MEASUREMENT OF THE EFFECTIVE PERMITTIVITY IN TRANSMISSION LINES BY MEANS OF FREQUENCY DOMAIN REFLECTOMETRY

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ABSTRACT

This work presents a procedure to measure the effective dielectric permittivity in transmission lines. The procedure is based on an improved Frequency Domain Reflectometry (FDR) method. In this technique, the measured reflection coefficient as a function of the frequency is used to synthesize the response of a terminated transmission line to an ideal delta pulse in different finite bandwidths. The time spent by this pulse to reach a highly reflective termination and return to the input of the transmission line was used to estimate the effective dielectric permittivity in the range 5 GHz - 20 GHz.

INTRODUCTION

The most suitable procedure to measure the permittivity of a dielectric material is highly dependent on different parameters such as available material shapes, losses and desired measurement frequency ranges. A number of methods can be found in the literature [1]-[7]. Those based on time domain reflectometry (TDR) demand for complicated instrumentation when measurements above 1 GHz must be made [1], [2]. Resonators can be used to make accurate estimations in narrow frequency bands [3], [4]. Furthermore, it is possible to estimate complex permittivities in broad frequency bands with open ended coaxial probes [5]-[7]. These offer excellent accuracies with rather simple models when air gaps between samples and probes are avoided.

A number of discontinuities and passive elements models used in computer aided design of microwave planar circuits depend on the substrate permittivity via the effective one. This has been a major motivation for the development of procedures based on direct measurements of the effective permittivity [5]. This paper is focused on a method that has been developed to measure effective permittivities via Frequency Domain Reflectometry (FDR). Three main questions are addressed in this work:

a) How can we take advantage of FDR techniques in dielectric permittivity measurements?

b) What are the main limitations of the simplest measurements?

c) How can we use electromagnetic simulation to extract the true dielectric permittivity from the measured one?

DESCRIPTION OF THE PROCEDURE

The proposed method is based on the synthesis of the response of a parallel plate transmission line to a delta pulse. The estimation of this response is made from broad band frequency domain measurements of the reflection coefficient. Standard FDR techniques have been applied so far to the detection of discontinuities in transmission lines and are well documented in the literature. These techniques can be extended to the estimation of the effective pemittivity by following three main steps:

I. **Synthesis of the response to a delta pulse.** An experiment is simulated in which a fictitious delta pulse is applied at the input of a parallel plate transmission line terminated in a short circuit. The reflected voltage at the input of the line is synthesized as a function of the time from the reflection coefficient measurements via the Fast Fourier Transform. Ideally, this voltage should be a delta function at the time of arrival, with an amplitude equal to that of the incident wave. In practice, the response is closer to a sinc function due the finiteness of the measurement bandwidth. If the material has negligible dispersion, the width of the main lobe only depends on the measurement bandwidth.

II. **Transformation of the time domain to the effective permittivity domain.** The time spent by the pulse in reaching the termination and coming back to the input line is used to obtain the propagation velocity, and from this the effective permittivity is calculated. Therefore, the time domain can be translated to an effective permittivity domain in a straightforward way. The frequency range in which the measurements are made specifies the band in which the permittivity is obtained.

III. **Estimation of the effective permittivity.** The final value obtained for the permittivity is indicated by the peak of the reflected voltage in the effective permittivity domain. The final resolution in permittivities is mainly dependent on the measurement bandwidth: the higher is the bandwidth the higher is the resolution. A numerical algorithm has been developed to calculate the arrival time of the pulses under low sampling rate conditions. The algorithm detects and corrects inaccuracies in the location of ill-behaved peaks. A figure of merit has been developed to test this accuracy from the width of the measured pulse and the relative amplitudes of the points adjacent to the peak. This figure is helpful to decide the proper value of the effective permittivity under conditions in which very low time resolutions (i.e., narrow frequency band measurements) are obtained. The algorithm detects the peak in the effective permittivity domain, takes the surrounding points and optimizes the effective permittivity to fit these points to the sinc function. From this optimization, the location of the maximum value of the sinc function provides the effective permittivity.

RESULTS AND DISCUSSION

In order to illustrate the method proposed here, we have made measurements of the effective dielectric permittivity in different transmission lines fabricated on a commonly used FR4 fiberglass substrate. The measured lines were parallel plate lines of 0.7 (line labelled as #PP07), 2 (#PP2) and 3 (#PP3) cm width, and a 50 Ohm microstrip line (#M50). The substrates has a thickness of 1.54 mm and a nominal dielectric permittivity of 4.4 at microwave frequencies. Table I shows the resulting effective permittivites, labelled as ε_{eff1}. The characterization of the parallel plate transmission line with 3 cm width was a good demonstration of the robustness of the proposed procedure, since the high mismatch in the transition to the coaxial connector led to a very weak reflected pulse. In addition, the low cost substrate used in the measurement presented relatively high losses above 10 GHz. Despite these difficulties, a good agreement between 3D electromagnetic simulation and measurement was obtained.

In order to verify the accuracy of the proposed method, a comparison was made with a more conventional technique. Different simulations were made with a 3D electromagnetic simulator based on the Finite Element Method. A conventional patch antenna with a resonant frequency of 4 GHz was fabricated and measured. An optimization was made to fit the simulated resonant frequency to the measured one, resulting in a dielectric permittivity of 4.45. This permittivity was used in the simulation of the parallel plate lines, resulting in the effective permittivities also shown in Table I, labelled as ε_{eff2}.

Table I. Calculated effective permittivity for the different lines

Line	**#PP07**	**#PP2**	**#PP3**	**#M50**
ε_{eff1}	3.85	4.17	4.22	3.22
ε_{eff2}	3.68	4.11	4.12	3.05

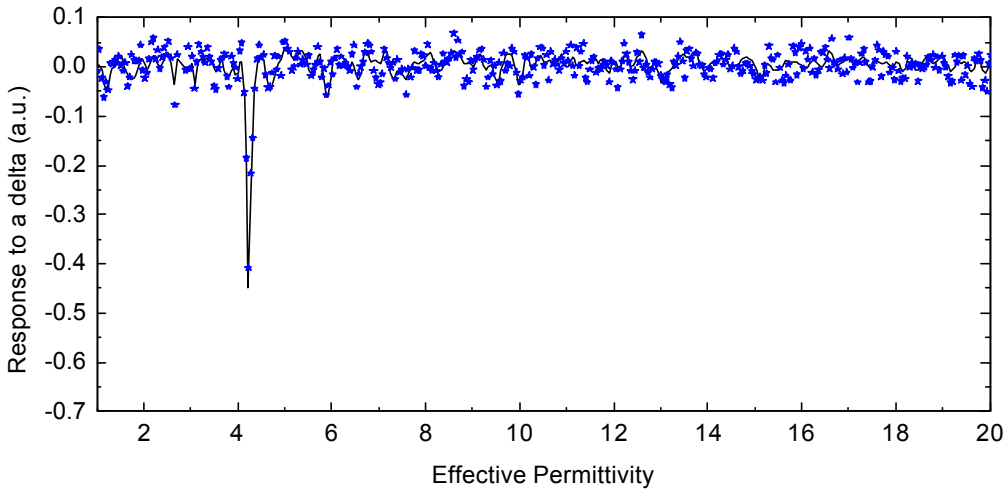

Figure 1. Response to a delta excitation in the effective permittivity domain.

Figure 1 shows an example of the response to a delta excitation. It corresponds to a shorted parallel plate with line #PP2. The measurements were performed in the range 50 MHz - 20 GHz. Solid lines correspond to a FFT filter of the response taken from the measurements, which are the asterisks.

The proposed procedure assumes that the variation of the dielectric permittivity with frequency is slow, and it is also limited by the fact that it does not differentiate between conductor and dielectric losses. However, besides its simplicity it features the following advantages:

a) It is not necessary to have a good preliminary estimation of the dielectric permittivity, since it provides no multiple solutions even when only one sample is used. Figure 1 clearly illustrates this fact.

b) It does not need an accurate knowledge of the transmission line termination.

c) It does need an accurate de-embedding of the transition between the connector and the transmission line.

The last two of these advantages were also observed by means of electromagnetic simulation. The reflection coefficients were calculated with a 3D simulator. Simulations of the transmission line with and without the connector were made and the resulting reflection coefficients were used to extract the values of the effective dielectric permittivity.

Despite the noticeable influence of the connector in the reflection coefficients, the resulting permittivities agreed with very low discrepancies. The final values are shown in Table II. Two different terminations were used in the simulation: an ideal electric wall (simulations 1 and 2) and a lossy gold wall (3 and 4). The transition simulated in 2 and 3 was considered by adding to the input of the line a short coaxial SMA-type connector, with ideal metallization and

Table II. Influence of the termination and coaxial to parallel plate transition

	Ideal short?	**Simulate transition?**	**Effective Permittivity**
Simulation 1	YES	NO	3.86
Simulation 2	YES	YES	4.17
Simulation 3	NO	YES	4.07
Simulation 4	NO	NO	3.92

filled with teflon. In these simulations, a de-embedding from the reference plane at input of the connector to the input of the line was made. However, the coaxial to parallel plate transition was not extracted from the resulting reflection coefficient. This needs a previous knowledge of the substrate dielectric permittivity.

CONCLUSIONS

We have discussed in this work the potential capabilities of Frequency Domain Reflectometry in the measurement of effective permittivities of planar transmission lines. The proposed procedure offers accurate estimations of the permittivities in the microwave range, and does not need for the fabrication of any specific structure. The samples used in this work were mostly pieces of substrates with double side metallization (parallel transmission lines). From these samples and an electromagnetic simulation it is possible to obtain the dielectric permittivity of the substrate with a good accuracy.

The method has also been applied to a 50 Ohm microstrip line, and the resulting values are in good agreement with those obtained for the other lines. This fact shows that the procedure can be applied to obtain reasonably good results in quasi-TEM lines, without the need for further refinements.

This paper has also illustrated with different measurements and 3D electromagnetic simulation that the method offers a good degree of robustness, since the influence of parasitics such as the coaxial to parallel plate transition or the termination losses is very weak.

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