tremely sharp peaks at the lateral spectral frequencies that coincide with the real parts of the surface-wave poles. Therefore a more sophisticated method should be utilized for accurate integration, such as a 20-point Gaussian quadrature. Besides, the original finite integration limits effectively may be replaced by $k_x/k_0 = -20.0$ and $+20.0$ without causing noticeable errors since a significant variation concentrates between the two points. Similarly, remarkable peaks exist in the low spectral range for the off-diagonal spectral matrix elements, and a major amplitude variation resides between $k_x/k_0 = -40.0$ and $+40.0$, which are recommended to replace the original infinite limits as well.

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A SIMPLE FREE-SPACE METHOD FOR MEASURING THE COMPLEX PERMITTIVITY OF SINGLE AND COMPOUND DIELECTRIC MATERIALS

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Received 27 January 2000

ABSTRACT: *A simple and efficient method for determining the complex permittivity of dielectric materials from both reflected and transmitted signals is presented. It is also novel because the technique is implemented using two pyramidal horns without any focusing mechanisms. The dielectric constant of a noninteractive and distributive (NID) mixture of dielectrics is also determined.* © 2000 John Wiley & Sons, Inc. Microwave Opt Technol Lett 26: 117–119, 2000.

Contract grant sponsor: IRCTR, Delft University, The Netherlands
Contract grant number: Project Agreement TU Delft IS 980077

Key words: *free-space method; complex permittivity; compound materials*

INTRODUCTION

Many papers have been published on the free-space measurement of the permittivity and permeability of materials [1–3]. Although the basic principles involved and parameters measured are the same, each method has its own novelty, uniqueness, and limitations. Free-space measurement of the dielectric constant of concrete [1] gives only the real part of the complex permittivity at very low frequency. The permittivity and permeability measurement with a focused beam for normal and oblique incidence [2] uses an ellipsoidal reflector. An elaborate free-space method using highly focused electromagnetic waves with spot-focused antennas [3] measures the complex permittivity and permeability. In this method, ε and μ are chosen from the multivalued solutions by properly selecting the sample thickness. The authors propose a simple free-space measurement technique for determining the complex permittivity of sample materials over a wide range of frequencies.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

The experimental setup consists of a vector network analyzer (VNA), an S-parameter test set, a sweep oscillator, an interfacing computer, and a microwave test bench. The test bench is made up of low-loss polystyrene materials in order to minimize unwanted reflection. The schematic diagram of the experimental setup is shown in Figure 1. Two identical antennas are mounted on the test bench, and the sample material in the form of a flat sheet is kept positioned at the reference plane. The measurements are carried out in the J- and X-bands. For J-band measurement, pyramidal horns of a half-power beam width (HPBW) of 22.5° (E-plane) and 21.5° (H-plane) and aperture dimensions 14 cm × 10.5 cm are used. For X-band, the antennas have an HPBW of 18° (E-plane) and 15.5° (H-plane) and aperture dimensions of 9.8 cm × 7.5 cm. To minimize unwanted reflection from the surroundings, the test bench is situated in the anechoic chamber.

To begin, the system is calibrated using the thru-reflect-line (TRL) technique. For J- and X-band measurements, calibration standards in the TRL option should be modified separately. To increase the accuracy of measurement, a gating option is also applied. In order to minimize the edge diffraction, the sample size should be more than 5λ. S_{11} and S_{21} are measured after fixing the sample sheet at the reference plane. The effective dielectric constant of a noninteractive distributive (NID) mixture of dielectrics also can be found from the S-parameter measurements. Sample sheets are kept together at the sample holder for the measurement. This method can be extended to any number of samples of known thickness and surface area.

THEORETICAL ANALYSIS

Consider a dielectric slab of thickness d placed in free space. Using the ray-tracing model, the total input reflection coefficient can be written in a geometric series that takes the

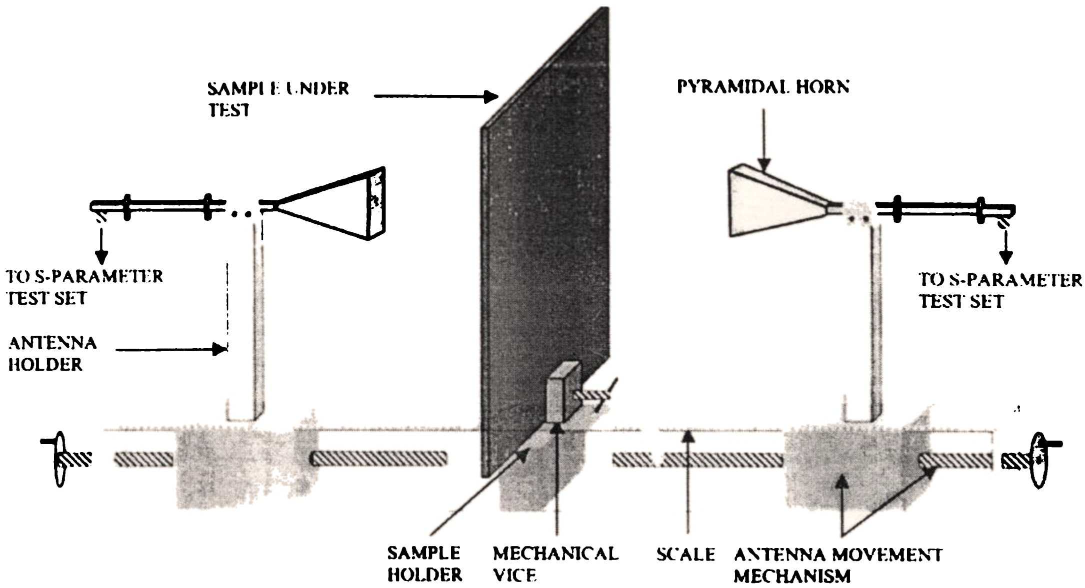

Figure 1 Schematic diagram of microwave test bench with the sample

form [4]

$$\Gamma_{in} = \Gamma_{12} + \frac{T_{12}T_{21}\Gamma_{21}e^{-2j\beta d}}{1 - \Gamma_{21}^2 e^{-2j\beta d}}. \quad (1)$$

Γ_{12} is the intrinsic reflection coefficient of the initial reflection, and $(T_{12}T_{21}\Gamma_{21}e^{-2j\beta d})$ is the contribution due to the first bounce within the slab. $\beta d = (2\pi d/\lambda) = (2\pi d\sqrt{\mu_r \varepsilon_r}/\lambda_0)$, where λ is the wavelength in the medium, λ_0 is the free-space wavelength, and μ_r and ε_r are the complex relative permeability and permittivity of the medium, respectively. We also know that $\Gamma_{21} = -\Gamma_{12}$, $T_{12} = 1 + \Gamma_{12}$, and $T_{21} = 1 + \Gamma_{21} = 1 - \Gamma_{12}$. The indexes 1 and 2 represent the air and the medium, respectively. Rearranging Eq. (1),

$$\Gamma_{in} = S_{11} = \frac{[1 - e^{-2j(\omega d/c)x}]}{[1 - \Gamma_{12}^2 e^{-2j(\omega d/c)x}]}\Gamma_{12}. \quad (2)$$

Usually for a dielectric medium, μ_r is taken as unity, and $\sqrt{\mu_r \varepsilon_r}$ is reduced to $\sqrt{\varepsilon_r} = \sqrt{\varepsilon_r' - j\varepsilon_r''} = x$.

Similarly, the total transmission coefficient T_{12} is evaluated as

$$T_{12} = S_{21} = \frac{[(1 - \Gamma_{12}^2)e^{-j(\omega d/c)x}]}{[1 - \Gamma_{12}^2 e^{-2j(\omega d/c)x}]}. \quad (3)$$

The reflection coefficient Γ_{12} at the air–medium interface is related to the impedances Z_0 and Z_1 of the air and dielectric slab, respectively, as $\Gamma_{12} = (Z_1 - Z_0)/(Z_1 + Z_0)$. But $Z_0 = 120\pi$ and $Z_1 = (Z_0/x)$. Solving S_{11} and S_{21} independently, x can be found, and hence, the complex dielectric constant ε_r. The exponentials in Eqs. (2) and (3) should be expanded to a sufficient number of terms for the convergence of the required solution.

The effective dielectric constant of a compound of different noninteracting and distributive materials [5] is given by the expression

$$\varepsilon_{r\,\mathrm{eff}} = \frac{\sum_{i=1}^{n} \varepsilon_{ri} t_i}{\sum_{i=1}^{n} t_i} \quad (4)$$

where ε_{ri} and t_i are the dielectric constant and the thickness of samples of the same cross-sectional area, respectively. Equation (4) can be used to verify the results obtained by the present method for the NID mixtures.

EXPERIMENTAL RESULTS

The complex permittivity and loss tangent of the different dielectric materials are determined from the measured values of S_{11} and S_{21}. It is observed that the complex permittivity calculated from S_{11} is identical to that from S_{21}. The results are in good agreement with the standard values [3]. Tables 1

TABLE 1 Complex Permittivity of Different Samples from the Reflection Measurement

Frequency (GHz)	Glass		Polystyrene		Glass Epoxy		NID Mixture (Polystyrene–Glass) Free Space		NID Mixture (Polystyrene–Glass) Theory [5]	
	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ
5.4	4.85	0.147	2.65	0.064	3.49	0.272	3.9	0.174	3.84	0.122
5.8	4.56	0.144	2.55	0.050	3.44	0.238	3.52	0.210	3.63	0.113
6.2	4.41	0.156	2.47	0.040	3.36	0.208	3.54	0.104	3.52	0.118
6.6	4.32	0.178	2.40	0.033	3.26	0.193	3.26	0.082	3.43	0.133

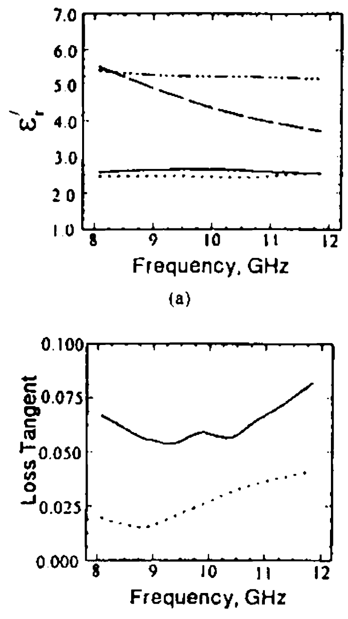

Figure 2 (a) Variation of ε_r' with frequency. —— polystyrene (from S_{11} measurement), ······ polystyrene (from S_{21} measurement), ----- glass (from S_{11} measurement), –·–·–·– glass (from S_{21} measurement). (b) Variation of loss tangent with frequency. —— average of values measured from S_{11} and S_{21} for polystyrene, ······ average of values measured from S_{11} and S_{21} for glass

and 2 show the complex permittivity of polystyrene (thickness = 4 mm), glass (thickness = 4.76 mm), glass epoxy (thickness = 1.56 mm), and NID mixtures of polystyrene–glass (thickness = 8.76 mm) and polystyrene–glass epoxy (thickness = 5.56 mm). Figure 2(a) shows the variation of ε_r' versus frequency, and Figure 2(b) shows the variation of average loss tangent versus frequency for glass and polystyrene in the X-band. From Tables 1 and 2, it can be seen that the effective dielectric constant obtained for NID mixtures by the present method is identical to that obtained from [5]. Thus, the determination of the effective dielectric constant is a clear support to the theory of NID mixture.

CONCLUSIONS

A novel free-space method of measuring the complex permittivity using two ordinary pyramidal horn antennas of sufficient flaring is presented. Measurement of reflection and transmission coefficients can be simultaneously done, and the complex permittivity is computed from both of the data. The absence of a focusing mechanism does not adversely affect the accuracy of S_{11} and S_{21}. It is observed that the sum of the reflected and transmitted power from a perfect dielectric polystyrene sheet is nearly equal to unity, and the energy loss due to nonfocusing is less than 1.2%. The complex permittivity measurement of compound materials has wide applications in industry. If the NID mixture is made up of layers of different constituents and the thickness of each layer and the effective dielectric constant are known, the unknown dielectric constant of a particular constituent can be determined.

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A FINITE-ELEMENT 3-D METHOD FOR THE DESIGN OF TWT COLLECTORS

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Received 9 February 2000

ABSTRACT: *This letter discusses the basic philosophy of a fully three-dimensional finite-element method for collector design together with its main features. In particular, attention is focused on the dedicated mesh generator and the strategy followed for the solution of the coupled electromagnetic and motional problem within the same finite-element discretization context. An example of simulation is carried out, and indications of future applications are also provided.* © 2000 John Wiley & Sons, Inc. Microwave Opt Technol Lett 26: 119–122, 2000.

Key words: *traveling-wave tubes; collector; efficiency*

TABLE 2 Complex Permittivity of Different Samples from the Transmission Measurement

Frequency (GHz)	Glass		Polystyrene		Glass Epoxy		NID Mixture (Polystyrene–Glass Epoxy) Free Space		NID Mixture (Polystyrene–Glass Epoxy) Theory [5]	
	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ	ε_r'	tan δ
5.4	5.26	0.296	2.64	0.081	3.77	0.082	2.94	0.024	2.96	0.080
5.8	5.24	0.288	2.76	0.047	3.70	0.078	2.90	0.021	3.03	0.056
6.2	5.15	0.295	2.83	0.017	3.65	0.074	2.88	0.017	3.06	0.036
6.6	5.01	0.297	2.85	0.015	3.61	0.078	2.85	0.014	3.06	0.036