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Electrical Material Property Measurements Using a Free-Field, Ultra-Wideband System*

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Abstract: We present nondestructive measurements of material properties using TEM horn antennas and an ultra-wideband measurement system. Time-domain gating and genetic algorithms are used to process the data and extract the dielectric properties of the material under test.

Introduction

This paper describes dielectric property measurements made on standard reference materials using a free-field ultra-wideband system. Transmission and reflection are measured in the frequency domain on bulk materials. These measurements are made using a free-field technique developed by the National Institute of Standards and Technology's (NIST) Time Domain Fields project. This technique allows us to isolate the front-surface/back-surface effects using a sequence of time-frequency transformations and gating. The dielectric properties of materials are then determined through a comparison with a plane-wave model using a genetic optimization algorithm.

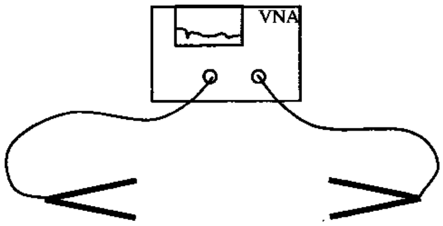
There are a number of free-field techniques used to measure the properties of bulk materials [1]. There is an ongoing need to know electrical properties of materials as they are manufactured. These measurements are typically performed in a cavity or transmission line, so they must be machined to proper dimensions [2, 3]. Free-field measurements can be performed either in-situ or in our measurement facility and so can be performed nondestructively.

This paper is divided into three sections. The first outlines the instrumentation and measurement setup, the second discusses the signal processing and a basic genetic algorithm program used for material parameter extraction. And the third concludes with preliminary experimental results.

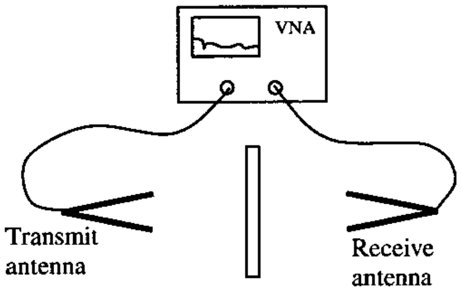
Measurement Setup

Instrumentation

Our measurement system, shown in Figure 1, uses a Vector Network Analyzer (VNA) to acquire the S-parameters of the material under test (MUT). This is a stepped-frequency measurement over the frequency range from 300 kHz to 4000 MHz. The system employs two TEM horn antennas to illuminate a rectangular slab of material and obtain reflection and transmission data. These types of antennas are phase-linear and ultra-wideband, with a short-impulse response suitable for this type of measurement [4-7]. The antennas used to cover this particular frequency band are 36 cm in length and have a relatively flat



Reference Measurement



Sample Measurement

Figure 1. Equipment setup for reference and sample measurements.

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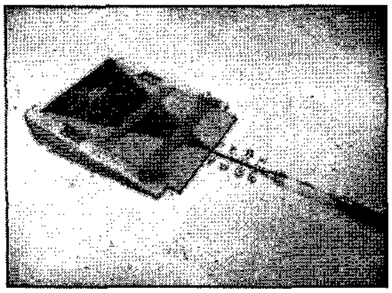

Figure 2. TEM half-horn on a ground plane.

frequency response from 100 MHz to 4000 MHz. One is shown in Figure 2. The 36 cm antenna has an impedance of 100 ohms and requires a balun for impedance transformation to 50 ohms.

The short-impulse response of these antennas allows us to discriminate between different events in the time domain so that signal-processing techniques such as gating are easier to apply to remove unwanted signals. Because the antennas are phase-linear, the original impulse is minimally distorted by the antenna. Most other antennas have either a non-linear phase response or an extended impulse response making detection and gating of specific signals more difficult.

Experimental design

We looked at two different measurement schemes: 1) the TEM full-horn free-field configuration and, 2) the TEM half-horn on a ground plane. The free-field method requires the materials to be suspended between two full TEM horn antennas as shown in Figure 3. The height and distance between the antennas is optimized so that ground bounce can be minimized or time-gated out of the spectrum. There are two main problems with this experimental design. The first is the balun which adds loss to the measurement and can result in common mode propagation along the coaxial feed. The other problem is that the sample must be suspended, which is somewhat difficult for a 1.89m x 1.89 m sample.

In the second method, the half-horn TEM antennas are placed on the ground plane, as shown in Figure 4, and the sample is oriented between them. The balun is eliminated, but the sample and coaxial feed must be in intimate electrical contact with the ground plane. The coaxial feed contact minimizes inductive reflections, and because this is an image measurement, the air gap between the sample and the ground plane must be made as small as possible. We prefer the second method because the setup is mechanically more stable.

The first set of measurements was made on several well-characterized dielectric reference materials to verify results obtained using the genetic algorithm utilized by the University of Missouri-Rolla team. These samples were: 1) cross-linked polystyrene, 2) polycarbonate, and 3) polyethylene [8]. Three sample sizes for the various materials were also used: 1) 0.95 m x 0.95 m, 2) 1.42 m x 1.42 m, and 3) 1.89 m x 1.89 m. The variability in sample size allows us to look at edge diffraction effects. Several antenna separations were also exploited to study the effects of plane-wave approximations. These separations were 1) 0.5 m, 2) 1.0 m, 3) 1.5 m, and 4) 2.0 m. We can use the distance information to help separate the edge diffraction effects from the front-surface/back-surface response.

We begin by making a background or reference measurement. The background measurement is taken without the sample and all four S-parameters (S_{11}, S_{22}, S_{21}, S_{12}) are acquired (see Figure 1a). The S_{21} reference measurement enables us to normalize out the antenna effects in the sample reflection and transmission measurements. The S_{11} and S_{22} reference measurement allow subtraction of the internal

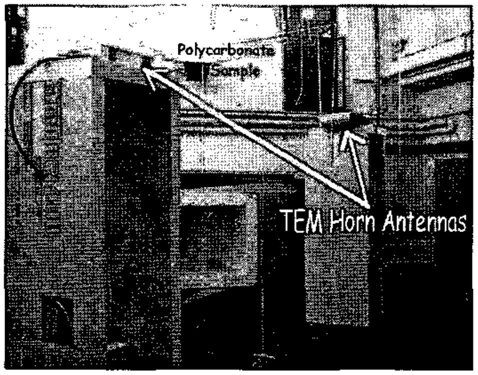

Figure 3. Free-field method in which sample suspended between antenna.

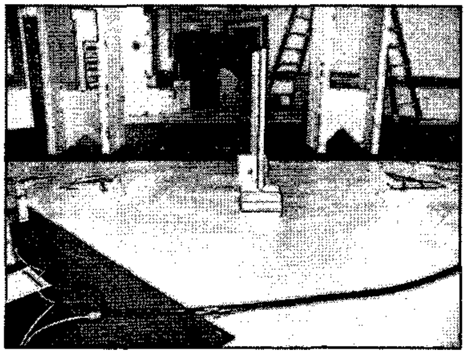

Figure 4. Half-horn on a ground plane. Sample located between two antenna.

reflections of the antennas. We compared the reference data from each method and found that the difference is directly related to the variability in antenna design.

Once the reference data are taken, we place the material sample between the antennas and take another measurement (see Figure 1b). Antenna alignment and distance is critical for this measurement.

Data processing and genetic algorithms

Time-domain gating

After measurements are made in the frequency domain the results are Fourier-transformed to the time domain so that signal processing can be performed. In the time domain, we can distinguish between events that are not directly related to the measurement of the sample, such as reflections from walls, ground bounce, and edge diffraction. We apply a time gate to isolate important events and apply mathematical filtering to maximize measurement fidelity. The gated data are transformed back into the frequency domain, where the spectrum now closely approximates a measurement of the material sample in free space.

After signal processing, we calculate either the transmission coefficient or the reflection coefficient, which will be used to extract the material parameters. As of this writing, we believe that the reflection coefficient is more accurate than the transmission coefficient for certain types of materials. The sample reflection coefficient R_{sample} is given by the following equation,

$$R_{sample} = \frac{S_{11(sample)} - S_{11(background)}}{S_{12(background)}} \qquad (1)$$

where $S_{11(sample)}$ is the measured sample response, and $S_{11(background)}$ is the measured response without the sample, so that the numerator is the sample response alone. This subtraction removes internal antenna reflections and isolates the sample backscatter. $S_{12(background)}$ is the transmission data that normalizes the measurement.

Genetic algorithms

Genetic algorithms (GA) are optimization algorithms used to solve many difficult problems [9]. Genetic algorithms search population spaces instead of the more common single-solution space, which can lead to local-minima errors. A very simple genetic algorithm uses genetic concepts to optimize the search. We begin by defining an objective function and then determine the fitness of the function using a set criterion. This fitness function tells us the likelihood that a particular solution will survive to the next generation. The fittest solutions are reproduced and crossed over with other solutions. Random mutations are also applied according to some predetermined probability, and the whole process is repeated until a convergence criterion is met.

In general, either the Debye or the Lorentzian equations are used to extract the dielectric parameters of a material. At present, we use the Debye equation given by

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau_p} - \frac{j\sigma}{\omega\varepsilon_0}, \qquad (2)$$

where ε_∞ is the high-frequency dielectric constant, ε_s is the low-frequency or static dielectric constant, ω_0 is the resonant frequency, τ_p is the pole relaxation time, and σ is the conductivity. We use the impedance equations to calculate a fitness index for each set of solutions. The objective function is the measured scattering parameter matrix [10, 11] and the convergence criterion is the difference between the measured and calculated reflection coefficients.

Results

We measured a 1.89 m x 1.89 m sheet of cross-linked polystyrene and shipped the gated reflection coefficient data to our university collaborators for analysis. The only information we gave them was the thickness of the sample, the experimental setup and the fact that it was a low-loss plastic. Using the GA software, the effective thickness and the real and imaginary parts of the dielectric constant could be extracted. Their fit to the reflection coefficient for the measured thickness is shown in Figure 5. The extracted Debye parameters (ε_∞, ε_s, τ_p, σ) and the relative error due to the variation of thickness, are given in Table 1.

Table 1. Results for cross-linked polystyrene using a GA.

Thickness (cm)	ε_s	ε_∞	τ (ns)	σ (S/m)
2.78	3.278	2.543	2.442	0.0252
2.85	3.195	2.508	2.85	0.0244
Difference (%)	1.4	2.5	16.7	3.2

Table 1 shows that the relaxation time τ is very sensitive to variations in sample thickness. The optimized thickness of the sample was 2.78 cm and the relative errors are calculated relative to this thickness.

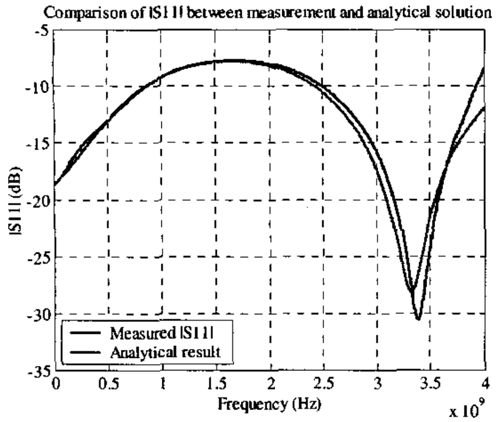

Figure 5. Comparison between measured and analytical results for a sample thickness of 2.85 cm.

We speculate that the difference between the measured and extracted parameters is related to the following sources of uncertainty:

1. Edge effects of the material sheet,
2. Nonplanar wave phase front,
3. Thickness nonuniformities,
4. Nonnormal incident wave,
5. Source not centered along midline.

Because the GA model tries to optimize the parameters by minimizing the mean error between the objective function and the evaluative function, a small frequency shift will increase the mean error considerably, so that the GA model will be more sensitive to the thickness of the sample.

Conclusion

We have shown how a time-domain system, a pair of short-impulse-response antennas and GA optimization can be used to measure and extract dielectric information on bulk reference samples in a controlled environment. After initial testing on a low-loss, low-permittivity sample, future tests will be performed on building materials such as a concrete wall, drywall, and plywood.

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