Limits of homogenization in electromagnetic composite material models: A show case in tissue analysis

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EM characterization of material composites – The proper knowledge of the electromagnetic (EM) properties of composites has become an integral part for the development of measurement equipment and techniques in industrial and medical applications. Due to its potential to resolve both material and structural/morphological features, mobile integrated electronic systems operating at lower THz frequencies has currently gained a great deal of interest [1]. Because of its simple applicability, the development of contactless, noninvasive material characterization/classification schemes turned out to be an appealing vision and has been successfully employed for e.g. the detection and assessment of delamination in glass fiber-reinforced composites by detecting their structural characteristics [2], [3], and to distinguish transgenic from non-transgenic rice seeds by using its spectral finger print [4] in the range of 60 GHz up to 4 THz. Another field of application for THz technology is medical imaging and diagnostics [5]. In this context, the assessment of e.g. burn injuries and the discrimination of healthy and cancerous tissue have proven to be particularly promising for investigations in reflection mode [6], [7].

Multi-scale modeling – In these reflectometry scenarios, computational EM multi-scale models are becoming increasingly important to maximize sensitivity and selectivity with respect to material textures and properties, which may be supported by machine learning and regression analysis approaches. The great difficulty in developing such tissue models, however, is the highly complex multiscale morphology of the biological tissue, which determines the macroscopic EM properties. The development of such virtual tissue models can therefore be regarded as one of the most meaningful benchmark problems with respect to the EM simulation of composite material systems.

Based on this premise, we developed a numerical three-stage methodology, which is implemented in the framework of a *multi-scale EM simulation workbench* to explore a generic hypodermis (HYP) tissue. First, the presented procedure is based on a hierarchically organized multiscale approach that starts on the skin's proper cellular length scale, and evolves step-by-step through the structural length scales of the tissue's morphology while using a numerical homogenization procedure that provides both the dispersive and tensorial EM material properties of the corresponding tissue composite [8]. Second, after this bottom-up homogenization, both tissue models, namely the heterogenous reference model and its effective material theory (EMT) representation are evaluated and compared in a numerical reflectometry setup shown in Fig. 1. And third, the validity limits of the HYP's homogenized material representation based on the EMT are explored within a subsequent Monte-Carlo analysis [9], which examines 1980 implementations of fictitious HYP derivatives with different volume fractions of the cellular and extracellular material $c_v \in \{0.05; 0.10; \ldots; 0.45\}$.

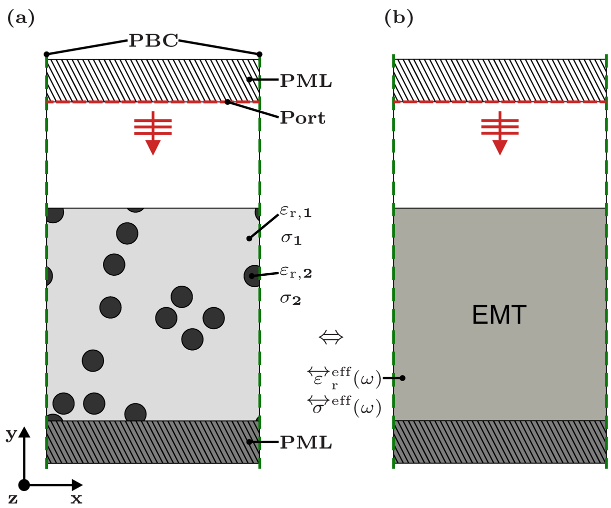

Fig. 1: Schematic of the simulated mm-wave/THz reflectometry setup that has been implemented in COMSOL Multiphysics: (a) the heterogeneous material structure; (b) the equivalent homogeneous representation based on the effective material theory (EMT).

Validity limits – The results of the Monte-Carlo analysis (cf. Fig. 2) revealed validity limits for HYP tissues at astonishingly low frequencies around 60-80 GHz above which the EMT representation breaks down. In the following great significance has been attributed to the documentation of this «collapse» since it may impact

future schemes of e.g. virtual histopathology in the mm-wave/THz range.
Currently we are working on the validation of our EM multi-scale modeling approach using various 3D printed artificial composites with different fillings. Some composites are undergoing corresponding frequency scaling in order address the interesting ranges in the frequency response of the power reflection as the latter has to be confined to the given operating bandwidth of the measurement setup.

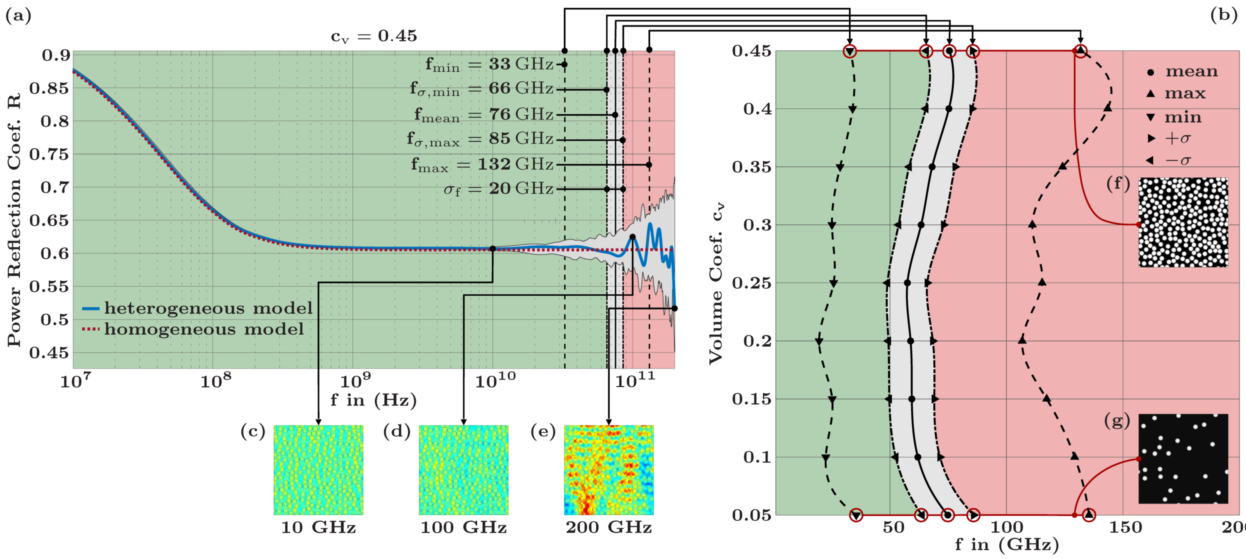

Fig. 2: Validity limits for several generic HYP derivatives:(a) spectral responses of the reflectance (showing the typical Maxwell-Wagner roll-off in the MHz range) of 1980 implementations for $\varepsilon_{r,1} = 80$; $\sigma_1 = 0.53$ S/m; $\varepsilon_{r,2} = 50$; $\sigma_1 = 0.12$ S/m; $d_{inc} = 50$ µm, and volume fraction $c_v = 0.45$; (b) Validity limits of the derivatives of a heterogeneous material structure (here the HYP tissue); (c), (d), (e) examples of the electric field distribution |E| at various frequencies (i.e. at 10 GHz, 100 GHz, 200 GHz, respectively); (f), (g) examples of the analyzed microstructures (i.e. for $c_v = 0.45$ and $c_v = 0.05$ respectively). The validity range of the EMT material model is colored in «green» while the forbidden range is marked «red».

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