Progress In Electromagnetics Research, PIER 77, 357–365, 2007

MEASURING THE PERMITTIVITY OF DIELECTRIC MATERIALS USING STDR APPROACH

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Abstract—This paper presents a new approach for measuring dielectric properties of materials. The proposed approach is based on applying the synthetic time domain reflectometry to a dielectric filled waveguide. The compromising measurement results show that this algorithm can be successfully applied for measuring other parameters of the materials. Also, the approach has been successfully applied to detect the discontinuities of as a multi-section microstrip line. This approach is very useful in measuring the electromagnetic parameters of the different liquids, gels, and solid materials.

1. INTRODUCTION

Electromagnetic properties of each material include the permittivity, permeability and conductivity. For dielectric materials either lossy or lossless, the most identifying parameter is the dielectric constant or permittivity [1]. There are many methods for measuring this parameter. Many of these methods require very complicated test sets. Also many of them have a limited dynamic range.

When the geometrical structure of the material under test is in the sheet form, free space techniques may be more suitable [2]. In these methods, the response (i.e., reflection, transmission and absorption) of this sheet to Electromagnetics waves is measured and analyzed. It is obvious that this method is not applicable for small samples of dielectrics.

Due to very narrow band structure of microwave resonators, the most sensitive approaches for measuring the electromagnetic properties of dielectric materials are resonant cavity and perturbation ones [3]. Therefore, they need more stable and accurate instruments. The cavity resonant method also needs a cavity having a high quality factor and also capable of frequency tuning. Kumar [4] has developed a resonant cavity based technique to evaluate the dielectric constant and loss factor of a homogeneous dielectric material using rectangular shaped perturbed cavity. He has measured the permittivity of Teflon at X band.

A partially-filled waveguide method has been developed by Bogle [5] to enhance the transmission quality and accuracy in electromagnetic material characterization measurements.

Qian [6] has used the open cavity and also the interferometer methods to study the sensitivity of these two methods to a small disturbance of permittivity. His method is suitable for the cases in which the relative dielectric constant is close to unity.

A very useful approach for measuring the dielectric properties of materials is time domain reflectometry (TDR) [7–11]. This is a time domain approach. It is based on the measurement of step or impulse response of the device under test (DUT).

Here, the synthetic TDR approach is applied to measuring the dielectric constant of dielectrics. The result is well matched with the information presented in the data sheet. Surely this approach can be applied to measure other parameters of materials. Also using the more accurate test sets, the accuracy of the measured results can be improved. The proposed algorithm is very useful for measuring the electromagnetic properties of oil products.

2. TDR BASICS

The performance of a microwave circuit is usually specified in frequency domain. However, since in the wave propagation phenomenon, time and distance are proportional to each other, time domain measurement can be interpreted in terms of physical layout of the circuit. The most usual time domain technique is TDR approach. This approach is based on measuring the step response of the reflection/transmission coefficients of the circuit. If there are some reflections on the circuit, the step response presents relative maxima in the corresponding points. Since the distance axis is the scaled version of the time axis, the horizontal axis of the step response, can be interpreted as distance. Therefore, the mismatched points can be exactly located. This method has been successfully applied to measure the fault location in a satellite system in our department. The measurement was so exact that even the loose connections and abrupt bends had some influences in the response. Although the algorithm is exact for TEM propagation mode, it can be modified and applied to non-TEM modes.

3. SDR APPROACH

TDR approach demands some accurate and fast time domain tools. However, the majority of microwave labs are equipped with the frequency domain tools. Here, a frequency domain technique is applied to measure the time domain response of a mismatched system. First, several measurements in a broad frequency range are performed to yield the reflection coefficient of the system as a function of frequency. Then using Fourier approach, the results are translated to time domain. This is why this technique is called synthetic time domain reflectometry (STDR).

In traditional TDR [7–10], a pulse function generator provides a repetitive signal to the device under test. A sampling gate linked to a sampling oscilloscope, monitors both the incident and reflected signals in the time domain, and the amplitudes of the signal yield the desired information. This kind of measurement is called real pulse TDR (RTDR), because the excitation signal is a real pulse. It is noticeable that RTDR is not easily applicable in microwave range because it needs fast pulse generator and oscilloscope. However, if we measure the frequency domain response, we can calculate the impulse or step response using the Fourier techniques. Here, the excitation signal is not a pulse but a set of frequency components. So this is called STDR.

STDR has several advantages compared to RTDR. It has higher resolution. Moreover, it can be used in dispersive lines such as waveguides. Besides, the start and stop frequencies can be chosen freely for broadband measurement. The only disadvantage is the computational requirement which can be solved by preparing suitable software, as we have done.

4. STDR IDEA

The mathematical concept behind STDR technique is the same as TDR concept. Each component of an electromagnetic field in simple one-dimensional case satisfies the wave equation as following:

$$\frac{\partial^2 U}{\partial t^2} = v^2 \frac{\partial^2 U}{\partial z^2} \tag{1}$$

The general solution of this equation is in the form of $f_1(z - vt)$ and $f_2(z + vt)$ in which f_1 and f_2 are two general well-posed functions. This theorem is the direct result of wave nature of $U(z, t)$.

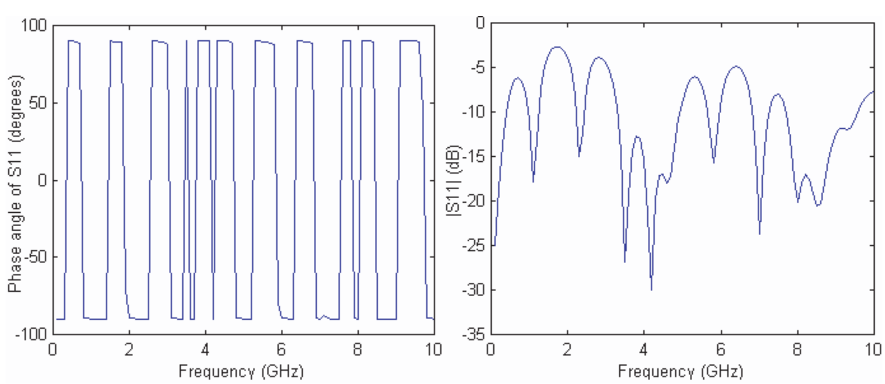
Now, if we measure a special characteristic of a wave in frequency or phasor domain, we can easily transform the result to time domain, by inverse Fourier transform. In STDR, we usually measure the reflection coefficient of different discontinuities. Since the time and space functionalities are similar, rescaling the result gives the characteristics versus distance.

It is obvious that the reflection coefficient of a transmission line is uniquely related to the dielectric properties of the transmission line. We have used this interrelation, to measure the dielectric constant of materials.

5. SIMULATION OF MICROSTRIP LINE USING STDR APPROACH

Fig. 1 shows a multi-section microstrip line used for simulation of reflection coefficient. The reflection coefficient is calculated using Q-TEM model of microstrip line, and is shown in Fig. 2. The time domain input and output signals have been calculated using Fourier approach. As seen in Fig. 3, the first influence of reflections from the discontinuities is observed after about 1.25 nano-seconds. This means that the average velocity of propagation is about 1.72×10^8 m/sec. As a result, the effective permittivity of the first microstrip line is about 3.02. This value is close to the result obtained by well-known

Figure 1. Layout of a multi-section microstrip line ($\varepsilon_r = 4.5$, $h = 1.5$ mm).



(a) (b)

Figure 2. Frequency domain reflection coefficient of the microstrip line system.

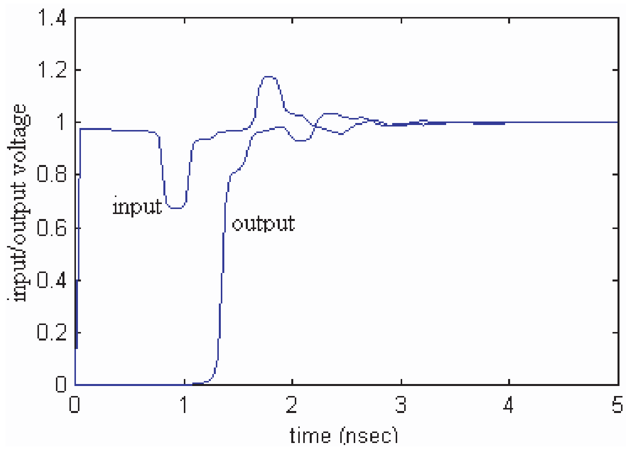


Figure 3. Time domain signals at the input and output ports of the microstrip line system.

microstrip equations. Taking into account other discontinuities, the characteristics of other sections of the line can be calculated. This method has been applied to a few microstrip lines and the calculated values of relative permittivity have been well matched with the existing data.

6. RESULTS FOR WAVEGUIDE STRUCTURE

Fig. 4 shows a waveguide which is partially filled by a dielectric. Figs. 5 and 6 show the frequency and time domain responses of the reflection coefficient of this waveguide. Having these results, the relative permittivity of the dielectric is calculated. The result is matched with the data of the dielectric. As seen in Fig. 6, both

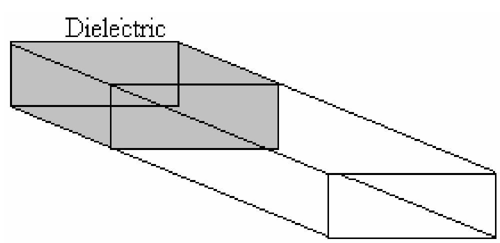


Figure 4. Schematic of a dielectric filled waveguide for measuring the relative dielectric permittivity.

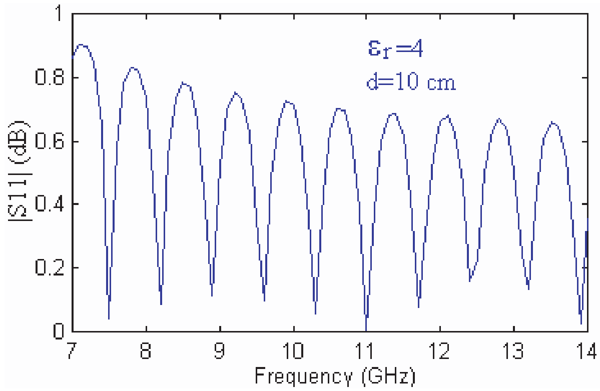


Figure 5. Frequency response of the reflection coefficient of the waveguide system.

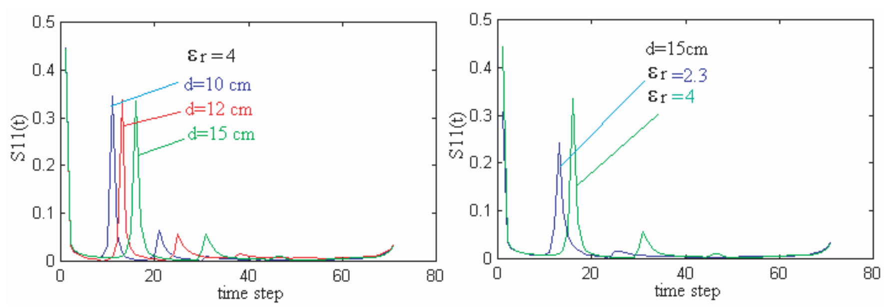


Figure 6. Time domain response of the reflection coefficient of the waveguide system.

the value of the relative permittivity and the location (or size) of the dielectric material have influences on the amplitude and the location of the maxima. Fig. 7 presents one of our measurement results. Although the measured values of frequency domain are slightly different from the simulations, the time domain results have an acceptable match. This shows that the attenuation of dielectric-filled waveguide does not degrade the results. This can be considered as an advantage of STDR approach.

It must be noted that the coaxial and microstrip lines are TEM and quasi-TEM structures, respectively. Therefore, there is negligible dispersion in these transmission lines. This means that the proposed technique is more accurate in these lines rather than in single conductor waveguide structures.

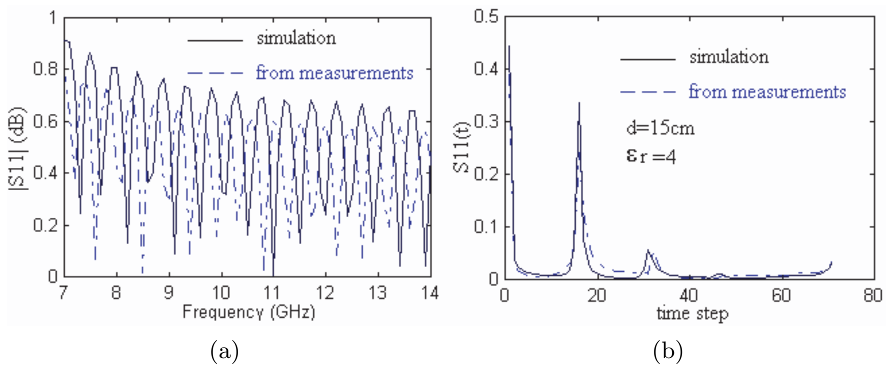


Figure 7. Comparison of measurement/simulated results of the time and frequency domain responses of the reflection coefficient for the waveguide system.

7. APPLICATION OF PERMITTIVITY INFORMATION

Knowing permittivity (together with permeability and conductivity) of materials has several applications. As an example that is obvious form section 5 of this paper, one can accurately characterize microstrip strip lines. The same is valid for other strip lines. As other applications of studying on Electromagnetics performances of dielectric materials, one can point to researchers performed by Thomas [12] and Bindu [13], which in the former, detection of buried pipelines has been studied and in the latter, electromagnetic properties of corn syrup has been measured. Finally application of measurement of permittivity on detection of gases materials is another practical application in oil industry.

At last, it should be emphasized that TDR approaches can take into account the non-homogeneity of materials. However extraction of electromagnetic information needs more robust mathematical formulation [14, 15]. This is what the authors are to follow in the next phase of their researches.

8. CONCLUSION

A combination of time and frequency domain approaches has been used to calculate the dielectric permittivity of materials. The simulation procedures for calculation of dielectric permittivity for a microstrip line, and that of a waveguide system have been studied. The results are well matched to those given by existing data and the measurements.

The STDR approach has been applied both to measure the dielectric permittivity of materials and to detect the locations of discontinuities of transmission lines. It is noticeable that having very fast time domain instruments, one may directly measure the permittivity of dielectric materials and the discontinuity of transmission lines. However, our measurements are performed at frequency domain, and this is a great advantage of the STDR approach.

The proposed technique can be used to characterize many kinds of dielectric materials. Also this approach may be developed to measure the lossy materials.

ACKNOWLEDGMENT

The authors would like to thank the responsible for Amirkabir University of Technology for supporting this research.

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