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Electromagnetic Analysis of Composite Coaxial Cells for Wideband Measurements of Highly Dispersive Materials

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Abstract

In this paper, a new transmission line matrix node is proposed for electromagnetic analysis of a composite coaxial cell which is used to characterize highly dispersive materials over a large frequency band. A variety of measurements using such a coaxial line cell have been done with different liquid samples to verify the wideband characteristics. It is shown that theoretical and experimental results have a very good agreement.

Introduction

Wideband measurements of highly dispersive materials are instrumental in the study of electromagnetic energy absorptions [1,2]. The coaxial line technique [3] demonstrates unmatched advantages compared to other approaches which are mainly attributed to its high measurement sensitivity, wideband TEM propagation and simple mechanical assembling. In this work, a new coaxial cell (Fig.1) is proposed for measurement of liquid or powder materials. The sample occupies the outer space near the inner face of cylindrical conductor. In this way, a high sensitivity over a wideband of frequency can be achieved by choosing an appropriate taking-up space of the material with respect to the whole cell, thereby adjusting the degree of field interaction between the electromagnetic wave and the sample. Therefore, a knowledge of electromagnetic propagation and scattering along the coaxial cell is mandatory in understanding the working mechanism and parametric dependence of electrical characteristics.

In this paper, the frequency domain transmission line matrix (FDTLM) method is used to analyze and characterize the proposed composite coaxial-line cell for wideband measurements. In particular, a new version of frequency domain symmetrical condensed node (FDSCN) is developed to model general dispersive medium. This node is also able to facilitate the accommodation of cylindrical topology, thereby enhancing the analysis and characterization precision for such a complex coaxial structure . In addition, a variety of measurements are carried out to verify theoretical predictions and electrical performance of the proposed cell over a large frequency range.

Theoretical Modeling

The FDTLM provides an unified algorithm to tackle complex electromagnetic problems. The node is the core of the TLM algorithm. In the previous work [4], a simple frequency domain node has been derived to analyze cylindrical microstrip discontinuities. It is unfortunate that for certain mesh size, however, the propagation constant on the cylindrical transmission line matrix grids may become zero or even negative. This leads to a undesirable situation of high node dispersion and poor space resolution. To remedy the illness of the original node, and at the same time, to accommodate the highly lossy dspersive mediums in the node, a new version of FDSCN is formulated in this work. The node used in the analysis is described in [4]. It can be considered as three shunt and three series elementary nodes that are coupled with each other at the center of the node. The admittances of the three series elementary nodes are expressed as follows,

$$Y_r = \frac{\Delta_l \Delta_r}{\Delta_\theta \Delta_z} \sqrt{\frac{\sigma_e + j\omega\varepsilon_0\varepsilon'}{\sigma_m + j\omega\mu_0\mu'}} \tag{1a}$$

$$Y_\theta = \frac{\Delta_l \Delta_\theta}{\Delta_r \Delta_z} \sqrt{\frac{\sigma_e + j\omega\varepsilon_0\varepsilon'}{\sigma_m + j\omega\mu_0\mu'}} \tag{1b}$$

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$$Y_z = \frac{\Delta_1 \Delta_z}{\Delta_\theta \Delta_r} \sqrt{\frac{\sigma_e + j\omega\varepsilon_0\varepsilon'}{\sigma_m + j\omega\mu_0\mu'}} \quad (1c)$$

where

$\Delta_1 = \sqrt{(\Delta_r^2\Delta_\theta^2 + \Delta_r^2\Delta_z^2 + \Delta_\theta^2\Delta_z^2) / (\Delta_r^2 + \Delta_\theta^2 + \Delta_z^2)}$.

Y_r is associated with the r-oriented series node including $\pm\theta z$ and $\pm z\theta$ polarized directions; Y_θ with the θ-oriented series node including $\pm rz$ and $\pm zr$ polarized directions; and Y_z with the z-oriented series node including $\pm r\theta$ and $\pm\theta r$ polarized directions. Δ_r,Δ_θ and Δ_z denote the dimensions of the node. The conductivity is defined as $\sigma_m = \omega\mu_0\mu''$ and $\sigma_e = \sigma_s + \omega\varepsilon_0\varepsilon''$. σ_s is the static electrical conductivity. $\varepsilon',\varepsilon''$ and μ',μ'' may be frequency-dependent.

The elements of symbolic scattering matrix are normally determined by enforcing the energy conservation and applying the voltage and current laws for the incident and reflected voltage waves at the center of the node. This yields,

$$a_n = c_n = (Y_s - Y_t) / 2(Y_s + Y_t) \quad (2a)$$

$$b_n = Y_s / (Y_s + Y_t) \quad (2b)$$

$$d_n = 0.5 \quad (2c)$$

where the subscripts *s* and *t* take appropriate values of *r*,*θ* or *z*, n = 1 ~ 6. In order to build up the entire FDTLM algorithm, the reference planes have to be moved from the centre of the node to its ports. It is equivalent to multiplying the incident and reflected waves with an appropriate phase delay factor such as $\exp(\gamma\Delta_h)$, where γ is the corresponding propagation constant of the node connecting line and Δ_h is the mesh size. A detailed procedure for determining the propagation constants of all connecting lines will be described somewhere else. The final results are obtained in the following,

$$\gamma_{rz} = \frac{\Delta_r\Delta_\theta^2}{\Delta_1(\Delta_r^2 + \Delta_\theta^2)}k \, , \; \gamma_{\theta z} = \frac{\Delta_\theta\Delta_r^2}{\Delta_1(\Delta_r^2 + \Delta_\theta^2)}k$$

$$\gamma_{r\theta} = \frac{\Delta_1\Delta_r}{\Delta_r^2 + \Delta_\theta^2}k \; , \; \gamma_{\theta r} = \frac{\Delta_1\Delta_\theta}{\Delta_r^2 + \Delta_\theta^2}k$$

$$\gamma_{zr} = \frac{\Delta_z(\Delta_r^2 + \Delta_\theta^2 - \Delta_1)}{\Delta_1(\Delta_r^2 + \Delta_\theta^2)}k \; , \; \gamma_{z\theta} = \gamma_{zr} \quad (3)$$

where *k* is the intrinsic wave number of the medium pertaining to the node. It is obvious that all above mentioned propagation constants of the connecting lines are always positive regardless of the variation of mesh size in the discrete space. It can be expected that the proposed node has better dispersive properties and higher space resolution for a graded TLM mesh.

Measurement Techniques

A wideband composite cell (see Fig.1) was made with a through coaxial-line (d = 2.89 mm, f = 7.15 mm) in which the chamber to be filled with a sample material is located near the outer conductor. The inner diameter of chamber is e = 6.25 mm, and the length c = 20.0 mm. Teflon container is used to hold liquid samples. The dimension is a = 2.84 mm, b = 2.64 mm. The injection of a liquid material is done through two holes on the outer conductor. Measurements are performed using a network analyzer (HP8510-C) using the TRL calibration via a APC7-mm standard at 45 MHz - 18 GHz frequency range.

Results

To examine the accuracy of our theoretical modeling and experimental results, measurements using this coaxial cell are made for different liquid samples. Fig.2 presents dispersion characteristics of complex permittivity of the liquid samples such as water and methanol. This indicates that it would be erroneous if the conventional analytical formula of ε'' in terms of conductivity. This is because for highly dispersive materials the imaginary part of permittivity is not always linearly dependent of conductivity.

Fig.3 shows a very good agreement of transmission coefficient between the theoretical and experimental results for the water sample under the room temperature. The discrepancy between them may be attributed to numerical precision of the algorithm, or measurement calibration errors, or both factors. It seems that the linear phase characteristics are well preserved regardless of highly dispersive nature of water. Combining the real and imaginary parts of the transmission coefficient indicates that electromagnetic energy is absorbed quasi-exponentially with a certain decaying factor as the frequency increases. This decaying factor is expected to be related to the geometrical dimensions of the cell and electrical property of the sample to be considered. In any case, this example demonstrates that a wideband measurement sensitivity can be readily achieved by an appropriate choice of the cell topology. Fig.4 presents a comparison of reflection coefficient between the measurement and theoretical prediction. The difference of results suggests that there are some perturbations that may come from the propagation of high-order modes between 10 and 15 GHz.

Similar to the situation of water, Fig.5 and Fig.6 show frequency-dependent characteristics of scattering parameters for the methanol sample. Clearly as indicated in Fig.5, the absorption is much less pronounced and wideband sensitivity of measurement using the transmission coefficient can be easily obtained. With regard to Fig.6 which shows a comparison of the reflection coefficient between the theoretical prediction and experimental results, it seems that the strong influence of high-order modes deforms significantly the decaying sinusoidal variation against frequency. The calibration should be made far from the active zone of high-order modes, and preferably be done at low frequencies.

Conclusions

A generalized TLM algorithm of cylindrical coordinate is proposed in this paper for material characterization in the frequency domain using a coaxial line cell. The proposed characterization technique using a composite coaxial through line promises a wideband measurement sensitivity, which is also well confirmed by the theoretical prediction. This coaxial cell is in particular suitable for a large class of highly dispersive liquid and powder materials such as water and methanol. The very good agreement between the theory and measurement indicates that electromagnetic modeling will play an important role in the material characterizations.

References

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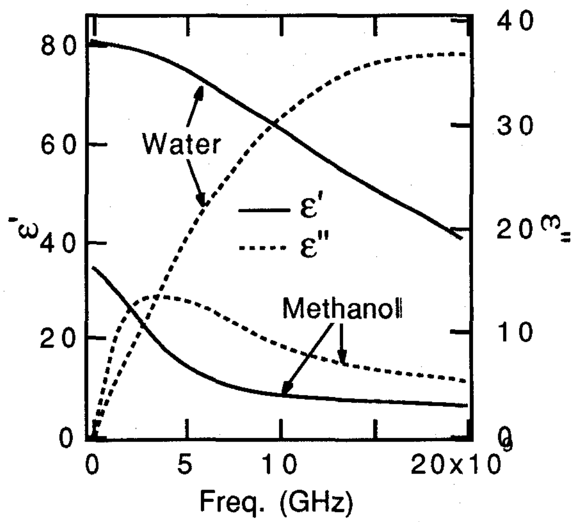

Fig. 2 Complex dielectric permittivities of water and methanol as a function of frequency.

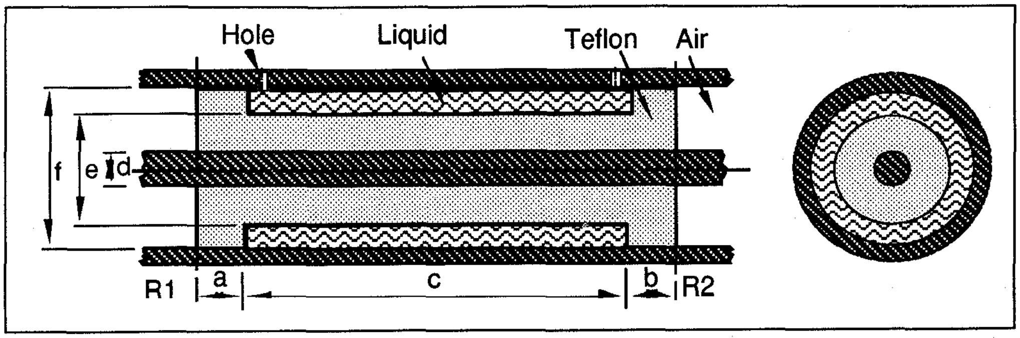

Fig. 1 A wideband coaxical cell for permittivity measurements

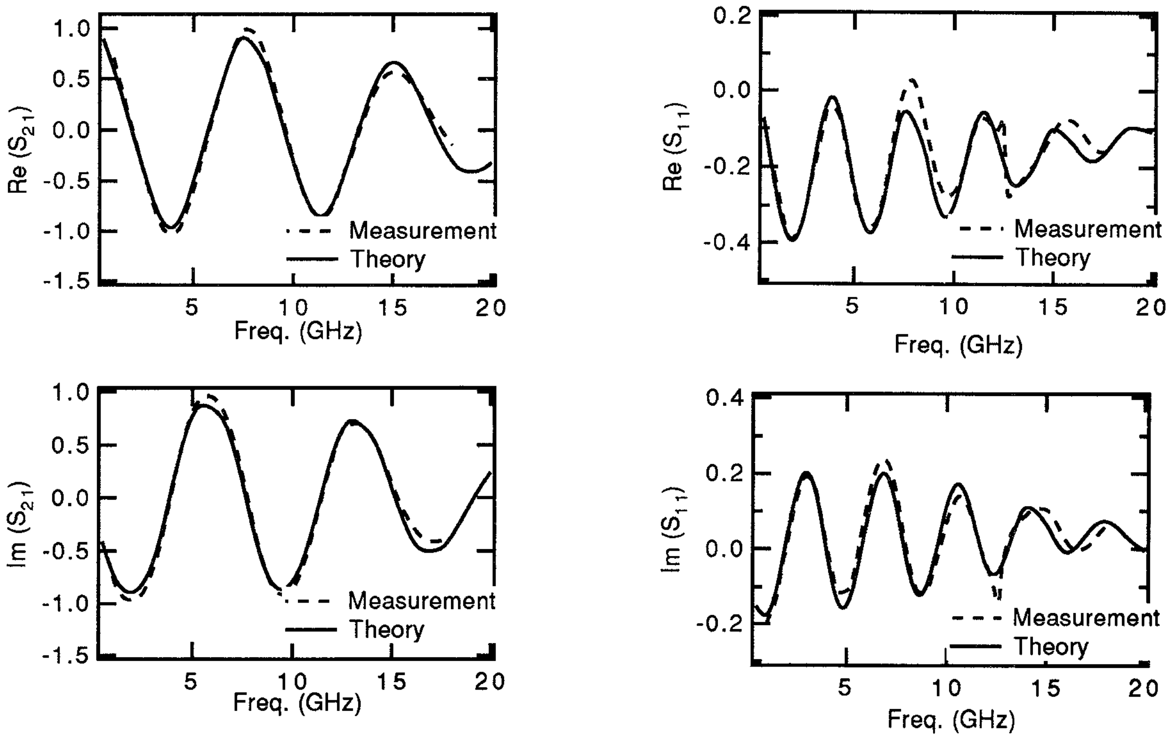

Fig. 3 Comparison of theoretical and measured results for the water sample.

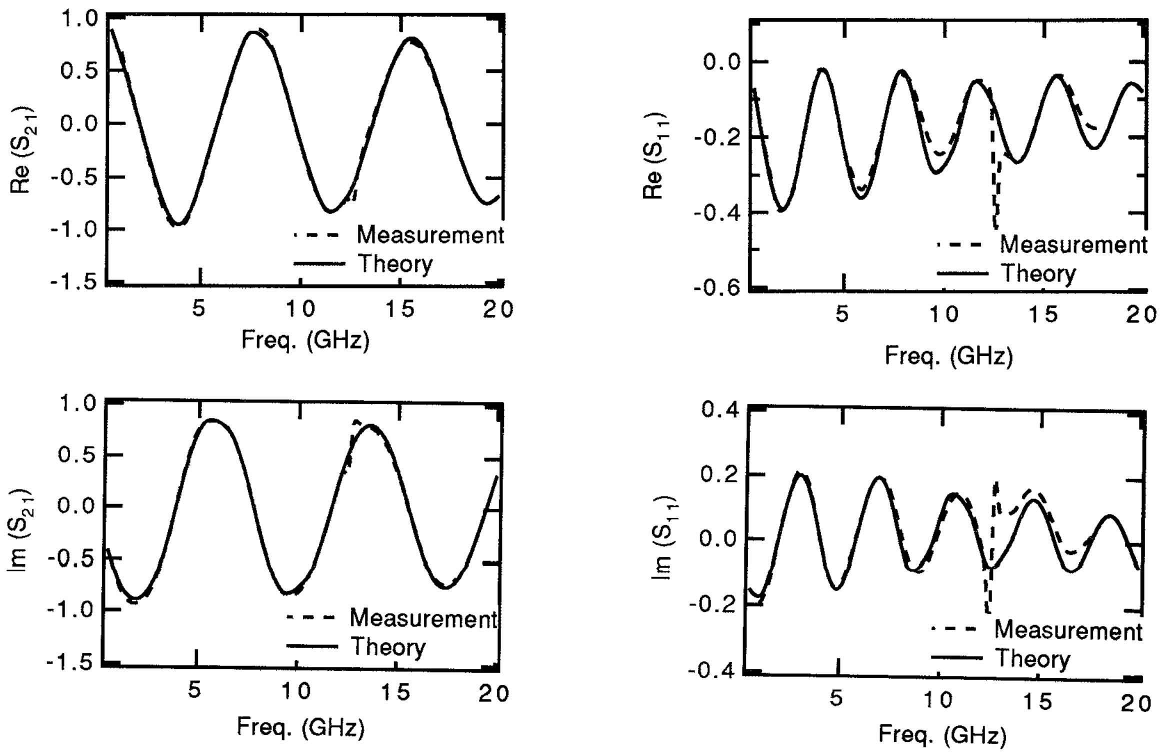

Fig. 4 Comparison of theoretical and measured results for the methanol sample.