PRECISE DIELECTRIC PROPERTIES DETERMINATION OF LAMINAR-SHAPED MATERIALS IN A PARTIALLY-FILLED WAVEGUIDE

J. M. Catalá-Civera, F. Peñaranda-Foix, D. Sánchez-Hernández and E. de los Reyes
Departamento de Comunicaciones, Universidad Politécnica de Valencia,
Camino de Vera S/N E-46071 Valencia, Spain.

Abstract. An enhanced technique for complex dielectric properties characterization of laminar-shaped materials is presented. The technique is based upon scattering measurements of a partially-filled rectangular waveguide. The influence of the different parameters regarding the achievable accuracy have also been analyzed in order to determine the optimum sample configuration. Measurements of some commercial dielectric substrates used for printed antenna design were performed and have been used for validation purposes.

I. INTRODUCTION

The precise permittivity determination of dielectric films has now become a very important task for ever-increasing microwave and mm-wave applications, and particularly with the extension of printed antennas into the new mm-wave and sub-THz applications. The electrical performance of a printed circuit board or a multichip module, for example, can be significantly affected by the dielectric properties of the substrate material [1]. Likewise, for the textile, leather and paper industries the precise knowledge of dielectric properties, along with other parameters such as moisture content, are essential for quality control and drying processes. Several techniques for accomplishing these measurements have previously been described in the literature [2]. In most techniques, the dielectric substrate is placed in a resonant cavity and the dielectric properties are calculated from measurements of the resonant frequency and Q-factor making use of the perturbational theory. Although perturbational techniques usually give accurate results, they are constrained by typically sample size and losses, and provide valid results only at a single frequency. Alternatively, in an extended technique based on transmission lines [3], the sample has to completely fill the inner dimensions of the waveguide. This technique introduces the problem of possible air gaps between the dielectric sample and the conducting boundaries, thus becoming extremely difficult to be implemented for certain cases. Moreover, the validity bandwidth of the response can be shortened by high order modes excitation. Although all these methods have shown their effectiveness, carrying out an analysis of the accuracy reached in the measurements is a very complicated task due to their own configuration restrictions.

Hence, in this paper, we describe an enhanced technique to obtain the dielectric properties of dielectric laminar materials from a partially-filled waveguide analysis and S-parameters measurements. The paper presents a method for inferring the complex permittivity by comparing the propagation constant extracted from experimental S-parameters, measured with an Automatic Network Analyzer (ANA), with a numerically generated propagation constant in a partially-filled waveguide. Using this technique, a precise fullwave characterization is possible, thus avoiding the main limitations of previous methods. The accuracy of the dielectric characterization has been deeply analyzed taking into account all the parameters involved, and simulated results of the optimum setup measurement are presented. Additionally, in order to validate this technique, some measurements of commercial dielectric substrates commonly used for printed antenna design have been carried out and the results are compared to values provided by the manufacturer.

II. PARTIALLY-FILLED RECTANGULAR WAVEGUIDES

Partially-filled rectangular waveguides contain a dielectric material with the interface perpendicular to the x axis, as illustrated in Fig. 1. In these waveguides, standard modes TE^z or TM^z cannot satisfy the boundary conditions of the structure, therefore some other mode configurations may exist within such a structure. These modes are referred as hybrid modes or *longitudinal section electric* (LSE^x) or *longitudinal section magnetic* (LSM^x) modes and they can be obtained as combinations of the standard modes [4]. The analysis of this electromagnetic problem was solved with the aid of auxiliary vector potentials. In (1) we have the characteristic equations of these modes,

$$\begin{array}{ll} \textit{LSE modes} & \textit{LSM modes} \\ h\cdot\cot(hd) = l\cdot tan(lc/2) & l\cdot\cot(hd) = (\varepsilon_{r2}/\varepsilon_{r1})h\cdot tan(lc/2) \\ l\cdot tan(hd) = -h\cdot tan(lc/2) & l\cdot\cot(hd) = -(\varepsilon_{r2}/\varepsilon_{r1})h\cdot\cot(lc/2) \end{array} \qquad (1)$$

where the values h and l represent the wave number and ε_{r2} and ε_{r1} the complex permittivity of each zone, respectively. The complex propagation constant in the waveguide is given by,

$$\gamma^2 = l^2 + (m\pi/b)^2 - \varepsilon_{r2}k_0^2 = h^2 + (m\pi/b)^2 - \varepsilon_{r1}k_0^2 \qquad (2)$$

Equations (1) and (2) are multi-valued transcendent equations of complex variable. Each solution of h and l gives the different mode configuration in the waveguide. The dominant mode is LSE_{10} (m=0) and for small c/a values the wideband margin is much larger than in completely-filled waveguides. The complex propagation constant can be extracted from the S-parameters of a segment of partially-filled waveguide of length L, using the same formulation employed for completely-filled waveguides [3]. Thus, assuming only one mode propagation, two parameters Γ y T are defined as,

$$\Gamma = (Z_1 - Z_o)/(Z_1 + Z_o) \qquad T = e^{-\gamma \cdot L} \qquad (3)$$

where Z_0 is the reference impedance and Z_1 and γ are the impedance and propagation constant of the partially-filled waveguide as shown in figure 1. The propagation constant is extracted from T in eqn. (3) with equations (4) and (5).

$$\Gamma = K \pm \sqrt{K^2 - 1} \qquad (4)$$

$$T = \frac{(S_{11}(\omega) + S_{21}(\omega)) - \Gamma}{1 - (S_{11}(\omega) + S_{21}(\omega))\cdot\Gamma} \qquad (5)$$

with $K = (S_{11}^2(\omega) - S_{21}^2(\omega) + 1)/(2\cdot S_{11}(\omega))$ and $S_{11}(\omega)$ and $S_{21}(\omega)$ representing S-parameters versus frequency. If the sample length L is greater than the wavelength, an ambiguity in phase can occur when determining γ from (3) and (5). This is due to phase uncertainty of the logarithm of a complex number. Yet, this ambiguity can be cleared out by performing a group delay analysis [3] or by taking measurements at different frequencies.

III. EXPERIMENTAL PROCEDURE AND ACCURACY

The measurement procedure consists of placing a rectangular fragment of unclad substrate inside the waveguide along the broad wall, as depicted in Fig. 1, and then measuring the S-parameters matrix of the structure with an ANA. To introduce the substrate in the waveguide, a longitudinal non-radiating slot has been drilled in the upper and lower sides of the waveguide. In general, the slot can be placed in any position along the waveguide, being the centered slot the most sensible one due to the dominant mode configuration. The complex propagation constant is determined with the procedure described in eqns. (3), (4) and (5). A new function is defined as the difference between the γ obtained from S-measurements and the numerically generated value from (1) and (2). Since eqn. (1) presents multiple roots and we want to ensure a rapid convergence to the final solution, this function was solved numerically using an initial seed obtained from the values provided by the perturbational method described in [2]. Finally, the dielectric properties obtained with this technique are used to check equation (1) and to examine whether the obtained values can excite high order modes since the assumption of only one mode propagation has been considered. The accuracy of the method depends upon several factors, such as material homogeneity, unascertained sample and waveguide configuration dimensions, waveguide losses, high order modes excitation and the instrumentation uncertainty used to perform the S-parameter measurements. The waveguide losses and sample holder length can be measured with the ANA and subtracted from the dielectric sample measurements. The existence of high order modes has been previously checked out and avoided, leaving the core of the error to the precision of the measurement equipment and to the unascertained sample dimensions. This measurement has been calculated using the partial derivative technique of eqns. (1), (2) and (5), and the solved equation is reproduced below,

$$\Delta\varepsilon_r = \sqrt{\left(\frac{\partial\varepsilon_r}{\partial|S_{11}|}\Delta|S_{11}|\right)^2 + \left(\frac{\partial\varepsilon_r}{\partial\vartheta_{11}}\Delta\vartheta_{11}\right)^2 + \left(\frac{\partial\varepsilon_r}{\partial|S_{21}|}\Delta|S_{21}|\right)^2 + \left(\frac{\partial\varepsilon_r}{\partial\vartheta_{21}}\Delta\theta_{21}\right)^2 + \left(\frac{\partial\varepsilon_r}{\partial L}\Delta L\right)^2} \qquad (6)$$

The measurement error illustrated in Fig. 2 has made use of eqn. (6), the effect of the precision of the HP-8720B automatic network analyzer with a full two port calibration procedure ($\Delta|S_{11}| = \Delta|S_{21}| = \pm 0{,}005$ and $\Delta|\theta_{11}| = \Delta|\theta_{21}| = \pm 1^\circ$), and several unascertained sample dimensions. From Fig 2, it is clearly observed that the error decreases with sample length, and it is strongly dependent on the sample dimensions unascertainty. From this figures we can conclude that this last parameter becomes fundamental to reach a great accuracy in the permittivity determination method.

IV. RESULTS

With the approach described above, 1,5 mm thick dielectric circuit substrates have been measured in a WR-340 waveguide, and results of complex permittivity and accuracy values are depicted in figures 3 and 4, respectively. The optimum sample length was chosen from preliminary measurements. The dielectric values depicted in Fig. 3 present an excellent agreement with the permittivity values provided by the manufacturer (3,05-j0,001 at 2,5 GHz [5]). The accuracy reached in the dielectric determination of the substrate, illustrated in Fig. 4, is lower than 6 % for an unascertained sample length of 0,5 mm.

V. CONCLUSIONS.

An enhanced rectangular partially-filled waveguide technique has been developed for accurate measurements of the complex permittivity laminar substrates commonly used for printed antenna design. In spite of the method being used to measure the dielectric properties of circuit substrates, it is versatile enough to measure other laminar materials, such as leather, paper, wood or textile products, which are also important for advanced indoor propagation prediction techniques. Likewise, the method can also be easily translated to higher frequency ranges. Additionally, the accuracy of the dielectric determination was studied in depth to further optimize the sample dimensions used in the measurements.

VI. ACKNOWLEDGEMENTS

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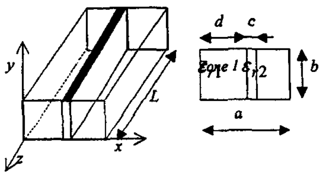

Fig. 1. Partially-filled waveguide configuration

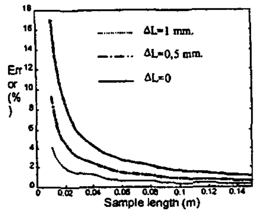

Fig. 2. Simulated error vs sample length at GHz for several unascertained sample dimensic

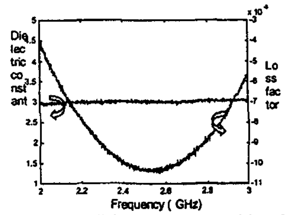

Fig. 3. Measured dielectric constant and loss factor vs frequency for 1,5 mm thick GML 1000 substrate.

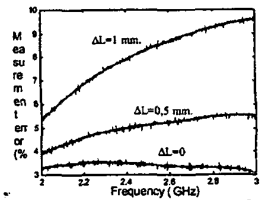

Fig. 4. Measurement error vs frequency for sev unascertained sample dimensions.

REFERENCES

[1] G-T. Voelker, G-W. Pan Lei and B. K. Gilbert, "Determination of complex permittivity of low-loss dielectrics", *IEEE Transactions on Microwave Theory and Tech.*, vol. 45, no. 10, pp. 1955-1960, 1997.

[2] R. Thomas and D. C. Dube, "Extended technique for complex permittivity measurements of dielectric films in the microwave region", *Electronics Letters*, Vol. 33, no. 3, pp. 218-220, January 1997.

[3] W. B. Weir, "Automatic Measurement of Complex Dielectric Constant and Permeability at Microwave Frequencies", *Proceedings of the IEEE*, Vol 62, N°1, pp. 33-36, January 1974.

[4] C.A. Balanis, "Advanced Engineering Electromagnetics", *John Wiley & Sons*, pp. 394-410, 1989.

[5] 1998 GIL Technologies Product Catalog.