On the Applicability of Homogenization in Composite Material Models for Tissue Analysis in the mm-wave Range

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Abstract— The proper knowledge of the electromagnetic (EM) properties of biological tissue has become an integral part, e.g., in diagnostics, in medical imaging or for monitoring the health status of patients. Dielectric spectroscopy attempts, e.g., to associate the EM properties of the skin with certain physiological states. However, in order to be able to make a reliable diagnosis using such measurements, detailed knowledge of the electromagnetic behavior of the skin is required, which is typically provided by a proper sensitivity and specificity analysis. The great difficulty in developing such skin models, however, is the highly complex multiscale morphology of the skin tissue, which determines the macroscopic EM properties of the skin.

Based on this premise, heuristic approaches (of restricted validity range) have been claimed to be highly efficient when modeling skin tissue in the mm-wave range Most of the (fitting) models rely, e.g., on simplified representations of the skin as a multi-layer structure with homogenized dispersive layer properties [1], where the latter is retrieved in the framework of the effective medium theory (EMT) using, e.g., extended analytic mixing formulas. A more rigorous approach is based on a hierarchically organized multiscale model that is rooted in the skin's proper cellular structure, in conjunction with a numerical homogenization procedure aiming at both the dispersive and tensorial EM material properties [2].

In our study we present a systematic numerical analysis on the validity range of the homogenized layer model for, e.g., a generic hypodermis (HYP) tissue surface in order to evaluate its applicability in mm-wave skin diagnostics. We use comprehensive computational electromagnetics analysis based on the two-dimensional finite-element-method (FEM) to examine the spectral response of the hypodermis (HYP) reflection and transmission properties in the frequency range between 10 MHz and 200 GHz. By comparing the proper heterogeneous composite layer model (cf. Fig. 1) with its homogenized dispersive and tensorial version (cf. EMT) it is shown that the latter model loses its validity at astonishingly low frequencies where it yields an inadequate EMT representation of the volume scattering properties.

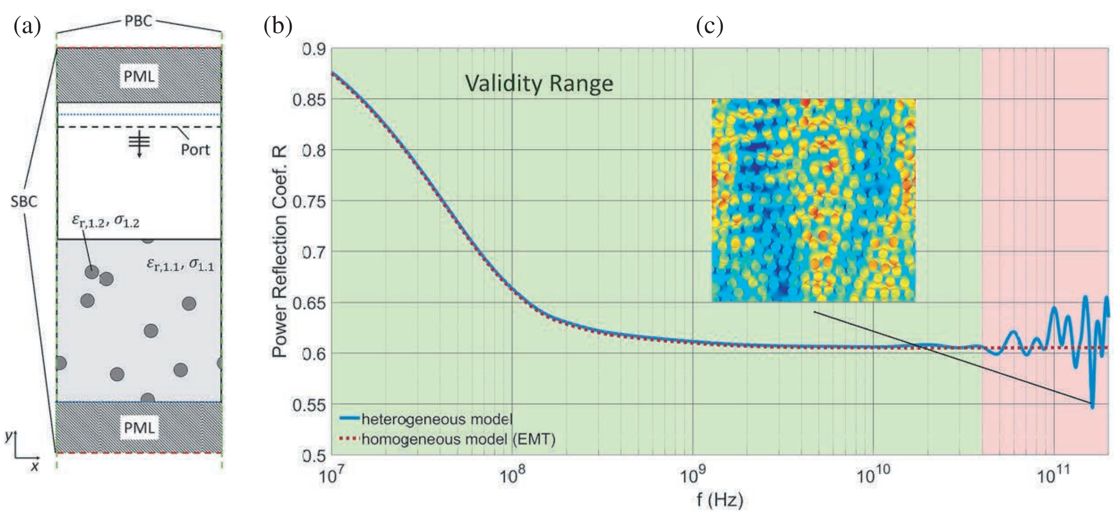

Figure 1: Comparison between the heterogeneous and homogenized (EMT) model of a generic skin surface: (a) simulation setup; (b) spectral responses of the reflectance (showing the typical Maxwell-Wagner roll-off in the MHz range) for $\varepsilon_{r,1,1} = 80$; $\sigma_{1,1} = 0.53\,\mathrm{S/m}$; $\varepsilon_{r,1,2} = 50$; $\sigma_{1,2} = 0.12\,\mathrm{S/m}$; $d_{inclusion} = 50\,\mu\mathrm{m}$; and volume fraction = 0.452; (c) exemplary electric field distribution $|\mathbf{E}|$ outside the validity range (i.e., at 179 GHz).

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1. Alekseev, S. I. and M. C. Ziskin, "Human skin permittivity determined by millimeter wave reflection measurements," *Bioelectromagnetics*, Vol. 28, No. 5, 331–339, April 2007.
2. Froehlich, J., S. Huclova, C. Beyer, and D. Erni, "Accurate multi-scale skin model suitable for determining sensitivity and specificity of changes of skin components," *Computational Biophysics of the Skin*, Bernard Querleux, ed., 353–394, book chapter 12, Singapore, Pan Stanford Publishing Pte. Ltd., ISBN-978-981-4463-84-3, 2014.

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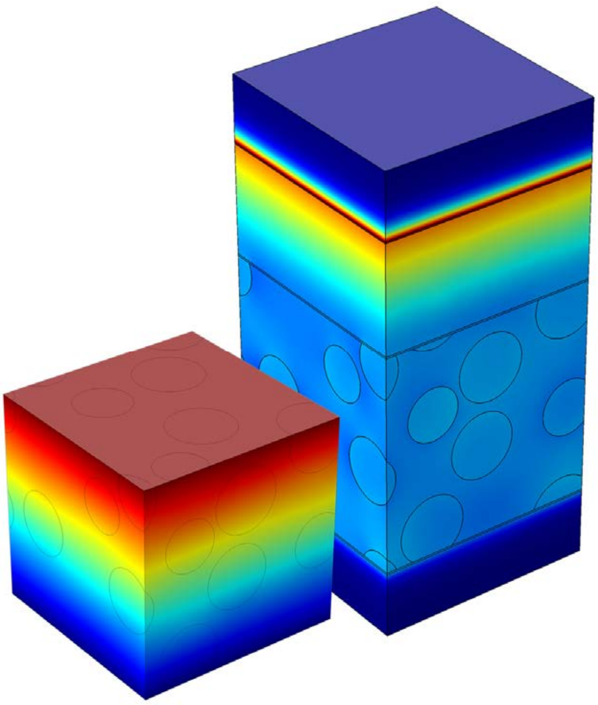
Agenda

- Introduction
- Homogenization
- Reflectometry
- Analysis
- Summary & Outlook



Introduction

Scientific Goals & Case Study

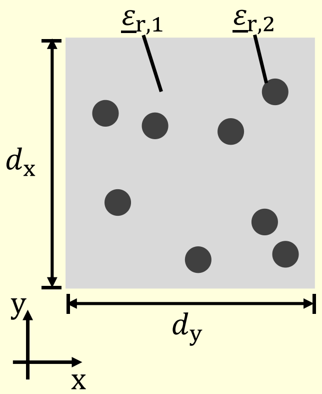
Scientific Context

- Multilayer skin models
- Stack of homogeneous layers
- Debye characteristic
- Fitted to measurement results

Scientific Goals

- Is homogenization based on numerical skin models valid in the mm-wave range?
- How to quantify validity limits?

Hypodermis (HYP)



Extracellular
$\varepsilon_{r,1} = 80$
$\sigma_1 = 0.53\ \frac{S}{m}$

Intracellular
$\varepsilon_{r,2} = 50$
$\sigma_2 = 0.12\ \frac{S}{m}$
$d_{cell} = 50\ \mu m$

$d_x = d_y = 1\ mm$

- 2D FEM model
- No membrane
- $\varepsilon_{r,i}$ & $\sigma_{r,i} \neq f(\omega)$
- Lower volume density

Introduction

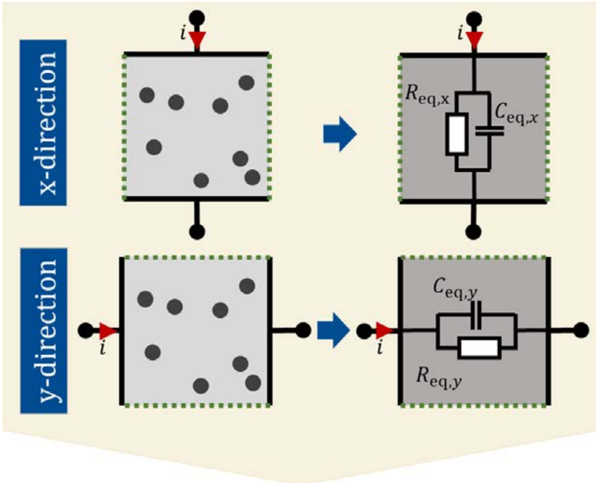
Methodology

Numerical Simulations		Analysis
Heterogeneous Material ⬇ Homogeneous Material	Power Reflection	Comparison Homogeneous vs. Heterogeneous Material ⬇ Quantification of Validity Limits
Step 1	Step 2	Step 3

Homogenization
Numerical EMT Model

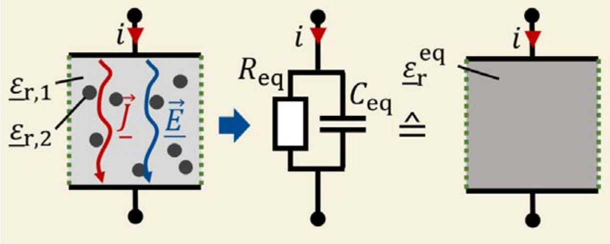
Model Features

- FEM based model
- Electrostatic model
- PBCs to prevent field distortions
- broad frequency range
  $f \in [10\ \text{MHz}, 200\ \text{GHz}]$
- Homogenization in x-, y-direction



Homogenization Process

Numerical Simulation | Data Extraction



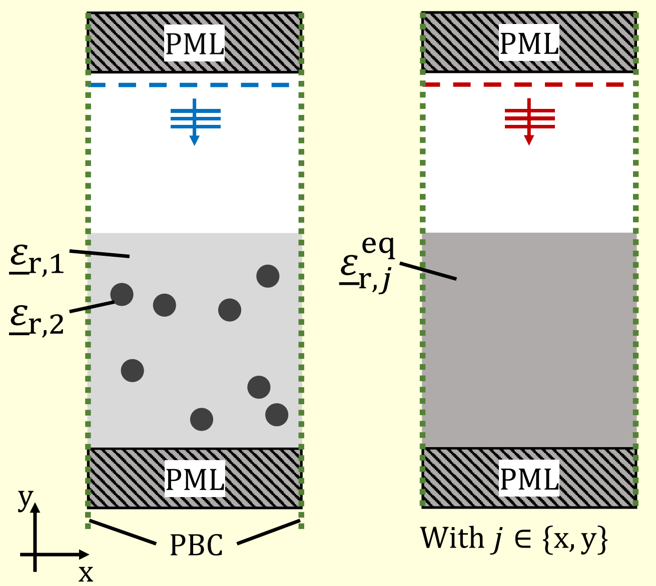
Equivalent Material Tensor

$$\overleftrightarrow{\underline{\varepsilon}}_r^{eq} = \begin{pmatrix} \underline{\varepsilon}_{r,x}^{eq} & 0 \\ 0 & \underline{\varepsilon}_{r,y}^{eq} \end{pmatrix}$$

Reflectometry
Free Space Simulation Model

Reflectometry Setup

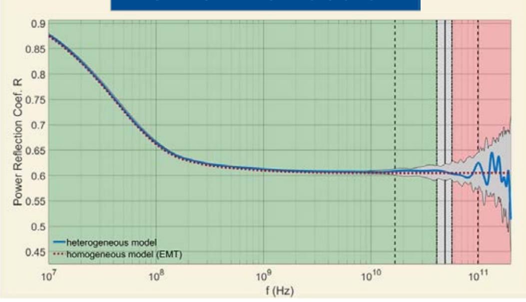
Heterogenous | Homogenous



Excitation:
- FEM based model
- Plane wave: TM & TE case
- $f \in [10\ \text{MHz}, 200\ \text{GHz}]$

Boundary Conditions:
- PML to emulate free space conditions
- PBC to reduce numerical demand
- Surrounding: air

Power Reflection

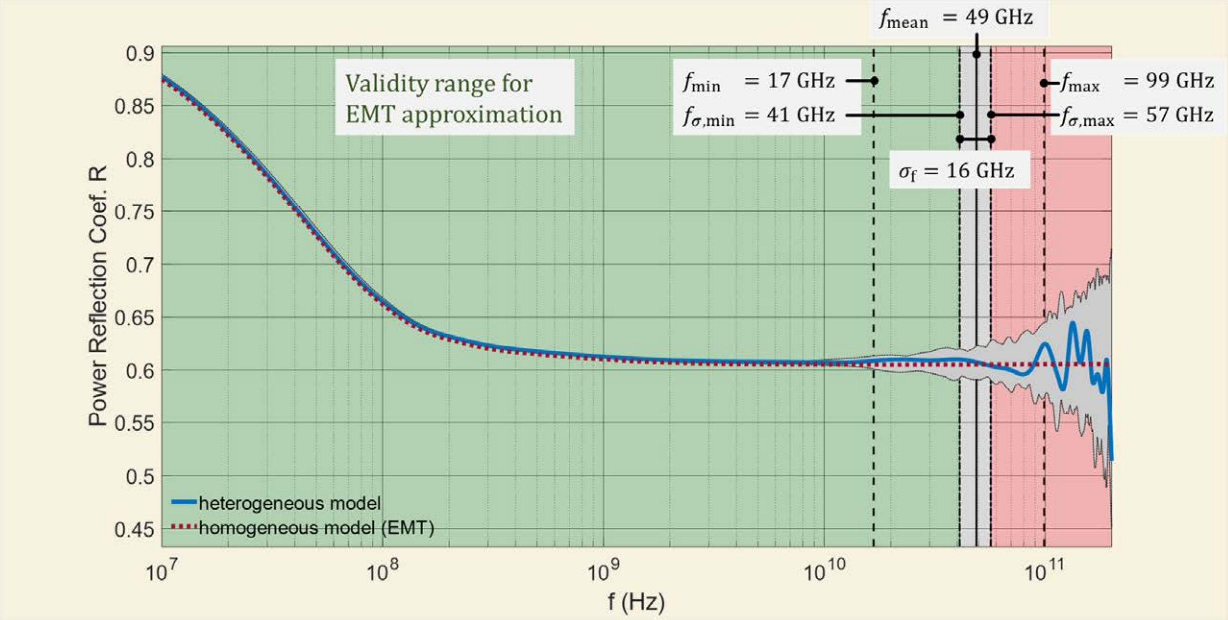


Reflectometry

EMT Limits Based on Power Reflection I

Simulated reflectometry: (220 realizations)

- Volume density 45 %
- Error margin 1 %

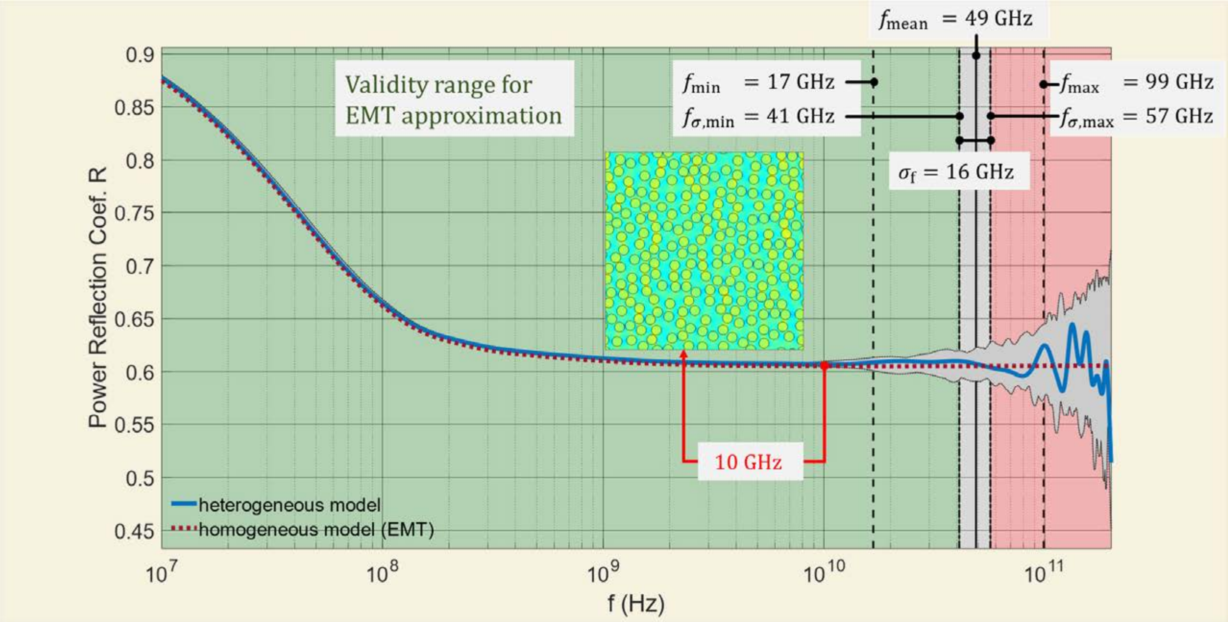


Reflectometry

EMT Limits Based on Power Reflection II

Simulated reflectometry: (220 realizations)

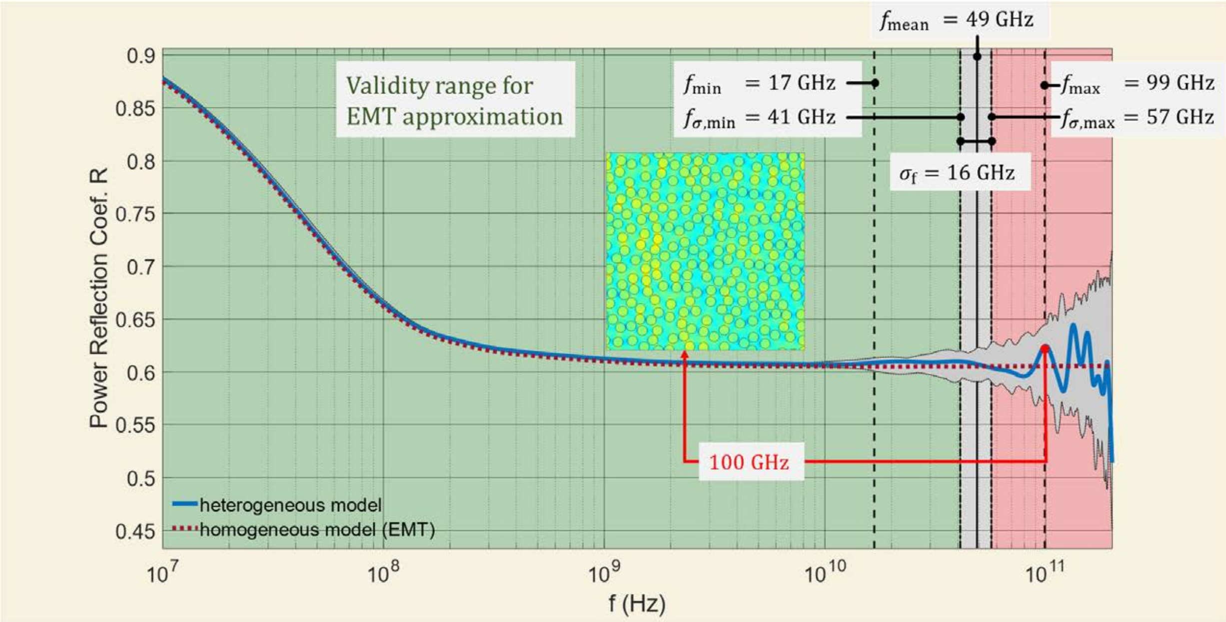
- Volume density 45 %
- Error margin 1 %



Reflectometry

EMT Limits Based on Power Reflection III

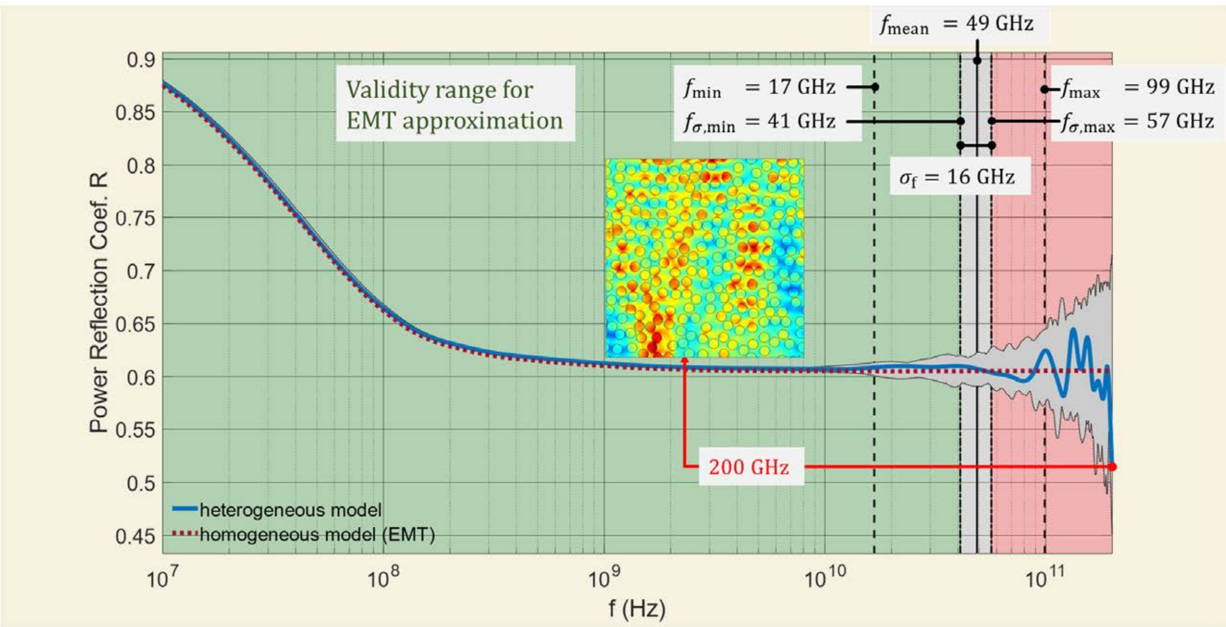
Simulated reflectometry: (220 realizations)
- Volume density 45 %
- Error margin 1 %



Reflectometry

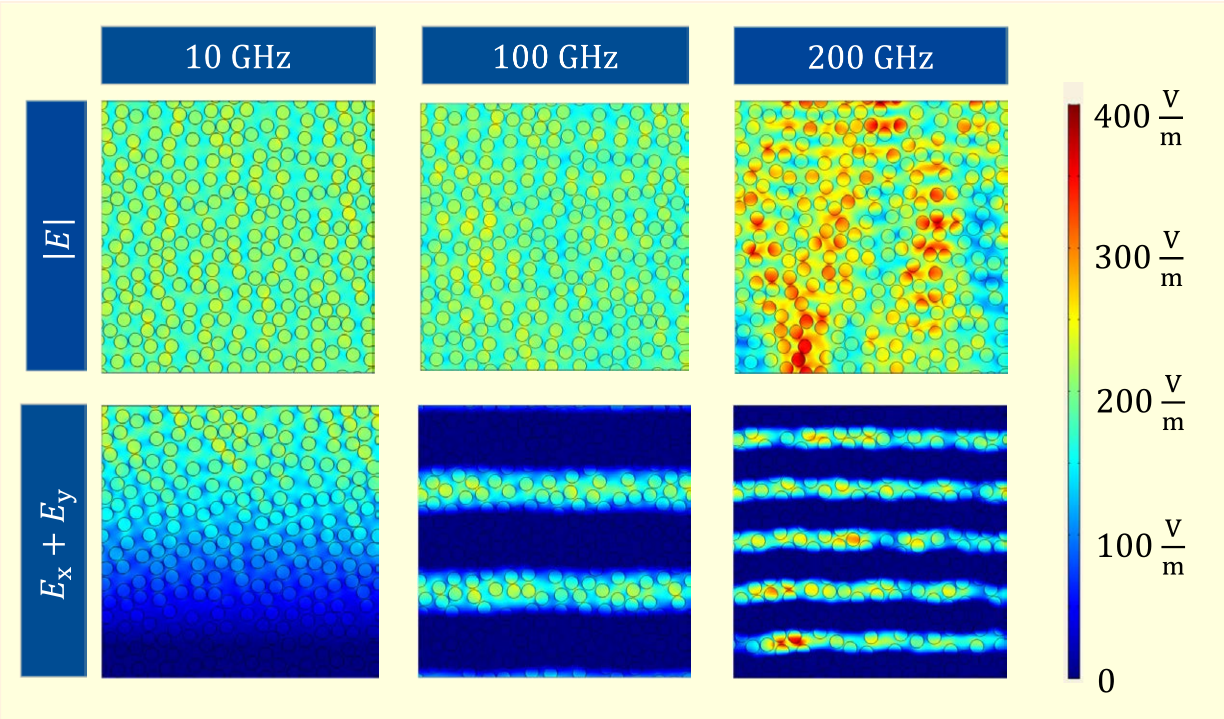
EMT Limits Based on Power Reflection IV

Simulated reflectometry: (220 realizations)
- Volume density 45 %
- Error margin 1 %



Reflectometry

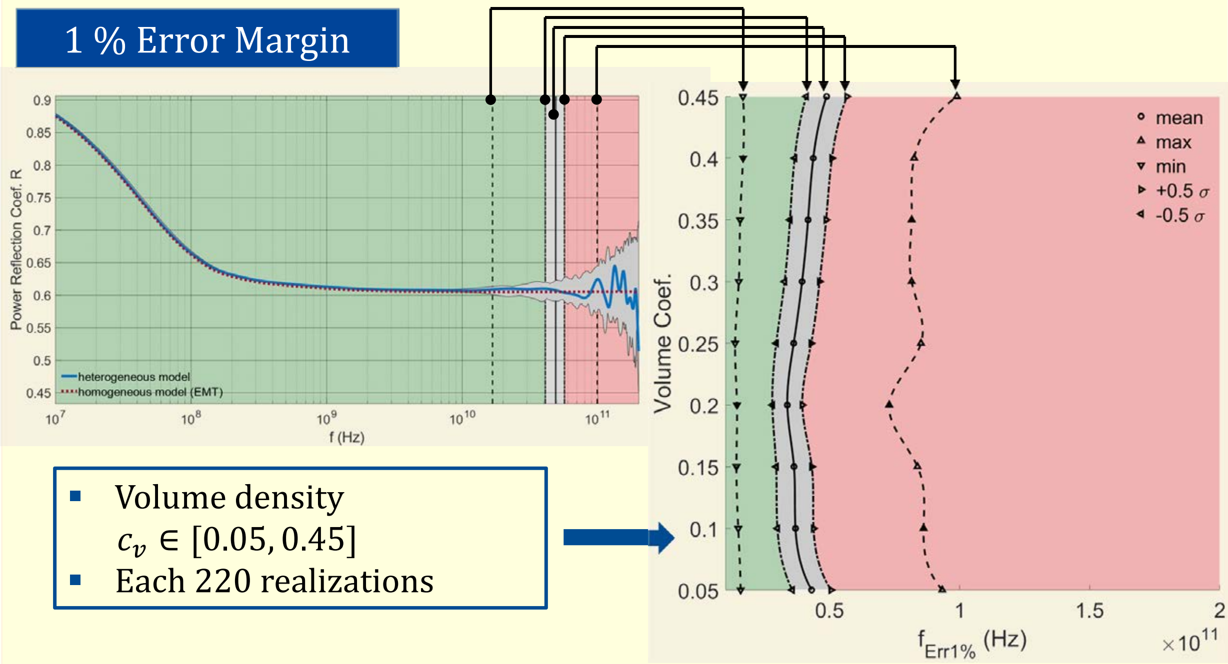
EMT Limits Based on Power Reflection IV



Analysis

Validity Limits of the EMT I

1 % Error Margin

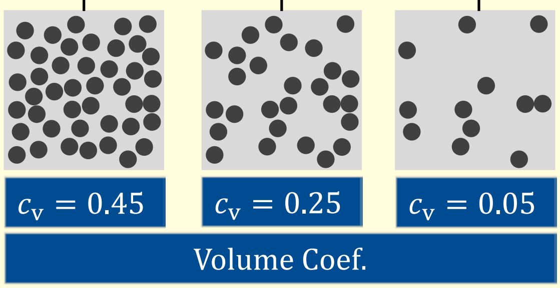


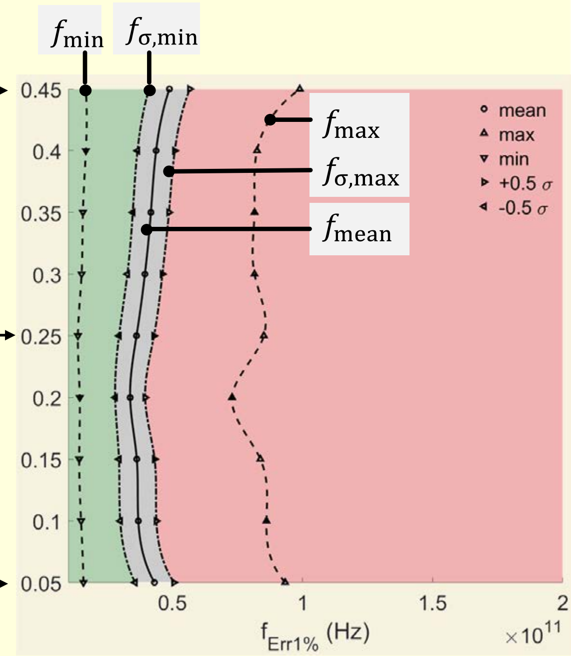
- Volume density $c_v \in [0.05, 0.45]$
- Each 220 realizations

Analysis

Validity Limits of the EMT II

1 % Error Margin



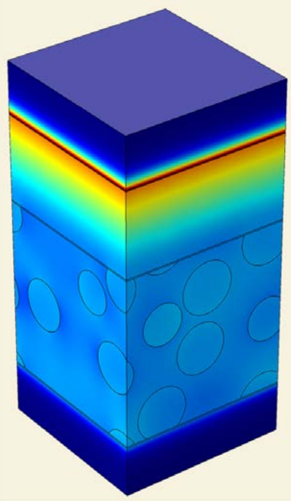


- Surprisingly constant boundary f_{min}
- Surprisingly constant σ_f

Analysis

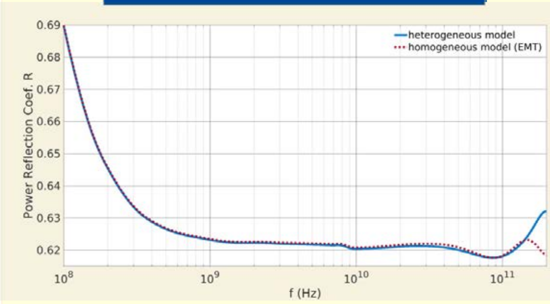
3D Reflectometry

3D Reflectometry Setup

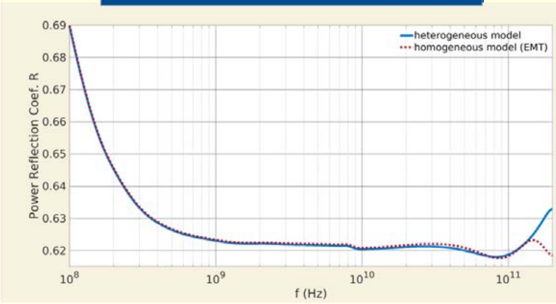


Exemplary 3D simulation:
- Volume density 29 %
- 3D results in agreement with 2D results

TE



TM



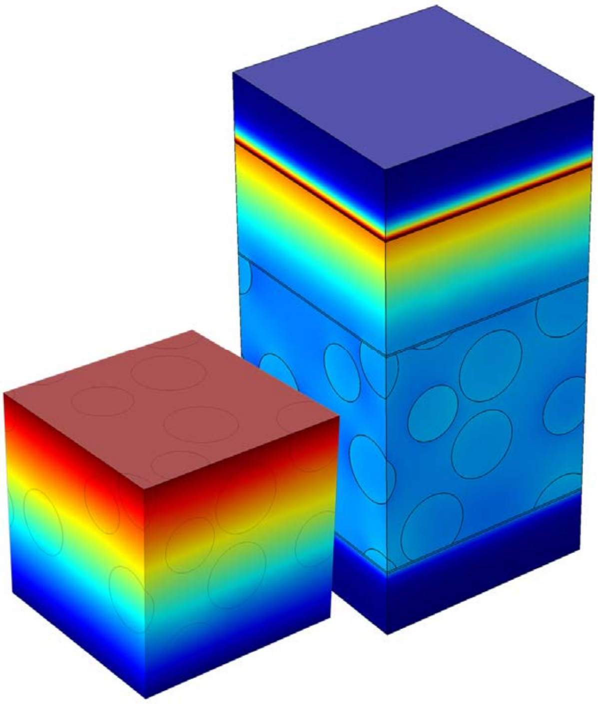
Summary & Outlook

Summary

- Resonances violate EMT approximation
- Homogenization of skin tissues need further examination in mm-wave range

Outlook

- Comparison of classical EMT models vs. numerical approaches
- Further 3D simulations



Thank you for listening!

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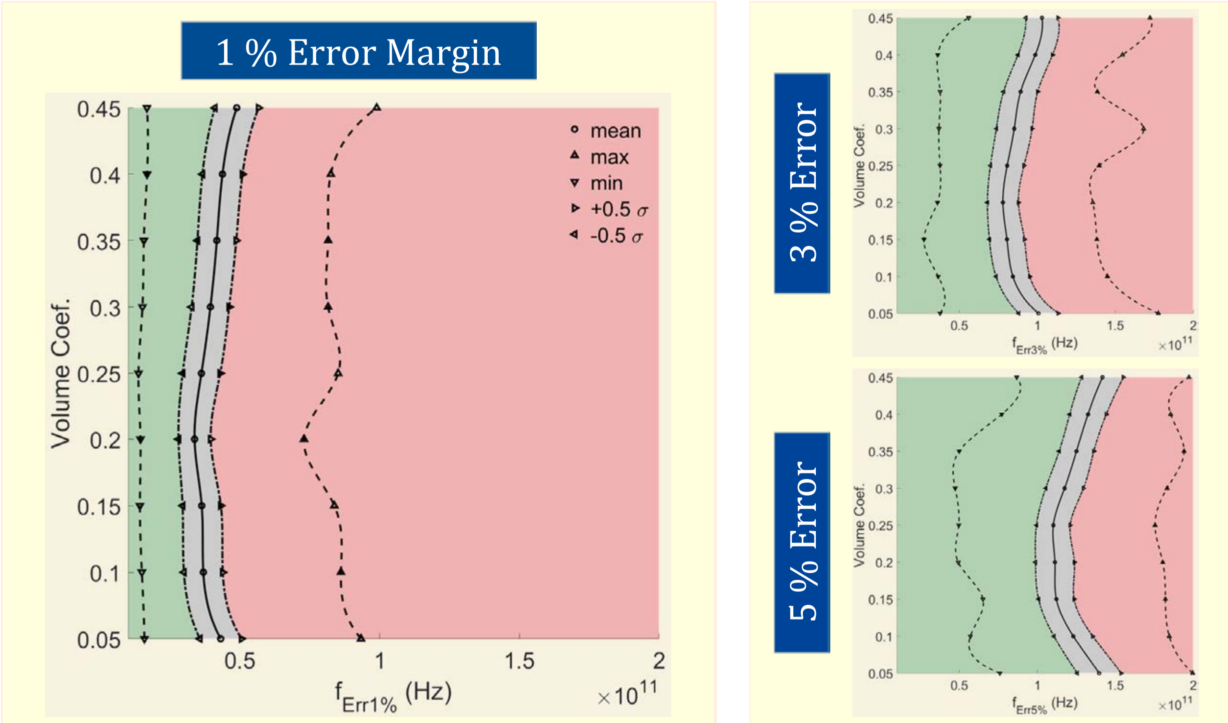
Open-Minded

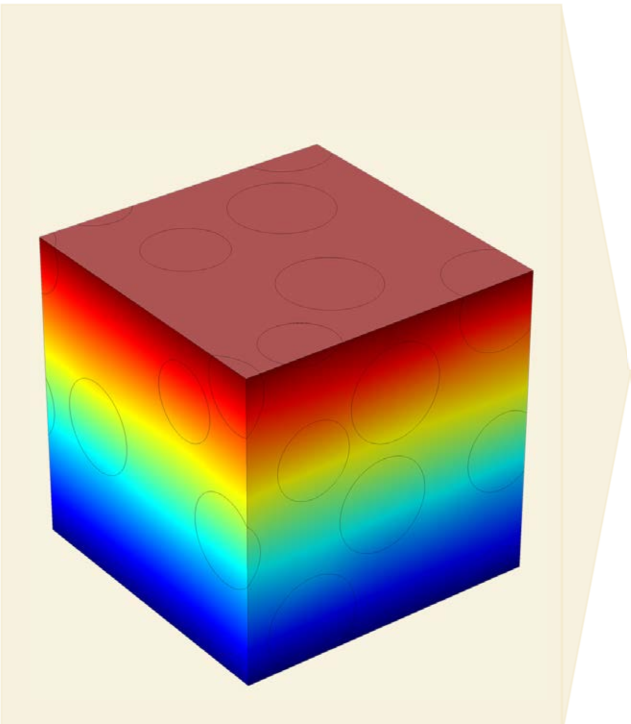
Analysis

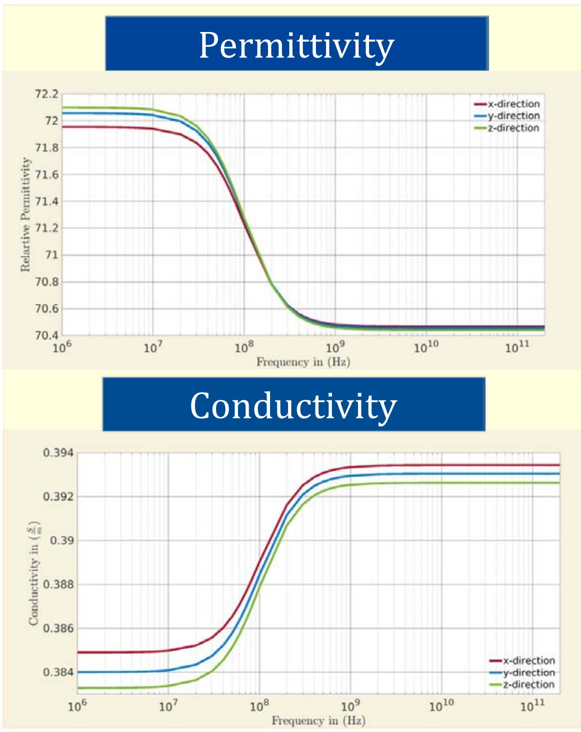
Validity Limits of the EMT III



3D Results

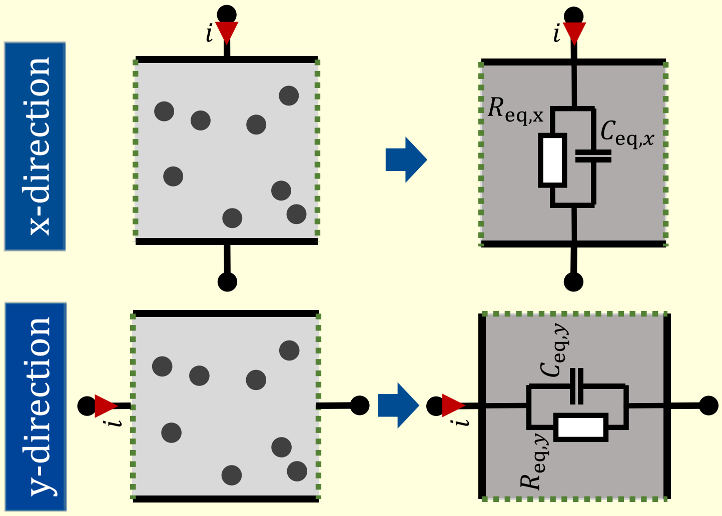
3D Homogenization





Homogenization
Numerical EMT Model II

Homogenization



Equivalent Material Parameters

$$\overleftrightarrow{\underline{\varepsilon}}_{r,1}^{eq} = \begin{pmatrix} \underline{\varepsilon}_{r,x}^{eq} & 0 & 0 \\ 0 & \underline{\varepsilon}_{r,y}^{eq} & 0 \\ 0 & 0 & \underline{\varepsilon}_{r,1} \end{pmatrix}$$

&

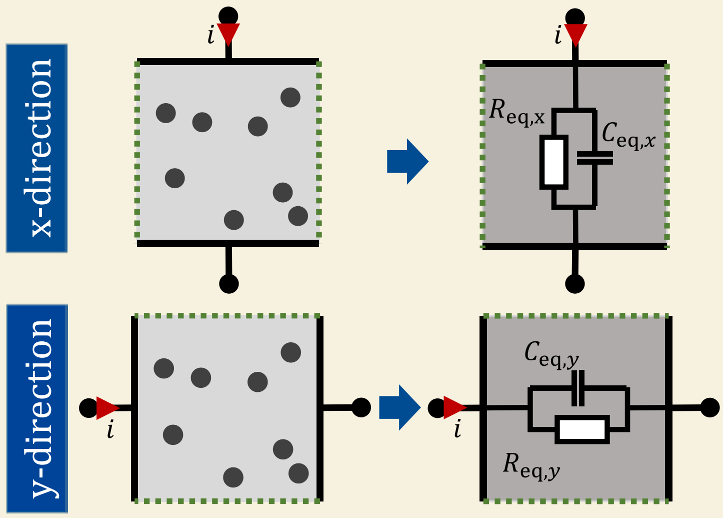
$$\overleftrightarrow{\underline{\varepsilon}}_{r,2}^{eq} = \begin{pmatrix} \underline{\varepsilon}_{r,x}^{eq} & 0 & 0 \\ 0 & \underline{\varepsilon}_{r,y}^{eq} & 0 \\ 0 & 0 & \underline{\varepsilon}_{r,2} \end{pmatrix}$$

Process

Result

Homogenization
Numerical EMT Model II

Homogenization



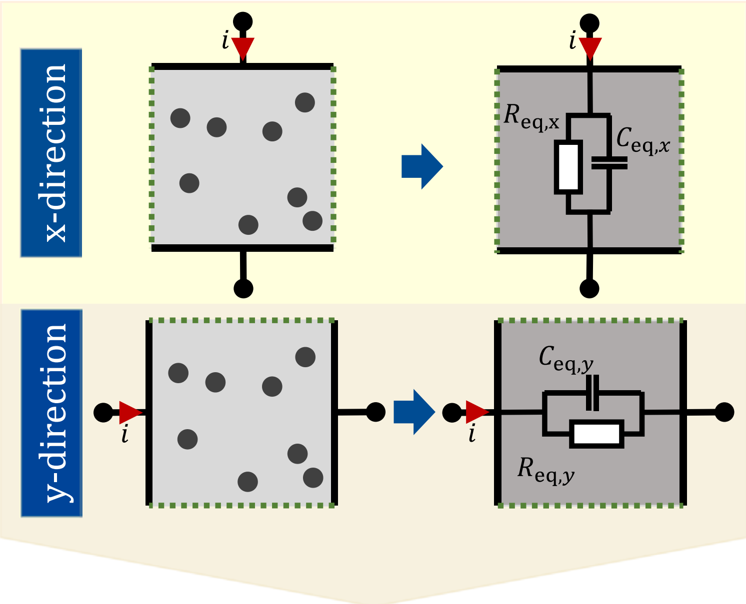
Equivalent Material Parameters

$$\overleftrightarrow{\underline{\varepsilon}}_{r}^{eq} = \begin{pmatrix} \underline{\varepsilon}_{r,x}^{eq} & 0 \\ 0 & \underline{\varepsilon}_{r,y}^{eq} \end{pmatrix}$$

Process

Result

Homogenization
Numerical EMT Model II



Equivalent Material Parameters

$$\overleftrightarrow{\underline{\varepsilon}}_{\mathrm{r}}^{\mathrm{eq}} = \begin{pmatrix} \underline{\varepsilon}_{\mathrm{r,x}}^{\mathrm{eq}} & 0 \\ 0 & \underline{\varepsilon}_{\mathrm{r},y}^{\mathrm{eq}} \end{pmatrix}$$

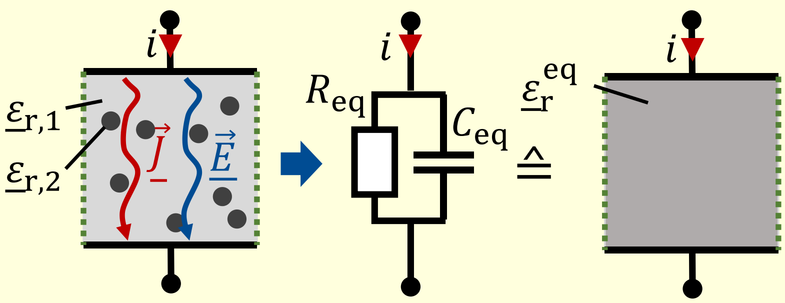
Result

Homogenization
Numerical EMT Model I

Homogenization Process

Numerical Simulation

Data Extraction



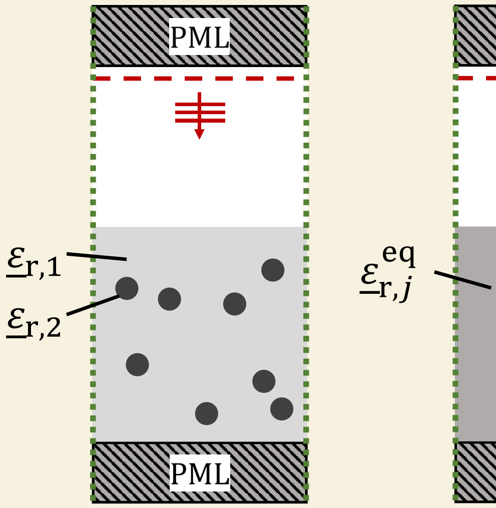
Model Features

- FEM based model
- Electrostatic model
- PBCs to prevent field distortions
- Large frequency range $f \in [1\ \text{MHz}, 200\ \text{GHz}]$
- Homogenization in x-, y- (and z-direction)

Reflectometry
Free Space Simulation Model II

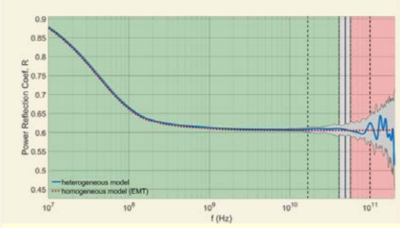
Reflectometry

Heterogenous | Homogenous

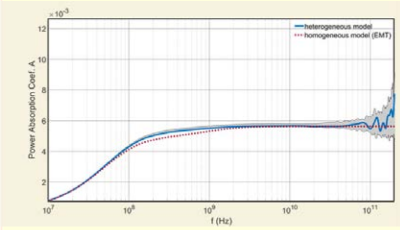


With $j \in \{x, y\}$

Power Reflection



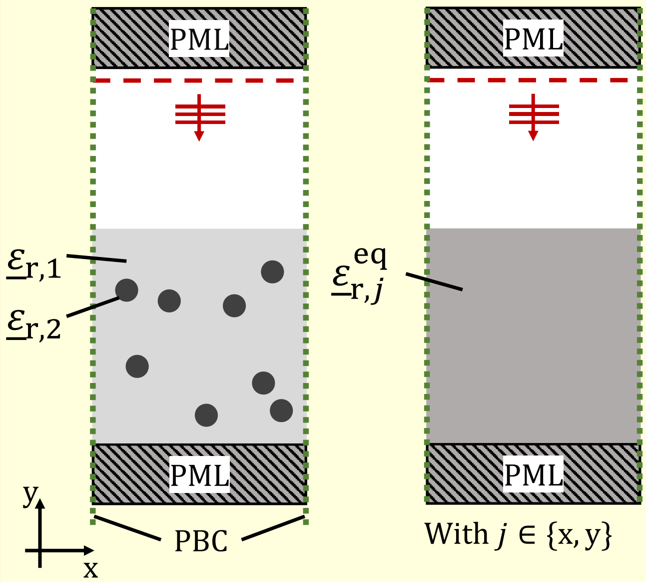
Absorption



Reflectometry
Free Space Simulation Model I

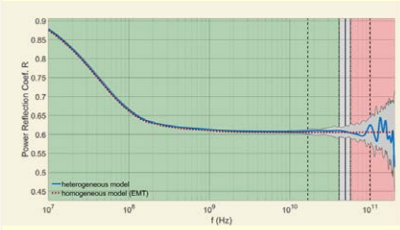
Reflectometry Set Up

Heterogenous | Homogenous

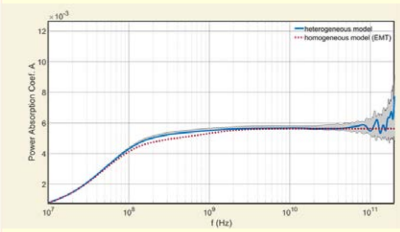


With $j \in \{x, y\}$

Power Reflection

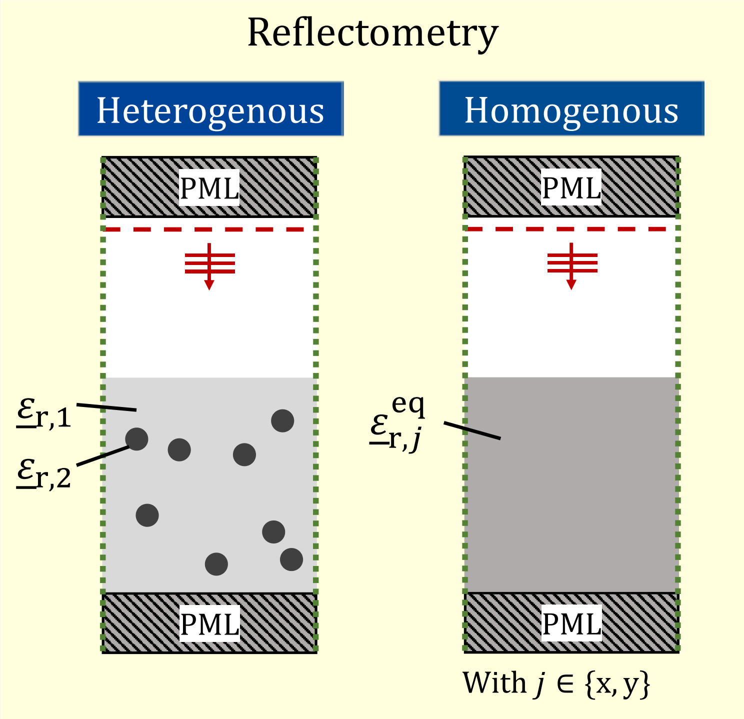


Absorption



Reflectometry

Free Space Simulation Model I



Model Features

- FEM based model
- Full set of Maxwell's Equations
- Plane wave excitation (TM & TE case)
- PMLs to emulate free space conditions
- PBCs to prevent field distortions
- Large frequency range $f \in [10\text{ MHz}, 200\text{ GHz}]$
- Simulation with heterogeneous and homogenized material