THREE-DIMENSIONAL FINITE-DIFFERENCE TIME-DOMAIN SIMULATION OF COAXIAL TRANSMISSION LINE FOR BROADBAND DIELECTRIC CHARACTERIZATION

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To my beloved parents,

Father, Noor Ahmad Bin Sakiban

Mother, Mestijah Binti Md Said

Thanks for all the sacrifies and love…

Dedicated to all my friends,

Izzati, Diana, Farhah, Asmahani, lab mates of computer instrumentation, and my husband Muhd Dinie

For the support given will not forgotten

Thank you for supporting me

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ABSTRACT

In this work, a part of a coaxial transmission line is used as a sample holder where the propagation of electromagnetic waves in the range of 500 MHz is studied using three-dimensional (3D) finite-difference time domain (FDTD) method. This study presents the results from the numerical simulations of electromagnetic waves in a mixture of dielectric materials. The effective relative permittivity of the mixture is calculated by recording one of the electric field components (E_y) of the transmitted and reflected electromagnetic pulses in the transmission line. The complex frequency spectra of these time-domain signals are then obtained by taking the Fourier transforms of the respective signals. These spectra are then used to calculate the complex transmission and reflection coefficients for the sample. The analysis of raw data is performed using open source package, GNU Octave. Finally a numerical procedure is developed to convert the raw data into an effective dielectric property of the mixture of materials. The influence of water contents on dielectric properties is studied using samples made from different mixtures of soil, water, and air. The results show that the effective dielectric permittivities of the mixtures are highly dependent on the soil's moisture content. Strong frequency dependence in the dielectric properties is observed especially at the low end of frequency range which can be attributed to the presence of the DC conductivity of water (5 μS/m) in the mixture. In general the results are consistent with those calculated using Maxwell-Garnett mixing formula especially at the high end of the frequency range.

ABSTRAK

Dalam kajian ini, sebahagian daripada talian penghantaran sepaksi digunakan sebagai pemegang sampel di mana perambatan gelombang elektromagnet dalam julat 500 MHz dikaji dengan menggunakan kaedah perbezaan terhingga domain masa (FDTD) tiga dimensi (3D). Kajian ini membentangkan hasil simulasi berangka daripada gelombang elektromagnet dalam campuran bahan dielektrik. Ketelusan relatif berkesan campuran dihitung dengan merekodkan salah satu komponen medan elektrik (E_y) dalam denyut elektromagnet yang dipancar dan dipantulkan dalam talian penghantaran. Spektrum frekuensi kompleks bagi isyarat domain masa ini diperoleh dengan menggunakan transformasi Fourier signal berkaitan. Spektrum ini kemudiannya digunakan untuk menghitung pekali pantulan dan penghantaran kompleks bagi sampel. Semua analisis data asal ini dilakukan dengan menggunakan pakej sumber terbuka, GNU Octave. Kemudian, suatu prosedur berangka dibangunkan untuk menukar data asal kepada sifat dielektrik berkesan campuran bahan. Pengaruh kandungan air pada sifat dielektrik dikaji menggunakan sampel yang diperbuat daripada campuran tanah, air, dan udara yang berbeza. Keputusan menunjukkan bahawa ketelusan dielektrik berkeasan bagi campuran adalah amat bergantung kepada kandungan kelembapan tanah. Pergantungan kuat terhadap frekuensi dalam sifat dielektrik dapat diperhatikan terutamanya di hujung julat frekuensi rendah yang boleh dikaitkan dengan kehadiran kekonduksian DC air (5 μS/m) dalam campuran. Secara umumnya, keputusan adalah konsisten dengan hasil yang dihitung menggunakan formula percampuran Maxwell-Garnett terutamanya di hujung julat frekuensi tinggi.

TABLE OF CONTENTS

3 METHODOLOGY

4 RESULTS

5 CONCLUSIONS AND RECOMMENDATIONS

LIST OF ABBREVIATIONS

ABC	-	Absorbing Boundary Conditions
3D	-	Three dimensional
FDTD	-	Finite Difference Time Domain
PML	-	Perfectly match layer
UPML	-	Unixial anisotropic perfectly match layer
PEC	-	(Ideal electric conductor)
PMC	-	(Ideal magnetic conductor)
ta	-	Polarization in the next direction of the axis of the light incident axis
tb	-	Polarization in the more next direction of the axis of the light incident axis
ra	-	Reflection in the next direction of the axis of the light incident axis
rb	-	Reflection in the more next direction of the axis of the light incident axis
TEM	-	Transverse electromagnetic

LIST OF APPENDICES

LIST OF FIGURES

LIST OF SYMBOLS

α - Polarizability

β - Fitting parameter for constant phase element

ε - Dielectric permittivity or dielectric constant

ε_r - Complex dielectric permittivity

ε_{eff} - Effective dielectric permittivity

σ - Conductivity

μ - Relative permeability

μ_r - Complex relative permeability

μ_{eff} - Effective relative permeability

n - Refractive index

n_{eff} - Effective refractive index

λ - Wavelength

λ_n - Wavelength in the medium

δ - Loss angle

c - Speed of light in vacuum or air (300mm/ns)

v - Phase velocity

π - Radian
θ - Phase angle
t - Time
k - Phase constant or wave number
f - Frequency
f_c - Centre frequency
f_{co} - Cut – off frequency
$f_{max,}$ f_m - Maximum frequency
f_{min} - Minimum frequency
Γ - Reflection coefficient
Δ - Delta or interval
Δt - Time interval
ω - Angular frequency
r_{in} - Inner radius
r_{out} - Outer radius
N_t - Fitting parameter for constant phase element
$\mathbf{B}$ - Magnetic induction vector
$\mathbf{D}$ - Electric displacement vector
$\mathbf{E}$ - Electric field
E_i - Incident electric field
E_r - Reflected electric field

E_t - Transmitted electric field

$\mathbf{H}$ - Magnetic field

$\mathbf{J}$ - Current density vector

L - Length of transmission line

$\mathbf{S}$ - Pointing vector

S_{11} - Reflection coefficient

S_{21} - Transmission coefficient

$|S_{11}|$, $|S_{21}|$ - Magnitude of the S-parameters (Complex S-parameters)

T - Transmission coefficient

Z - Impedance

z - Effective impedance

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Accurate extraction of reflection coefficient, Γ from finite-different time-domain (FDTD) simulations is an important practical problem. The value of Γ is used to obtain the S-parameters of the analysed circuit. A common approach consists of matching the outputs by means of high quality absorbing boundary conditions (ABC's) which permits to assume S_{11} to be equal to Γ at the input. Recently, a more elaborate method has been proposed by Sharkov in 1995, which multiple calculations of reflection coefficient at different ports allow to obtain the S parameters with good accuracy, even for relatively poor ABC's. In either case, the main problem of Γ extraction resides in separating the incident and reflected waves at the considered port. To solve this problem, two basic approaches have been reported so far (Sharkov, 1995).

The first approach consists of running the simulation twice or concurrently on two models, one run is for the analyzed circuit and the other for a nonreflecting structure with the identical input. The second simulation provides a pure incident wave. It can be reduced to the two-dimensional (2D) simulation of the cross section of the line (V.J.Brankovic, 1995), but at the expense of repcating it independently for each relevant frequency. Although good results in applying this approach have been reported, it is clear advantage is the necessity of double simulation, which significantly increases the employed computer resources and complicates the use of program.

The second approach (W.K. Gwarek, 1988) assumes that for reference, either wave impedance or characteristic impedance of the line is a priori known (analytically or heuristically). After application of correction factors due to the shifts between the **E** and **H** fields in time and space, this method gives very good results for homogeneously filled transverse electromagnetic (TEM) lines (J. Fang, 1995) which are when the wave impedance does not change with frequency or waveguides when it changes according to an analytically known rule. However, in application to inhomogeneous quasi-TEM lines, even if the quasi-static wave impedance is known, significant errors appear due to dispersive properties that are difficult to predict.

1.1.1 Effective Permittivity of Dielectric Mixtures

The study of the electromagnetic behavior and characterization of dielectric mixtures is a classical problem which was already been addressed by Maxwell more than a century ago. Nowadays, this initial interest has not decayed at all. On the contrary, new artificial materials have renewed and drastically increased this attention due to the design of new and even unknown applications non-existing in natural media. The quasi-static initial works have been substituted or completed with high frequency applications, such as perfect lens manufacturing, sub-wavelength microwave devices, enhanced radiation by small antennas and others.

In addition, the availability of powerful computers has also modified the way in which these and other related problems are addressed. In this sense, the first attempts to model dielectric mixtures were concentrated on obtaining theoretical formulas to predict the effective permittivity of composite materials consisting of mixtures with several homogeneous components.

The Maxwell Garnett (MG) mixing rule yields;

$$\frac{\varepsilon_{eff} - \varepsilon_2}{\varepsilon_{eff} + (d-1)\varepsilon_2} = p_1 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + (d-1)\varepsilon_2} \tag{1.1}$$

Another famous mixing rule is the Bruggeman formula (D.A.G Bruggeman, 1935);

$$p_1 \frac{\varepsilon_1 - \varepsilon_{eff}}{\varepsilon_1 + (d-a)\varepsilon_{eff}} = p_2 \frac{\varepsilon_2 - \varepsilon_{eff}}{\varepsilon_2 + (d-1)\varepsilon_{eff}} \tag{1.2}$$

In both equations, the dimensionally d equals 2 if the problem is two-dimensional or equal to 3 in the case of considering a three-dimensional media. Besides the two simple approximation described above, many other mixing models exists. Nevertheless, it can be shown that in most case, it is impossible to completely determine the effective permittivity by the volume fractions and effective permittivity of phases.

1.1.2 Transmission Line Method

The transmission line method (P.B. Johns, 1971) is used for the modeling of composite mixtures. As it happens with the FDTD method, transmission line method is a low frequency numerical method which has been extensively used for the modeling of wave propagation problems, mainly electromagnetic nature but also for problems in acoustic or particle diffusion. The method is not only a numerical model to solve certain phenomenon, but also a conceptual approach which does not consider analytical equations governing the phenomenon, but directly considers the original phenomenon by means of equivalent transmission line. This conceptual nature of transmission line method makes this method a powerful tool transmission which allows considering challenging problems from a hybrid numerical-theoretical point of view in an elegant and suitable way.

1.2 **Problem Statement**

Beginning with the development of finite difference equations and leading to the complete FDTD algorithm, the FDTD modeling of problems can be undertaken with computer resources readily available to individual user. FDTD methods are relatively forward and intuitively follow from a physical understanding of Maxwell’s equation. The full range of useful quantities can be calculated such as the transmission or reflection of light. In this research, the suitable coaxial transmission line for broadband materials for high efficiency will be finder. To find the suitable one, it needs to do a lot of sample and consume a lot of time to make the sample and test it. So, by simulating each material, it can compute and found the better sample holder for broadband material. It also include under several theoretical approaches for modeling dielectric properties of heterogeneous media. Strong frequency dependence in the dielectric properties is observe especially at the low and high end of frequency range which can be attribute to the presence of the DC conductivity of water in the mixture. Effective dielectric properties of heterogeneous mixtures can be obtained from FDTD simulation using wave propagation on coaxial transmission line as a sample holder.

1.3 Objective of the Research

The main objectives of this study are:

1. To simulate the effectiveness of the coaxial transmission line for characterization of dielectric materials for over a range frequency using FDTD method.
2. To determine the broadband dielectric properties of heterogeneous materials using part of the transmission line as a sample holder.
3. To compare the effectiveness of dielectric properties obtained to those calculated using mixture formula.

1.3 Scope of Study

This research are studied using three-dimensional finite-difference time-domain (3D FDTD) method comes with commercial package otherwise known as EastFDTD. This research is using a transmission line model as a sample holder and uses the input for range of frequencies 100-500 MHz. This research includes three mixtures using sand, water, air, and soil models.

1.5 Significance of Study

FDTD methods are well suited for analysis of problems with complex geometrical features as well as those containing arbitrarily inhomogeneous materials. FDTD method actually can save more costs than the vector analyzer network (VNA) and others method to get the propagation electromagnetic wave due to the different frequencies. Also, the FDTD method does not require the derivation of a Green's function or the solution of matrix equation. FDTD methods have emerged as the methods with arguably the broadest range of applicability. This is especially true for electromagnetic problems involving complex and dispersive media, photonics applications, and modeling of high speed circuits and devices.

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