

An Accurate Method for Measuring the Dielectric Constant of Printed Wiring Board Materials

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An Accurate Method for Measuring the Dielectric Constant of Printed Wiring Board Materials

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Abstract

A new time-domain reflectometry measurement method is described that provides accurate measurements of the average high-frequency (0.1 GHz to 10 GHz) dielectric constant of printed wiring board materials and that is suitable for "factory floor" use. A parallel-plate transmission line is used for the sample geometry. Only simple numerical processes are required to extract the characteristic impedance and dielectric constant of the sample from the acquired data. The long-term measurement reproducibility and short-term measurement repeatability of the method are described.

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Introduction

A time-domain reflectometry (TDR) measurement method has been recently reported for measuring the average high-frequency (0.1 GHz to 10 GHz) relative dielectric constant (real part of the relative complex permittivity), &, of printed wiring board (PWB) materials.^{1,2} PWBs are used as substrates on which integrated circuits and discrete electronic devices are mounted and electrically connected. These electrical connections, or interconnects, may behave as transmission lines (TLs) in high-speed/high-frequency applications thus making the electromagnetic wave propagation properties of the interconnect important. The electrical properties of the PWB TLs are dependent on a variety of variables that include dielectric and conductor properties and the physical dimensions of the TLs. This work focuses on a measurement method for determining ε_r' and, in particular, on a method for obtaining the average highfrequency (0.1 GHz to 10 GHz) value of &' An average value is sought because a scalar is typically all that is used for PWB circuit design and &' is fairly constant for most PWB dielectrics over this frequency range.

Although a variety of frequency-domain (for examples, see Refs. 3 to 6) and time-domain (for examples, see Refs. 7 to 10) methods have been developed for determining ϵ'_{r} , this method addresses measurement requirements unique to the PWB industry, namely: that the measurement system be an inexpensive, easy to use, robust "factory floor" system, and allow for quick and easy sample preparation. The measurement method described here addresses the unique PWB requirements by affording simple sample fabrication (no chemical or photolithographic process) and fast data acquisition

and parameter extraction (under three minutes to acquire the sample and reference data), and because it is inexpensive and easy to use (TDR-capable oscilloscope), accurate (agreement with frequencydomain methods is better than 1%), and robust (insensitive to position of sample in sample holder). These attributes make the method suitable for both the laboratory and factory floor environments. This work also addresses anecdotal claims of an apparent discrepancy between the results obtained using timedomain and frequency-domain methods. For materials that are dielectrically anisotropic, such as most PWB materials, the dielectric sample must be aligned properly with respect to the applied electric field to measure the &' that is experienced by a wave propagating along a PWB TL. The sample geometries used here ensure the proper orientation.

Experimental

Measurement System

The measurement system uses an equivalent-time, nominally 50 Ω input impedance, TDR-capable, sampling oscilloscope and a computer controller to obtain the reflection coefficient data from which ε_r is extracted (to be discussed later). In the TDR mode, the oscilloscope delivers a rectangular voltage pulse to the sample and then records the pulse that is reflected from the sample. The reflected pulse is a consequence of the impedance discontinuity between the oscilloscope and the sample and, therefore, provides a measurement of the sample's impedance from which ε_r is extracted. The TDR signal that is observed is represented by the trace shown in Figure 1. The duration of the steps in Figure 1 corresponds to the round-trip propagation time of the TL. The amplitude of the steps reflects the impedance



Figure 1 - Idealized TDR Signal

discontinuities between the TL and the oscilloscope and between the TL and its termination. For this work, the termination is an open circuit and only the first reflected step is used.

Sample

The sample is a parallel-plate transmission line (PPTL) structure (see Figure 2). Sample preparation for the PPTL is extremely simple. A TL of length, L, having a uniform width, W, is removed (by a shear or router) from a sheet of laminate. Both sides of the laminate must be metal clad. The sample is prepared so that the long edges of the PPTL are as parallel as possible. Deviations from being parallel increase the measurement uncertainty. The edges are deburred to ensure that the electric field is uniform along the length of the samples. To facilitate handling, sample widths of approximately 1.25 cm were used. The lengths of the samples were long enough so that line lengths did not affect the measured signal.¹



Figure 2 - Schematic of PWB Sample.

The width of the sample is given by W, the length by L, the total thickness by t_r , the dielectric thickness by t_d , and the conductor thickness by t_m .

Sample Holder

The measurement results presented here were taken using three different sample holder designs, SH1, SH2, and SH3. SH2 and SH3 are shown in Figure 3; SH3 incorporates a ground contact with knife edges. SH1 is described in Ref. 1 and is a SMA-connectorized PWB receptacle with four solder tabs, one on each corner. Design improvements resulted in improved measurement reproducibility and repeatability.



Figure 3 - Schematic of PWB Sample Holder with Sample in Place.

The sample is tilted 2° from the perpendicular to exaggerate the effect of tilt on sample electrical contact.

Extraction of &

The ϵ' of the sample is extracted from the PPTL impedance, Z_T . The Z_T is obtained from the TL reflection coefficient, ρ ,

$$\rho = \frac{Z_T - Z_0}{Z_T + Z_0} \tag{1}$$

where Z_0 is the input impedance of the oscilloscope. Solving for Z_T gives:

$$Z_T = Z_0 \frac{l+\rho}{l-\rho} \tag{2}$$

The ε' is then obtained using¹:

$$\varepsilon_{\rm r} = \left(\frac{\left[120 \cosh^{-1} \left(\frac{t_{\rm T} - t_{\rm m}}{t_{\rm m}} \right) - Z_{\rm r} \right] \pi (t_{\rm T} - 2t_{\rm m})}{Z_{\rm T} \left[\pi (t_{\rm T} - 2t_{\rm m}) + W \cosh^{-1} \left(\frac{t_{\rm T} - t_{\rm m}}{t_{\rm m}} \right) \right]} \right)^2$$
(3)

where t_T is the total sample thickness and t_m is the metal thickness.

During measurements using a reference short circuit, it was noticed that the short-circuit reflection coefficient, ρ_{sc} , was not equal to -1 and that a reflection coefficient offset error, ρ_{off} , was present. Accordingly, reflection coefficients obtained were corrected for these two errors:¹

SAMPLE	reflection coefficient, ρ	total thickness, t _T (m)	metal thickness, t _m (m)	width, W (m)	ε΄r {target}
S7 (1 ply)	-5.174e-1 ± 1.42e-2	1.6586e-4	3.43e-5 ± 3.43e-6	8.1255e-4	5.412 {4.11 ^{‡2} }
S8 (2 ply)	-5.025e-1 ± 8.46e-3	2.0371e-4	3.43e-5 ± 3.43e-6	1.4790e-3	3.261 {4.11 ^{‡2} }
S9 (4 ply)	-5.626e-1 ± 5.79e-3	3.2182e-4	3.43e-5 ± 3.43e-6	3.2286e-3	3.753 {4.11 ^{‡2} }
S10 (8 ply)	-5.654e-1 ± 9.51e-3	5.9055e-4	$3.43e-5 \pm 3.43e-6$	6.8153e-3	3.825 {4.11 ^{‡2} }
S11 (16 ply)	-5.678e-1 ± 1.25e-2	1.0950e-3	3.43e-5 ± 3.43e-6	1.3515e-2	3.940 {4.11 ^{‡2} }
S12	-5.705e-1 ± 9.03e-3	1.5305e-3	$1.72e-5 \pm 1.72e-6$	1.9204e-2	4.348
S13	-5.676e-1 ± 5.01e-3	1.4831e-3	$1.72e-5 \pm 1.72e-6$	1.8964e-2	4.111
S14	-5.907e-1 ± 8.55e-3	1.5127e-3	6.86e-5 ± 6.86e-6	1.8868e-2	4.318 {4.384 [†] }
S15	-5.833e-1 ± 1.12e-2	1.3404e-3	3.43e-5 ± 3.43e-6	1.0641e-2	10.20 $\{10.2^{\ddagger1}\}$
S16	-5.595e-1 ± 1.12e-2	1.3802e-3	3.43e-5 ± 3.43e-6	1.3467e-2	6.040 $\{6.15^{\ddagger1}\}$
S17	-6.049e-1 ± 1.48e-2	7.9451e-4	3.43e-5 ± 3.43e-6	1.4130e-2	2.335 $\{2.2^{\ddagger1}\}$

Table 1 - Measured Physical Parameters, Observed Reflection Coefficient, and Extracted Er Using SH1

measured values obtained by NIST, Boulder, Co; measured at 16 GHz

^{‡1} Manufacturer specification, measured at 10 GHz

^{‡2} manufacturer specification, measured at 1 MHz

$$\rho = \frac{\rho_{\rm obs} - \rho_{\rm off}}{\rho_{\rm off} - \rho_{\rm sc}} \tag{4}$$

where ρ_{obs} is the observed sample reflection coefficient.

The ε_r found with this technique is the average over the frequency range of the measurement. The lower limit of this range is dependent on the duration of the displayed TDR signal. For example, an observation time of 10 ns corresponds to a lower limit of 1/10 ns or 100 MHz. The upper limit is based on the approximation f=.35/t_{fall}, where t_{fall} is the observed 90% to 10% transition caused by the impedance discontinuity between the PPTL and the TDR, and f is frequency. So, for a 10 ns window and t_{fall}≈35 ps, the bandwidth is 0.1 GHz to 10 GHz: this is what is assumed here.

Results

Comparison to Frequency Domain Measurements

Various PPTL samples were prepared and measured using SH1. The results are shown in Table 1. The values in curly brackets in the far right column are values obtained from frequency-domain measurement methods performed by either the manufacturer or the National Institute of Standards and Technology's (NIST's) Radio Frequency Technology Division in Boulder, CO. Measurement uncertainties will be discussed later. Samples S8 through S11 show a continuous increase in the extracted ϵ' with increasing number of plies. This increase may be due to an unexpected thickness dependence of the measurement process or to the construction of the PWB itself.¹ Consequently, it may be difficult to ascertain if the apparent ply-dependent ϵ' for S8 to S11 in Table 1 are real, or a measurement artifact.

Measurement Errors and Calculated Measurement Uncertainty

The calculated measurement uncertainties, u_T , for the samples of Table 1 are shown in the far right column of Table 2. Note: these uncertainties are the result of an uncertainty analysis¹ and do not represent measurement repeatability or reproducibility, which will be discussed later. The variables included in the uncertainty analysis were: ρ , ρ_{sc} , ρ_{off} , t_T , t_m , W, and Z_0 . The uncertainty contributions of these variables to u_T are displayed in Table 2. The measurement uncertainties presented in Table 2. The measurement uncertainties presented in Table 2 represent three standard deviations (3σ). The largest contributors to u_T are uncertainties in t_m and in ρ_{obs} . For the data presented in Table 2, the values used for Z_0 , ρ_{sc} , and ρ_{off} and their associated 3σ uncertainties

SAMPLE	from Pobs	from psc	from poff	from t _T	from t _m	from W	from Z ₀	u _T
S7 (1 ply)	4.50e-1	5.65e-2	2.04e-2	1.40e-1	1.38	2.75e-2	1.16e-1	1.47
S8 (2 ply)	1.57e-1	3.22e-2	1.23e-2	9.60e-3	6.64e-1	7.83e-2	6.93e-2	6.90e-1
S9 (4 ply)	1.23e-1	4.44e-2	1.34e-2	5.33e-2	4.96e-1	5.23e-3	7.82e-2	5.24e-1
S10 (8 ply)	2.23e-1	4.54e-2	1.35e-2	3.38e-2	3.31e-1	2.57e-3	7.90e-2	4.10e-1
S11 (16 ply)	3.01e-1	4.68e-2	1.38e-2	2.23e-2	2.47e-1	1.39e-3	8.10e-2	4.01e-1
S12	2.39e-1	5.19e-2	1.51e-2	2.44e-2	1.87e-1	1.06e-3	8.88e-2	3.22e-1
S13	1.25e-1	4.86e-2	1.43e-2	2.36e-2	1.78e-1	1.01e-3	8.40e-2	2.40e-1
S14	2.25e-1	5.33e-2	1.43e-2	1.52e-2	3.08e-1	1.01e-3	8.51e-2	3.93e-1
S15	7.14e-1	1.28e-1	3.53e-2	4.92e-2	5.79e-1	4.32e-3	2.09e-1	9.53e-1
S16	4.07e-1	6.98e-2	2.13e-2	2.89e-2	3.41e-1	2.05e-3	1.24e-1	5.51e-1
S17	2.26e-1	3.16e-2	7.80e-3	1.68e-2	1.71e-1	7.77e-4	4.79e-2	2.90e-1
average	2.91e-1	5.53e-2	1.65e-2	3.79e-2	4.44e-1	1.14e-2	9.66e-2	5.68e-1

Table 2 - Measurement Uncertainties Using SH1. All Uncertainties Represent Three Standard Deviations.

were: $Z_0 = 50 \ \Omega \pm 0.5 \ \Omega$, $\rho_{sc} = -0.994 \pm 3.36 \times 10^{-3}$, and $\rho_{off} = 2.2094 \times 10^{-2} \pm 1.37 \times 10^{-3}$. The 3σ uncertainties for W and t_T were 2.45e-6 m (0.0001 in) and for t_m was 10% of t_m .

The uncertainty in ρ_{obs} includes measurement noise and variations in the physical dimensions of the PPTL, that is, of W(x), t_T(x), and t_m(x), where x is position along the PPTL. Since samples S7 through S17 were prepared using a shear, any imperfections in the shear blade could have significant effects on W(x) and consequently on ρ_{obs} . This may explain the larger u_T for S7, which was very narrow (about 800 µm wide).

Errors in the measurement of pobs may be also caused by: 1) lack of repeatability of sample insertion, and 2) the position of the sample holder center pin with respect to sample center.¹ The repeatability issue was examined by taking ten consecutive data sets, where a set consisted of a reference (short circuit) and a sample measurement, and comparing the reference and sample data. The mean and 30 standard deviation of pobs for the reference and sample sets were -9.8987x10⁻¹ $\pm 3.273 \times 10^{-3}$ and $-5.87579 \times 10^{-1} \pm 2.30 \times 10^{-3}$, which shows that sample insertion contributes negligibly to measurement error. The effect of the position of the center pin on the measurement was also examined. This was done by performing five measurements on a 19 mm wide sample where the center pin was placed at different positions relative to the center of the sample Table 3 shows the for each measurement. measurement results: Dobs is relatively insensitive to center pin location.

The uncertainty in t_m was based on the Institute for Interconnecting and Packaging Electronic Circuits' (IPC) specification ANSI/IPC-MF-150F: the variation in conductor thickness is less than $\pm 5\%$ for

wrought copper foils and less than $\pm 10\%$ for electrodeposited copper foils, and the density of copper is 8.93 gr/cm³ $\pm 1\%$. Using the ANSI/IPC specification gives smaller uncertainties in t_m than that obtainable from simple thickness measurements. However, the effect of copper roughness must still be considered.¹

Table 3 - Mean and 30 Standard Deviation for Pobs

center pin position relative to sample center	reflection coefficient
5 mm to the left	-6.0111e-1 ± 6.15e-3
2.5 mm to the left	$-6.0100e-1 \pm 4.20e-3$
centered	$-6.0074e-1 \pm 3.83e-3$
2.5 mm to the right	-6.0077e-1 ± 4.37e-3
5 mm to the right	-6.0136e-1 ± 6.15e-3

The u_T are much greater than the variations in the extracted ε_r . To verify this, six additional samples were sheared from the same sheet from which S11 was obtained and then the average extracted ε' from these six samples calculated. The average extracted ε' was 3.953 and had a 3σ variation of 0.093. This 3σ variation is about four times less than the u_T (0.401) for S11.

Measurement Repeatability and Reproducibility

The long-term (over a period of one year) reproducibility and short-term (within one hour) repeatability of measurements performed on four different samples, S1 through S4, using sampler holder SH2 are presented. (Definitions of and conditions for repeatability and reproducibility of measurements can be found in Ref. 11 or references therein.) Each of the four samples has a different dielectric and physical dimensions and were prepared with a routing tool. Measurements using SH2 resulted in reduced measurement variation compared to measurements using SH1. The samples were placed in an airtight container with a desiccant after day 70.

Measurement sets for S1 through S4 were taken over a period exceeding 400 days. A measurement set for this work consisted of five pairs of acquired waveforms where each pair included a reference waveform and a sample waveform. For each waveform pair for a given sample, a relative dielectric constant value, $\varepsilon_{r'S,n,p}$ (where S refers to the sample number; n to the measurement day, $1 \le n \le N$; and p to the waveform pair, $1 \le p \le 5$) was obtained. Average values and standard deviations of the $\varepsilon_{r'S,n,p}$ ($\varepsilon_{r'S,n}$ and $\sigma_{S,n}$) were then calculated for each of the N measurement days for each sample to determine short-term measurement repeatability.

The results of these measurements, the $\varepsilon'_{S,n}$ and $\sigma_{S,n}$ values, are shown in Figure 4 and Table 4. (The "Day" column labeled "A" through "F" in Table 4 represents the measurement days when SH3 was used: the data for days "A" through "F" were taken within 60 days of day 416.) Table 5 shows the mean values, ε'_{s} , and standard deviations, σ_s , of the $\epsilon'_{s,n}$ values; and the mean values, $\mu_{\sigma,S}$, and standard deviations, $\sigma_{\sigma,S}$, of the $\sigma_{S,n}$ values. The values shown in the two rightmost columns in Table 5 were obtained using SH3; this will be discussed later. The short-term measurement repeatability (1 o) varies from about 0.3% to about 2.5% (see Table 4). The larger deviations are usually caused by one spurious waveform, spurious meaning that the waveform values deviate a few percent relative Although spurious data may be to the average. recognized easily and rejected by an experienced user, this may not be true for a factory floor operator. Consequently, the spurious waveforms were used in computing the average values, &',S,n, and uncertainties, $\sigma_{S,n}$, that are shown in Table 5. The spurious waveforms are probably caused by sample insertion repeatability.2

From Table 4 and Figure 4 we can also see that measurement variation over the test period is low, especially for sample S3. Sample S2 may have exhibited the largest σ_s because it was thin and would sway after being placed in the sample holder which would affect the electrical location of the sample within the sample holder.²

The $\mu_{\sigma,S}$ and $\sigma_{\sigma,S}$ are used as indicators of measurement repeatability: $\mu_{\sigma,S}$ indicates the average variability in measurement values and $\sigma_{\sigma,S}$ indicates the scatter or variation in measurement repeatability. For example, if $\sigma_{\sigma,S} >> \mu_{\sigma,S}$ (the scatter in measurement repeatability is greater than the average repeatability), then spurious waveforms probably existed and were used in the calculation of α' . Consequently, it may be possible to improve the measurement process by removing the cause of the spurious waveform. On the other hand, if $\sigma_{\sigma,s} \ll \mu_{\sigma,s}$, then measurement repeatability improvement is unlikely. However, for S1 through S4, $\sigma_{\sigma,s} \approx \mu_{\sigma,s}$, which implies measurement improvement is possible (to be discussed shortly). The long-term reproducibility can be obtained from σ_s in Table 5: 0.1% for S1, 0.7% for S2, 0.2% for S3, and 0.1% for S4. The large σ_s for S2 was probably caused by poor sample holder design, as will be discussed later. The σ_s also provide an indication of drift in the measurement process, and the σ_s values presented here indicate very low drift.



Figure 4 - Dielectric Constant Measurement Results

The upper panel shows the temperature variations during the course of the study and the bottom panel shows the measured dielectric constant for the four different samples as a function of elapsed time, in days.

To reduce the scatter in the measurement repeatability, the sample holder SH3 was designed. The knife edge contacts of SH3 were expected to reduce possible contact repeatability problems at the base plate and sample. The rows labeled A through F in Table 4 and the two rightmost columns of Table 5 show the results of the six measurement sets taken with SH3 for S2 and S4. We can see from Table 5 that SH3 reduced the scatter in measurement repeatability significantly for S2 and S4 and reduced σ_S of S2 to values similar to those for the other samples. However, the average variation in the measurement, indicated by $\mu_{\sigma,S}$, did not change when using SH3. Additional measurements indicated that $\mu_{\sigma,S}$ is limited by oscilloscope repeatability.²

Table 4 - Dielecti	ric Constant	Measurement	Results
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	Tuble I			T	
Day	S1 {6.0}	S2 {3.52}	S3 {3.0}	S4 {10.8}	Temperature (°C)
0	6.123 ± 0.084	3.807 ± 0.023	2.900 ± 0.014	10.860 ± 0.036	22.6
8	5.942 ± 0.104	3.552 ± 0.050	2.908 ± 0.028	10.710 ± 0.085	22.9
16	6.055 ± 0.118	3.485 ± 0.100	2.918 ± 0.015	10.832 ± 0.053	22.9
22	6.002 ± 0.023	3.722 ± 0.058	2.906 ± 0.028	10.884 ± 0.094	23.8
36	6.043 ± 0.037	3.414 ± 0.025	2.920 ± 0.017	10.886 ± 0.185	23.8
42	6.031 ± 0.092	3.667 ± 0.031	2.904 ± 0.008	10.901 ± 0.141	23.8
49	6.026 ± 0.018	3.411 ± 0.026	2.934 ± 0.022	10.764 ± 0.023	23.5
56	6.023 ± 0.019	3.380 ± 0.024	2.925 ± 0.020	10.830 ± 0.024	23.0
70	6.015 ± 0.018	3.420 ± 0.025	2.914 ± 0.007	10.829 ± 0.029	23.0
128	6.042 ± 0.018	3.363 ± 0.031	2.909 ± 0.004	10.822 ± 0.029	22.7
134	6.024 ± 0.015	3.342 ± 0.032	2.935 ± 0.031	10.910 ± 0.034	22.6
141	5.998 ± 0.026	3.344 ± 0.024	2.897 ± 0.007	10.844 ± 0.084	22.8
147	6.032 ± 0.033	3.330 ± 0.024	2.809 ± 0.008	10.846 ± 0.009	22.7
154	6.000 ± 0.027	3.356 ± 0.028	2.943 ± 0.004	10.852 ± 0.020	22.9
163	6.010 ± 0.024	3.402 ± 0.013	2.897 ± 0.019	10.807 ± 0.025	23.1
169	5.977 ± 0.008	3.326 ± 0.005	2.895 ± 0.001	10.686 ± 0.008	22.7
177	5.956 ± 0.023	3.373 ± 0.031	2.909 ± 0.008	10.819 ± 0.012	22.5
183	6.018 ± 0.013	3.303 ± 0.014	2.898 ± 0.005	10.760 ± 0.006	22.7
189	5.968 ± 0.013	3.348 ± 0.022	2.904 ± 0.010	10.767 ± 0.041	22.9
197	6.007 ± 0.021	3.300 ± 0.017	2.889 ± 0.004	10.771 ± 0.010	22.7
206	5.969 ± 0.003	3.360 ± 0.017	2.900 ± 0.011	10.755 ± 0.010	23.1
219	6.125 ± 0.012	3.586 ± 0.034	2.969 ± 0.009	10.795 ± 0.046	22.8
234	6.036 ± 0.008	3.549 ± 0.024	2.969 ± 0.003	10.825 ± 0.009	22.9
256	6.039 ± 0.007	3.600 ± 0.021	2.952 ± 0.003	10.833 ± 0.056	23.0
275	6.064 ± 0.015	3.629 ± 0.057	2.959 ± 0.011	10.776 ± 0.059	23.1
285	5.969 ± 0.018	3.573 ± 0.043	2.962 ± 0.013	10.894 ± 0.009	23.2
303	6.051 ± 0.011	3.607 ± 0.058	2.950 ± 0.003	10.847 ± 0.025	23.1
317	5.993 ± 0.025	3.377 ± 0.025	2.927 ± 0.010	10.759 ± 0.113	23.3
336	6.052 ± 0.018	3.482 ± 0.085	2.955 ± 0.018	10.736 ± 0.078	23.2
351	5.995 ± 0.031	3.524 ± 0.007	2.960 ± 0.009	10.854 ±0.059	23.0
371	6.054 ± 0.021	3.580 ± 0.033	2.968 ± 0.003	10.835 ± 0.021	23.1
387	6.104 ± 0.022	3.671 ± 0.071	3.002 ± 0.007	10.865 ± 0.017	23.4
399	5.999 ± 0.017	3.551 ± 0.031	2.969 ± 0.004	10.749 ± 0.018	23.2
416	6.082 ± 0.029	3.541 ± 0.018	3.001 ± 0.010	10.786 ± 0.125	23.4
A	0.000	3.485 ± 0.017		10.814 ± 0.026	22.6
B		3.489 ± 0.024		10.800 ± 0.020	22.7
C		3.508 ± 0.025		10.807 ± 0.020	22.8
D		3.466 ± 0.030		10.733 ± 0.010	22.8
F		3.502 ± 0.021		10.794 ± 0.024	22.7
F		3.505 ± 0.023		10.787 ± 0.024	22.8

 $\varepsilon'_{r,S,n}\sigma_{S,n}$, for four samples during approximately a 400 day period. The values in the rows with "Day" column entries labeled A through F were taken using the new sample holder. The values in curly brackets in the first row are the ε'_r obtained from frequency domain measurements.

Conclusions

A TDR based measurement method has been described for determining the real part of the permittivity of the dielectrics of printed wiring board materials. The measurement system is inexpensive and easy to use. Sample preparation is easy and measurements are insensitive to the position of the sample within the sample holder. The long-term reproducibility and short-term repeatability of the measurement system are better than 0.5%. The measurement results are within 2% of that reported by frequency-domain methods using the poorest performing sample holder (SH1) and within 1% for the best performing sample holder (SH3).

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	S1	S2	S3	S4	S2*	S4*
$\varepsilon_{r,S}^{*} = \frac{1}{N} \sum_{n=1}^{N} \varepsilon_{r,S,n}^{*} (5)$	6.024	3.482	2.928	10.81	3.491	10.79
$\sigma_{\rm S} = \sqrt{\frac{1}{\rm N}} \sqrt{\frac{1}{\rm N} \sum_{\rm n=1}^{\rm N} (\mathcal{E}'_{\rm r,S,n} - \mathcal{E}'_{\rm r,S})^2} $ (6)	0.006	0.023	0.006	0.009	0.007	0.012
$\mu_{\sigma,S} = \frac{1}{N} \sum_{n=1}^{N} \sigma_{S,n} (7)$	0.029	0.033	0.011	0.047	0.027	0.023
$\sigma_{\sigma,S} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (\sigma_{S,n} - \mu_{\sigma,S})^2} $ (8)	0.027	0.021	0.008	0.043	0.007	0.005

Table 5 - Statistics of the &',S,n and OS,n.

The two far right columns indicated by S2^{*} and S4^{*} are the results of six (N = 6) measurement sets taken with the new sample holder. The other columns correspond to data from thirty-four (N = 34) measurement sets that were taken with the old sample holder. The values shown in this table include the coverage factor k [2]: $k \approx 1.01$ for N = 34 and k = 1.09 for N = 6.

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