Predicting Effective Dielectric Properties of Composites for Nonlinear Transmission Lines using Effective Medium Theories and CST Microwave Studios

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Abstract: *We present computational and theoretical assessments on the effective dielectric properties of the nonlinear composites comprised of ferroelectric ceramic inclusions (barium strontium titanate (BST)) and/or ferromagnetic inclusions (nickel zinc ferrite (NZF)) in a linear host to serve as materials for nonlinear transmission lines (NLTLs). We compare classical effective medium theories (EMTs) and computational models using CST Microwave Studio (CST MWS) to predict the dielectric and magnetic properties of the composites in the linear region to measurements. The composite models in CST MWS agree well with measurements and the Lichtenecker rule for NZF composites, while classical EMTs generally fail to estimate effective properties for the cases with high volume loadings and strong dielectric contrast.*

Keywords: High power microwaves; Nonlinear transmission lines; Effective medium theories; CST Microwave Studio; Barium strontium titanate; Nickel zinc ferrite.

Introduction

Nonlinear transmission lines (NLTLs) can sharpen pulses to create an electromagnetic shockwave to produce oscillations under certain conditions from 100 MHz to low GHz for high power microwave (HPM) generation [1]. NLTLs provide frequency agility, compactness, durability, and reliability for a solid-state radiofrequency (RF) sources [2]. NLTLs are composed nonlinear media, typically ferroelectric ceramics and ferrites incorporated in transmission lines with various topologies.

Lumped element and gyromagnetic NLTLs have been applied for pulse sharping and RF generation by using bulk ferroelectric ceramics and/or ferrites as nonlinear media to induce shockwaves and oscillations [1-2]. In this work, we evaluate and explore the feasibility of alternative nonlinear media for NLTLs involving designing composites comprised of nonlinear dielectric inclusions (barium strontium titanate (BST)) and/or nonlinear inductive inclusions (nickel zinc ferrites (NZF)) in a polymer base host material. This is analogous to electromagnetic interference designs incorporating stainless steel inclusions of various shapes in a plastic to tune the composite's effective properties at GHz by manipulating the volume fractions of the inclusions [3]. Appropriately designing NLTL composites requires predicting these effective dielectric properties both in linear (for a fixed and low voltage and current) and nonlinear (voltage-dependent permittivity and current-dependent permeability) regimes prior to designing HPM systems comprised of them.

As a first step, we used CST MWS, which uses the unit cell approach [4], and effective medium theories (EMTs) derived in the quasi-static limit [5] to predict the effective permittivity and permeability of the composites in the linear regime. The front and back (*z*-direction) use the open boundary condition, whereas the left and right (*x*-direction) apply the perfect magnetic conductor (PMC) boundary condition and the top and bottom (y-direction) use the perfect electric conductor (PEC) boundary condition [4], as shown in Figure 1.

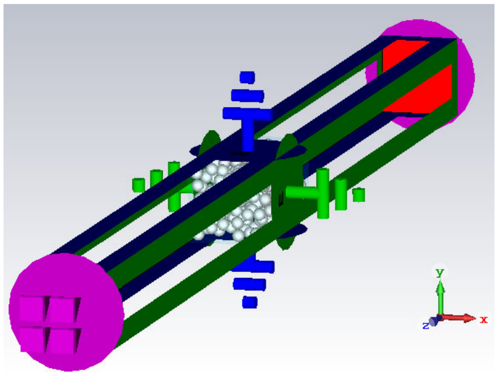

Figure 1. An illustration of the unit cell simulation of a composite model in CST MWS. Background material type: normal.

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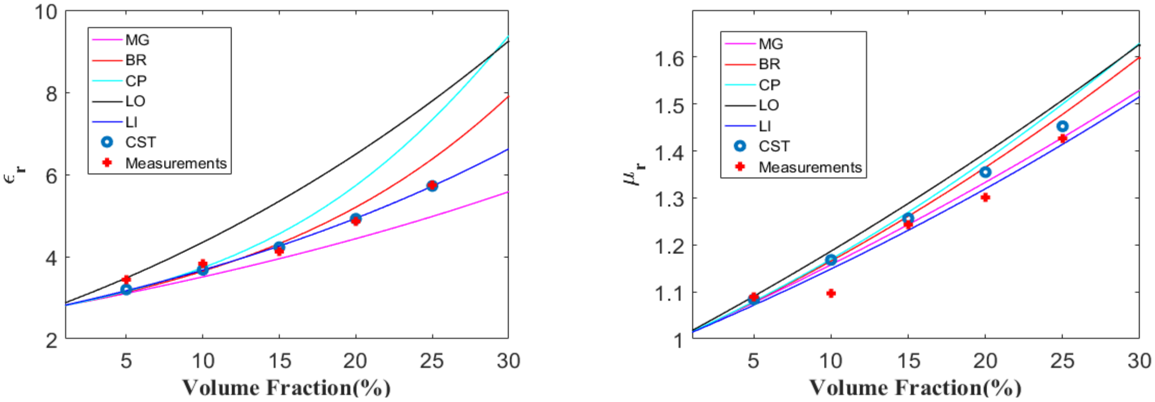

Figure 2. Results comparison of the effective real permittivity (left) and permeability (right) of NZF composites as a function of inclusion volume fraction at 1 GHz. The applied classical effective medium theories (EMTs): MG: Maxwell- Garnett, BR: Bruggeman, CP: coherent potential, LO: Looyenga, LI: Lichtenecker [5].

Figure 2 compares these results to experimental measurements for NZF composites at 1GHz with various inclusion volume fractions. CST models agree well with measurements and the LI rule, while EMTs give consistent estimations for low volume loadings and weak dielectric contrast (e.g. permeability).

Composite homogeneity is critical for applying EMTs and CST MWS to predict the dielectric properties and for future application in NLTLs. Using a 3D X-ray microscope, we observed that the inclusions were distributed homogeneously, validating the application of the quasi-static limit in the models based on the largest aggregation size of the inclusions.

Classical EMTs are generally limited to cases where the volume loading of inclusions is low, or the electrical contrast is not too great [5]. Unlike the results of NZF composites in Figure 2, most classical EMTs failed to estimate the effective permittivity of the BST composites due to a strong dielectric contrast between the inclusions and the host for permittivity. One alternative used to address this large contrast in the past applied generalized EMTs (GEMTs), which contained semi-empirical terms that could be fit [3,6]. Benchmarked numerical simulation tools may permit the assessment of the the two fitting exponents in a GEMT to provide another avenue for accurately predicting the effective properties [3, 6].

After benchmarking the composite models in CST MWS for linear dielectric and magnetic properties, we may develop nonlinear EMTs to describe the dielectric properties of the nonlinear composites for guiding future NLTLs design and ultimately coupling to HPM system design to predict and optimize RF generation.

Acknowledgments

This work was supported by the Office of Naval Research (Grant Number N00014-18-1-2341).

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