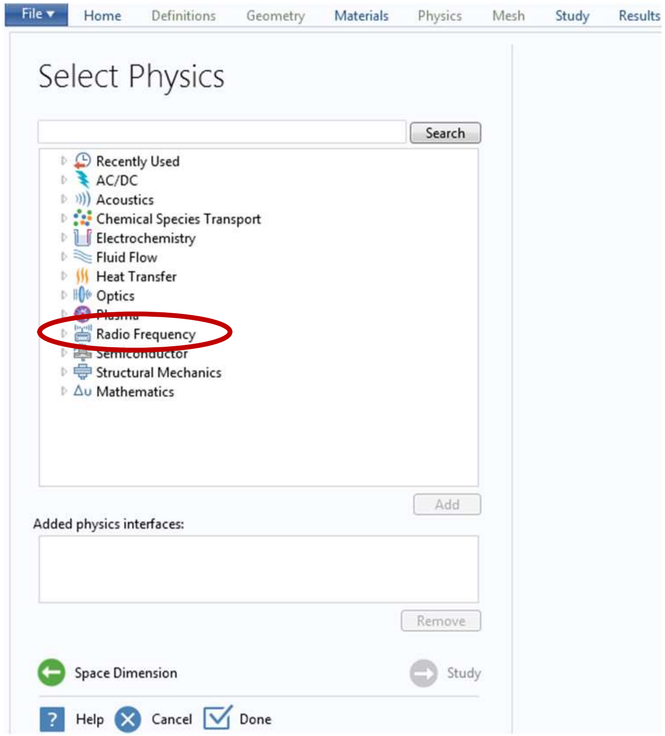


COMSOL: Last Time

Command to start Comsol: comsol







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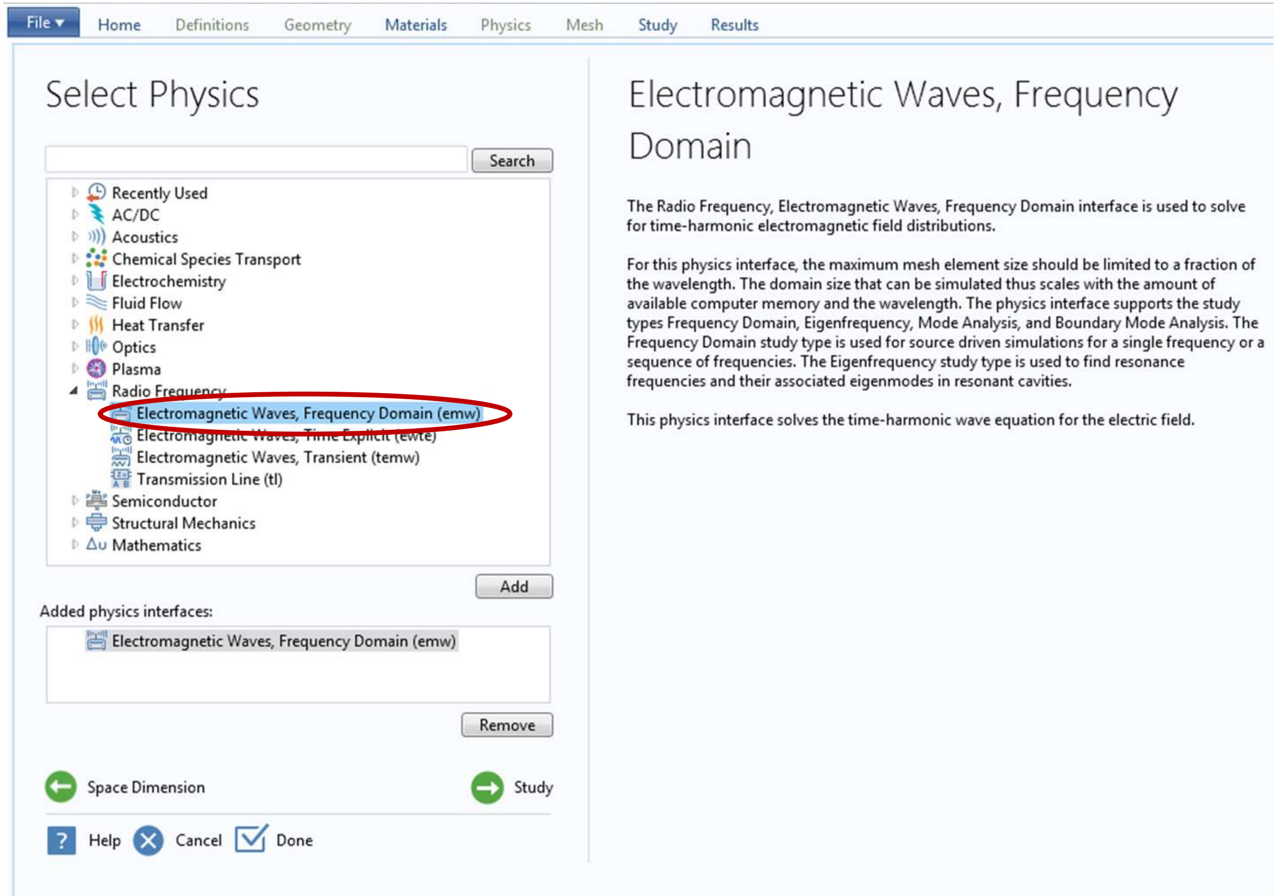
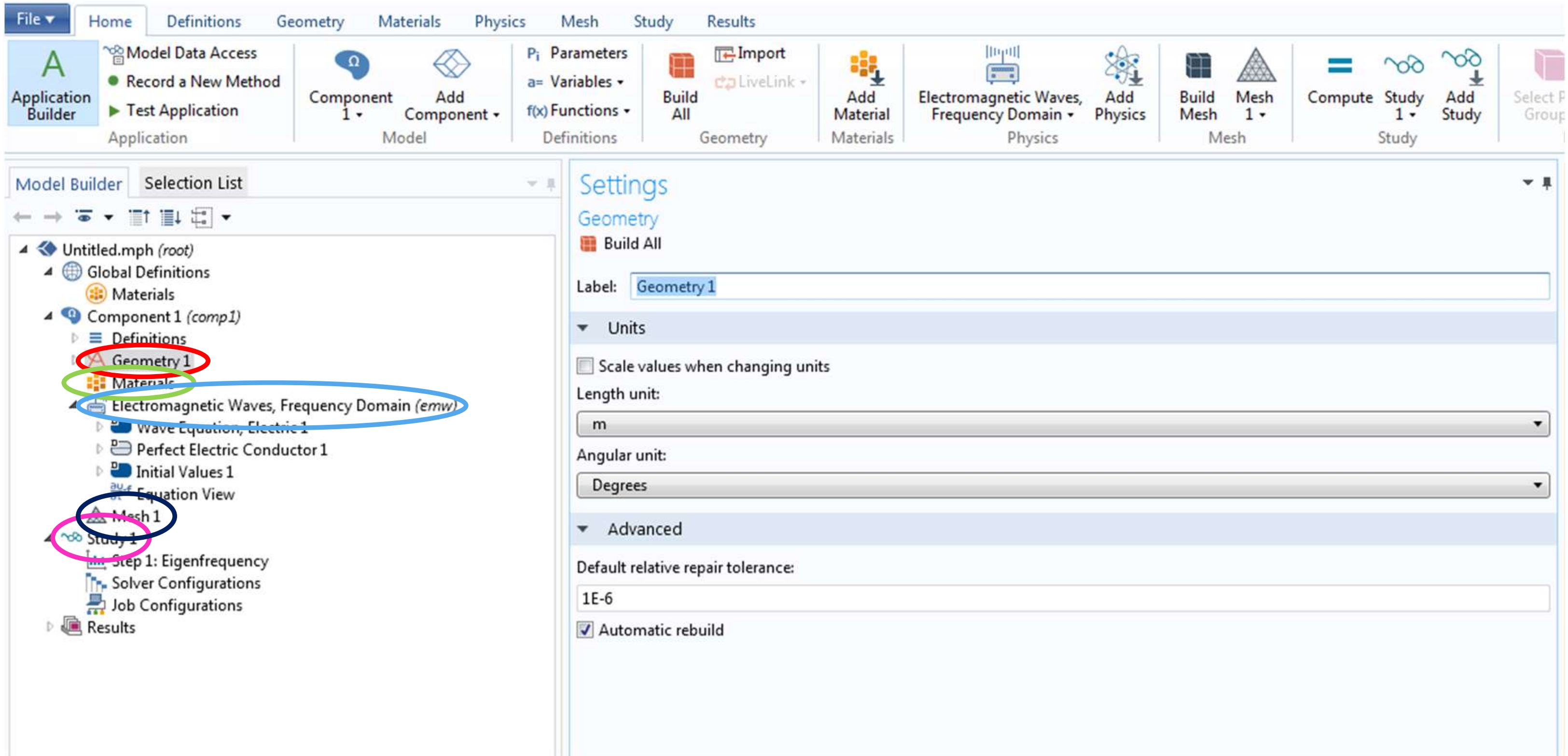
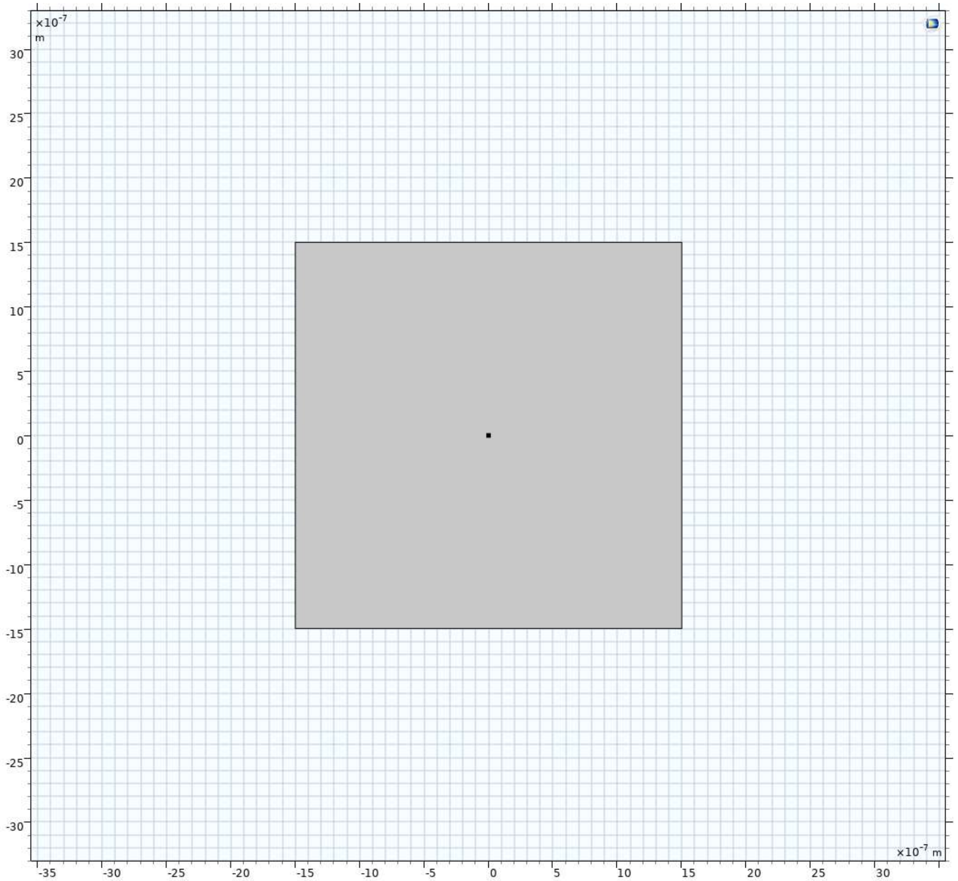


COMSOL: Last Time



COMSOL: Last Time

- Define simulation domain
- Build geometry



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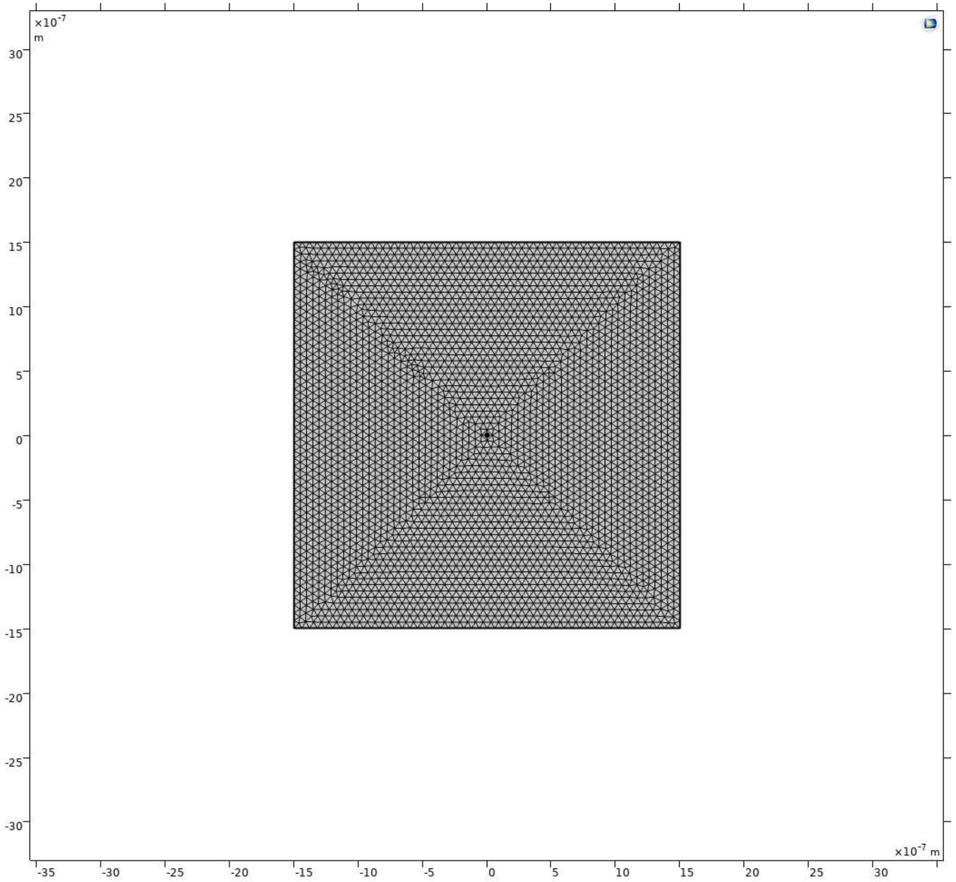
COMSOL: Last Time

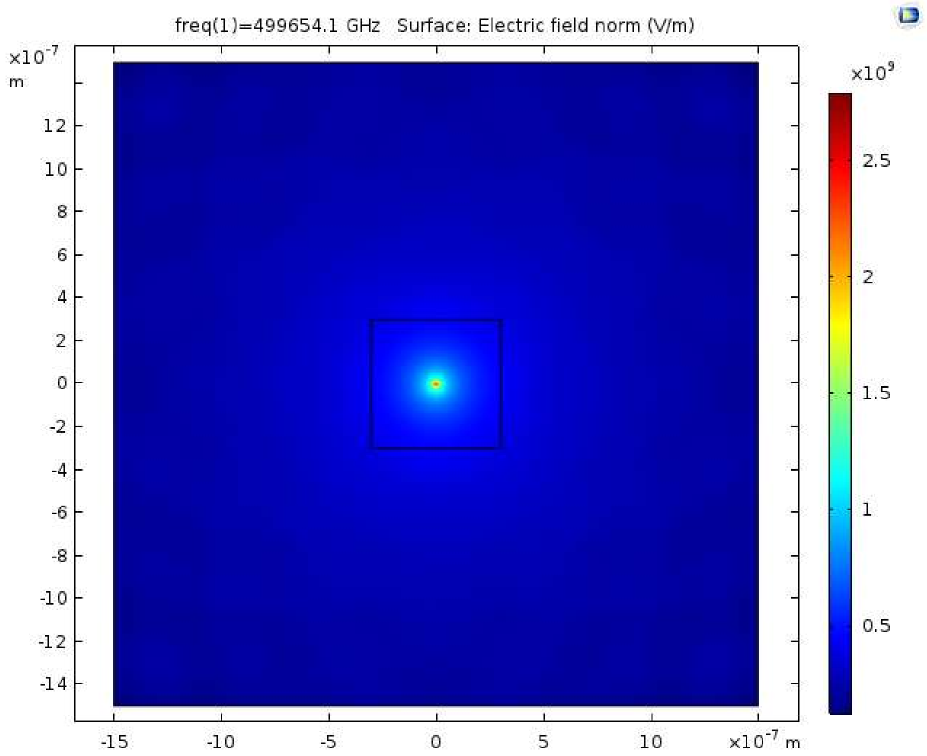
- Discretization of simulation domain
  - Build mesh

- Mesh size determines accuracy of solution
  - Too large mesh ⇒ wrong results

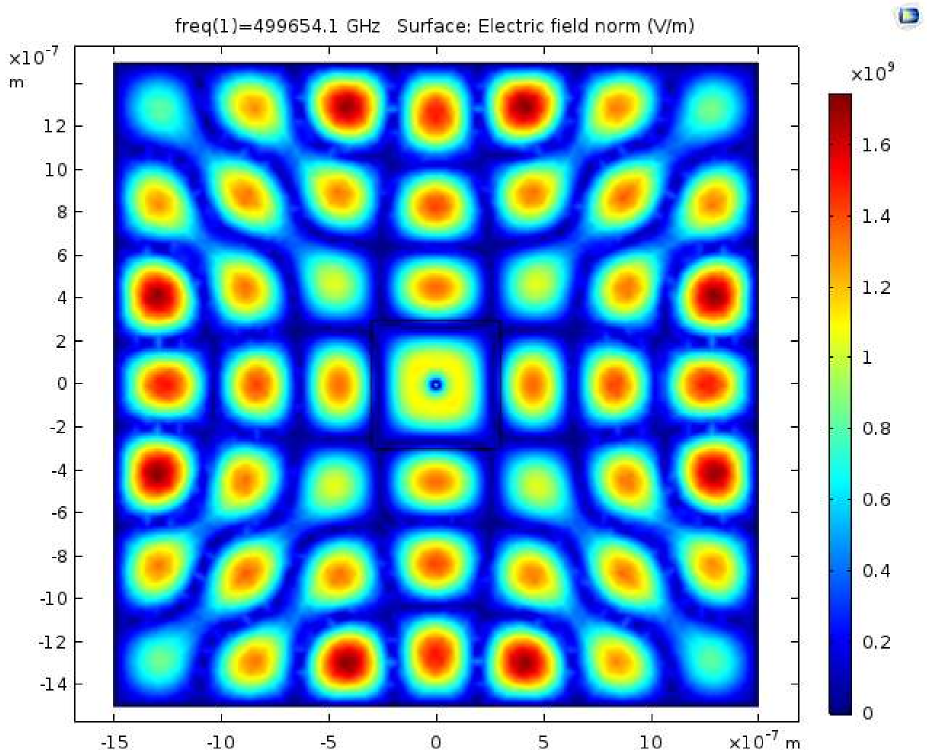
- Accuracy vs. simulation time
  - **Today**: Optimization by manual refinement



COMSOL: Last Time



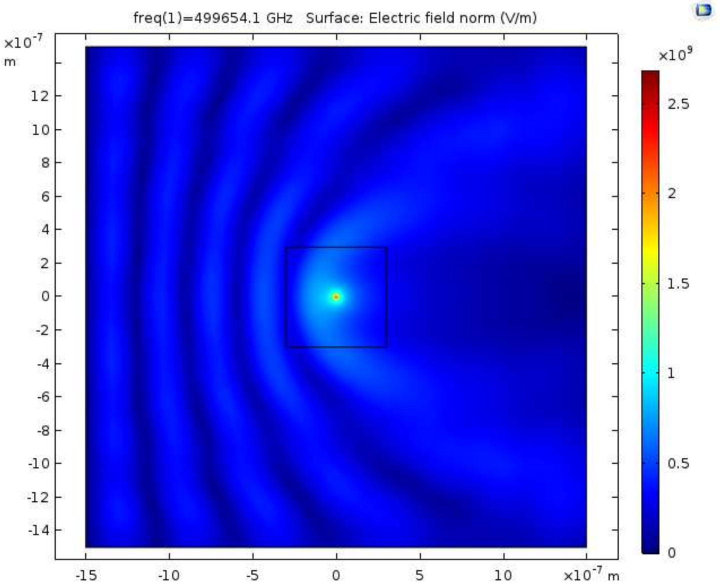
Scattering Boundaries



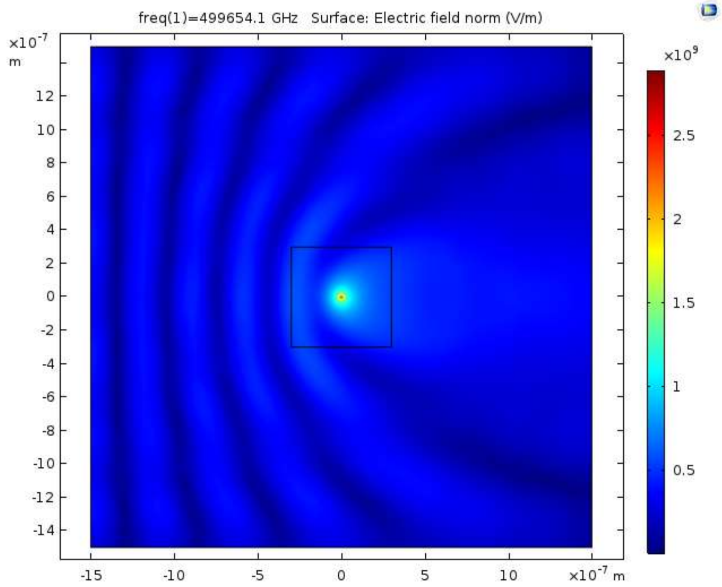
PEC Boundaries

COMSOL: Today

- Mirror effect by using different boundary conditions

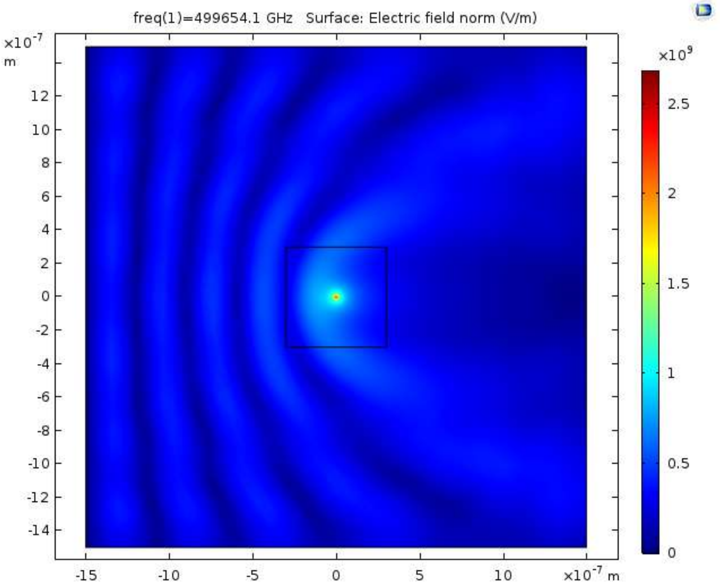


Can you see the difference?
Can you guess the boundary conditions?

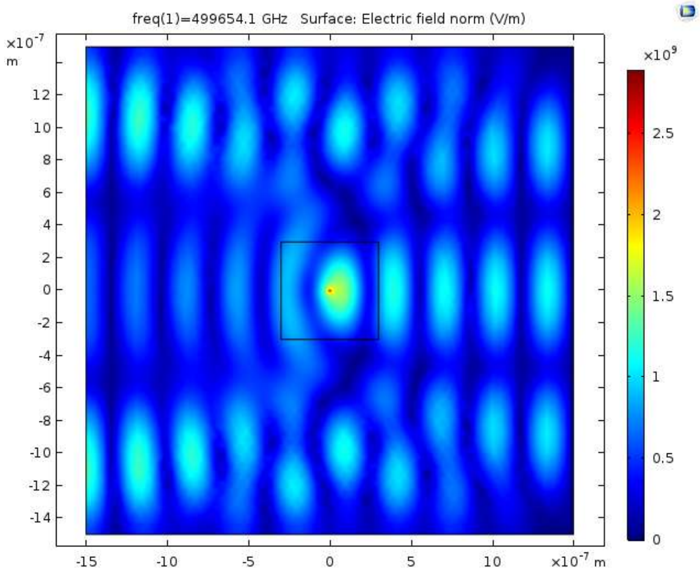


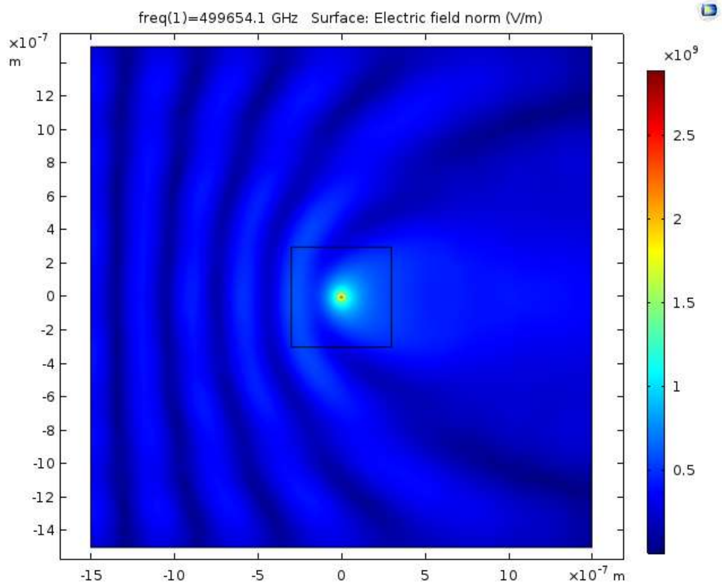
COMSOL: Today

- Mirror effect by using different boundary conditions



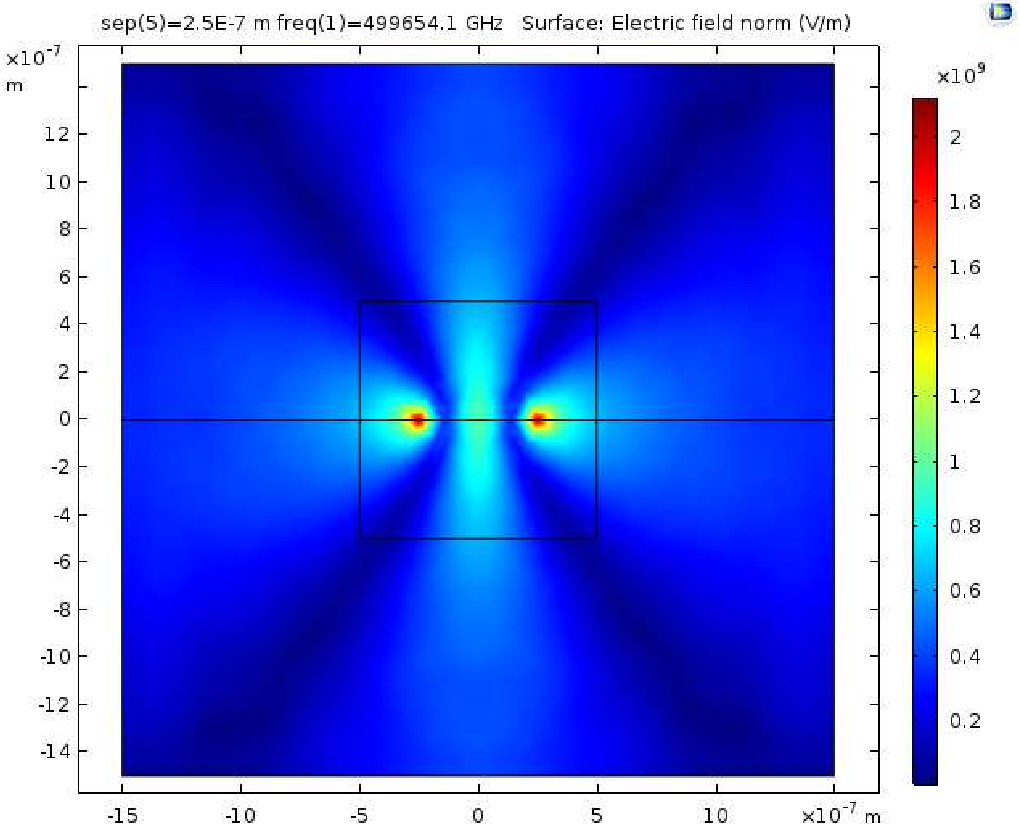
Can you see the difference?
Can you guess the boundary conditions?





COMSOL: Today

- Mirror effect by using boundary conditions
- Double Source



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