

# Long-Term Repeatability of a TDR-Based Printed Wiring Board Dielectric Constant Measurement System

N. G. Paulter

**Abstract**—A new time-domain-reflectometry-based method has been recently developed that provides accurate determinations of the dielectric constant of printed wiring board dielectrics over the frequency range of 0.1 GHz to 10 GHz. The long-term measurement reproducibility, as well as the short-term measurement repeatability, of that method were investigated and the results are reported here.

**Index Terms**—Dielectric constant, high-speed/high-frequency, measurement repeatability, printed wiring board, time-domain reflectometry.

## I. INTRODUCTION

A NEW time-domain-reflectometry (TDR) measurement method has been reported recently for measuring the high-frequency (0.1 GHz to 10 GHz) relative dielectric constant values,  $\epsilon_r$ , of printed wiring board (PWB) materials [1]. The advantages of this method over other methods are: simple sample fabrication (no chemical or photolithographic process), fast data acquisition and parameter extraction (under 3 min to acquire the sample and reference data), inexpensive and easy to use (TDR-capable oscilloscope), accurate (agreement with frequency-domain 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 paper reports the long-term (greater than one year) reproducibility and short-term (less than one hour) repeatability of measurements performed on four different samples, using the new TDR method. (Definitions of and conditions for repeatability and reproducibility of measurements can be found in [2] or references therein.) Each of the four samples (see Fig. 1) has a different dielectric and physical dimensions (see Table I). The samples were prepared by using a routing tool so that the conductor extends to the edge of the dielectric and completely covers the large parallel surfaces of the dielectric: this coverage is important because of the model used to extract the dielectric constants [1]. The sample holder used initially for this study was improved relative to that used to obtain the results reported in [1] and the results reported here show, correspondingly, smaller measurement variations.

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The author is with the Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (e-mail: nicholas.paulter@nist.gov).

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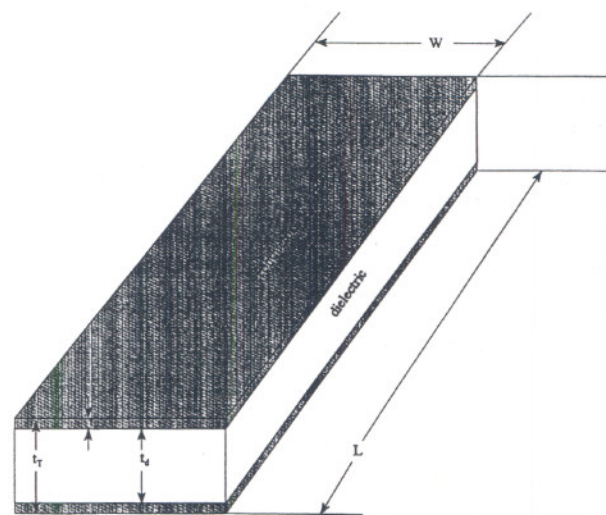


Fig. 1. Sketch of sample used to measure dielectric constant of printed wiring board dielectrics. The width of the sample is given by  $W$ , the length by  $L$ , the total thickness by  $t_T$ , the dielectric thickness by  $t_d$ , and the conductor thickness by  $t_m$ .

TABLE I  
SAMPLE CHARACTERISTICS. THE DIELECTRIC CONSTANT VALUES WERE OBTAINED FROM EITHER MANUFACTURER SPECIFICATIONS OR RESONANT-CAVITY METHODS PERFORMED BY THE ELECTROMAGNETIC FIELDS DIVISION, NIST, BOULDER, CO

	S1	S2	S3	S4
sample width (m)	$1.20 \times 10^{-2}$	$1.27 \times 10^{-2}$	$1.28 \times 10^{-2}$	$1.20 \times 10^{-2}$
sample thickness (m)	$7.00 \times 10^{-4}$	$2.86 \times 10^{-4}$	$8.38 \times 10^{-4}$	$1.25 \times 10^{-3}$
conductor thickness (m)	$3.43 \times 10^{-5}$	$3.43 \times 10^{-5}$	$3.43 \times 10^{-5}$	$1.71 \times 10^{-5}$
sample length (m)	0.255	0.277	0.306	0.255
dielectric constant	6.0	3.52	3.0	10.8

## II. EXPERIMENTAL

Measurement sets for each of the four samples were taken over a period exceeding 400 days. A measurement set consists of five pairs of acquired waveforms where each pair includes a reference waveform and a sample waveform. The reference waveform is obtained with the sample holder in place but without the sample. Both sample and reference acquired waveforms are the result of 512 waveforms internally averaged in the oscilloscope. For each waveform pair taken for a given sample, a relative dielectric constant value,  $\epsilon_{r,S,n,p}$  (where  $S$  refers to the sample number;  $n$  to the measurement day,



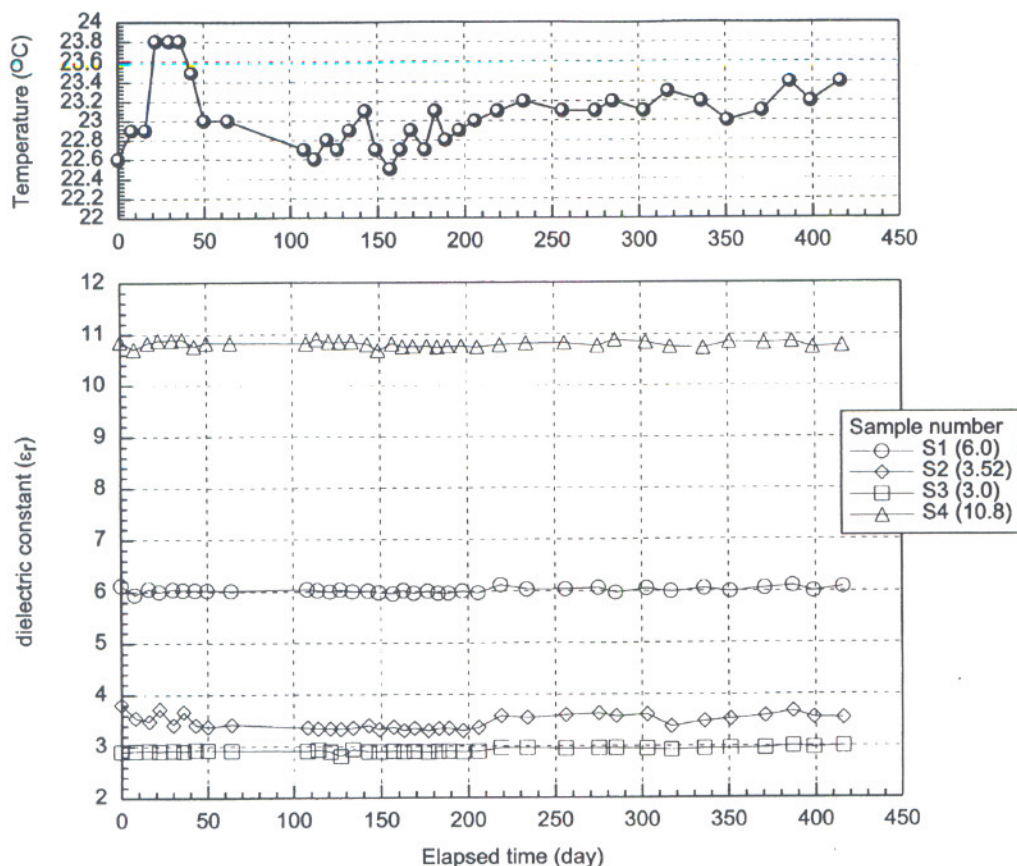


Fig. 2. Dielectric constant measurement results. The upper panel shows the temperature variations during the course of the study and the bottom panel shows the measured dielectric constant for the four different samples as a function of elapsed time, in days.

$1 \leq n \leq N$ ; and  $p$  to the waveform pair,  $1 \leq p \leq 5$ ) was obtained. Average values and standard deviations of the  $\epsilon_{r,S,n,p}$  ( $\epsilon_{r,S,n}$  and  $\sigma_{S,n}$ ) were then calculated for each of the  $N$  measurement days for each sample. The purpose for calculating  $\epsilon_{r,S,n}$  and  $\sigma_{S,n}$  was to determine the short-term measurement repeatability. The samples were placed in an airtight container with a desiccant after day 70.

The number of elements (or sampled points) used per waveform was 2048. This number was chosen because measurement results with 2048 elements exhibited less variation than those from 1024- or 512-element waveforms. More than 2048 elements did not decrease variation in measurement results. The effect of element number on measurement variation is consistent with the parameter extraction process, namely, that the extracted  $\epsilon_{r,S,n,p}$  is based on average values of three specific regions from the reference waveform and their corresponding regions in the sample waveform [1]. These waveform regions exhibit nominally steady-state voltage values that correspond to the pulse baseline, the pulse amplitude into 50  $\Omega$ , and the pulse amplitude reflected from the load impedance. The load impedance is either an open circuit (reference measurement) or the sample impedance. Increasing the number of elements in the waveform reduces noise and variation in  $\epsilon_{r,S,n,p}$  by improving the statistics of the average values of the steady-state regions and by increasing the accuracy of determining the location and duration of these regions [1].

### III. RESULTS

Some of the measurement results, the  $\epsilon_{r,S,n}$  and  $\sigma_{S,n}$  values, are shown in Fig. 2 and Table II. (The values in the rows with "day" entries of A through F were obtained using a redesigned sample holder; this will be discussed later.) Table III shows the mean values,  $\epsilon_{r,S}$ , and standard deviations,  $\sigma_{S}$ , of the  $\epsilon_{r,S,n}$  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 III were obtained using a redesigned sample holder; this will be discussed later.) We can see from the data of Table II that the short-term measurement repeatability (one standard deviation) varies from about 0.3% to 2.5%. The larger deviations are usually caused by one spurious waveform; spurious here meaning that the waveform values deviate a few percent relative to the average. Even though this type of spurious data may be easily identified and rejected by an experienced user, this would not necessarily be the case for a factory-floor operator. Consequently, these spurious waveforms are included in computing the average values,  $\epsilon_{r,S,n}$ , and uncertainties,  $\sigma_{S,n}$ , shown in Table II. Possible causes for the spurious waveform include sample insertion repeatability and oscilloscope fluctuations. The oscilloscope, however, was ruled out as a significant contributor because spurious waveforms were not observed for baseline waveforms. The baseline waveform is obtained



TABLE II  
DIELECTRIC CONSTANT MEASUREMENT RESULTS,  $\epsilon_r$ ,  $S_1$ ,  $S_2$ ,  $S_3$ ,  $S_4$  AND  $\sigma_{S,n}$ , 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

Day	S1	S2	S3	S4	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		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
E		3.502 ± 0.021		10.794 ± 0.024	22.7
F		3.505 ± 0.023		10.787 ± 0.024	22.8

TABLE III

STATISTICS OF THE  $\epsilon_{r,s,n}$  AND  $\sigma_{s,n}$ . 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 34 ( $N = 34$ ) 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  $N = 6$

	S1	S2	S3	S4	S2*	S4*
$\epsilon_{r,s} = \frac{1}{N} \sum_{n=1}^N \epsilon_{r,s,n}$	6.024	3.482	2.928	10.81	3.491	10.79
$\sigma_s = \sqrt{\frac{1}{N} \sum_{n=1}^N (\epsilon_{r,s,n} - \epsilon_{r,s})^2}$	0.006	0.023	0.006	0.009	0.007	0.012
$\mu_{\sigma,s} = \frac{1}{N} \sum_{n=1}^N \sigma_{s,n}$	0.029	0.033	0.011	0.047	0.027	0.023
$\sigma_{\sigma,s} = \sqrt{\frac{1}{N} \sum_{n=1}^N (\sigma_{s,n} - \mu_{\sigma,s})^2}$	0.027	0.021	0.008	0.043	0.007	0.005

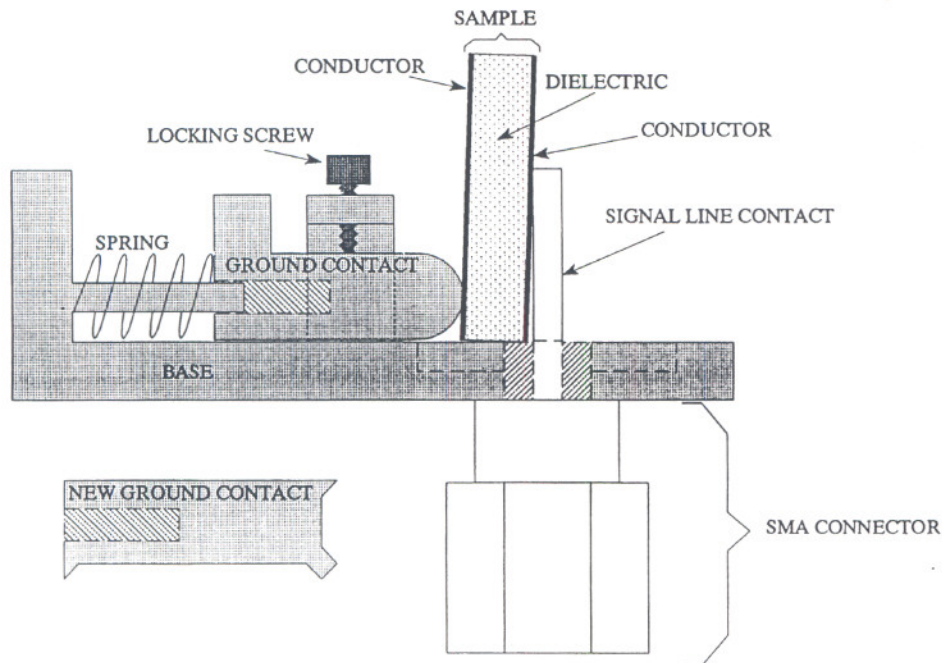


Fig. 3. Sketch of sample holder with sample in place. The sample is tilted  $2^\circ$  from the perpendicular to exaggerate the effect of tilt on sample electrical contact.

from measurements made with the sample holder removed and the TDR input port either unterminated (open circuit) or terminated by a short circuit. Sample insertion being the cause of the occasional spurious waveform is supported by the fact that the reference waveform (without the sample) does not vary more than the baseline waveforms whereas sample waveforms do vary more than the baseline waveforms. To further test whether sample insertion repeatability was the cause of the occasional spurious waveform, the measurement was implemented in two different ways and the corresponding  $\sigma_{S,n}$

values compared. In one implementation,  $M$  values of  $\epsilon_{r,S,n,p}$  were obtained using one sample waveform and  $M$  unique reference waveforms and, in the second implementation,  $M$  values of  $\epsilon_{r,S,n,p}$  were obtained using  $M$  unique reference waveforms and  $M$  unique sample waveforms. It was observed that the variation in  $\epsilon_{r,S,n,p}$  for the first implementation was approximately four times less than that of the second implementation.

We can also see from Table II and Fig. 2 that measurement variation over the test period is low, especially for sample



S3. Sample S2 may have exhibited the largest  $\sigma_S$  because it was thin and would sway after being placed in the sample holder. This movement would affect the electrical location of the sample within the sample holder (see Fig. 3), which would then affect the amplitude of the average values of the steady-state waveform regions used to extract  $\epsilon_{r,S,n,p}$ .

The  $\mu_{\sigma,S}$  and  $\sigma_{\sigma,S}$  are good 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. The situation where  $\sigma_{\sigma,S} \gg \mu_{\sigma,S}$  (the scatter in measurement repeatability is greater than the average repeatability) implies the existence of spurious waveforms and, consequently, the potential 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 probably not possible. For all four samples here,  $\sigma_{\sigma,S} \approx \mu_{\sigma,S}$ , which implies improvement to the measurement process may be possible. The relative long-term reproducibility can be obtained from  $\sigma_S$  in Table III: 0.1% for S1, 0.7% for S2, 0.2% for S3, and 0.1% for S4. The large value for S2 was probably caused by poor sample holder design, as will be discussed later. Long-term reproducibility also provides a measure of drift in the measurement process, and the values presented here indicate very low drift.

In an attempt to reduce the scatter in the measurement repeatability, the sample holder was redesigned. This sample holder is very similar to the one shown in Fig. 3 except that the sliding ground contact has been modified (see object labeled "new ground contact" in Fig. 3). The modified ground contact has four full-width knife-edge contacts. The knife-edge contacts were expected to reduce possible contact repeatability problems at the base plate and sample by forcing the contacting areas to be at very distinct and reproducible locations, namely, at the knife edges. The rows labeled A through F in Table II and the two rightmost columns of Table III show the results of the six measurement sets taken with the new sample holder for each of the samples S2 and S4. We can see from the data shown in Table III that the new sample holder reduced the scatter in measurement repeatability significantly for S2 and S4. The new sample holder also reduced  $\sigma_S$  of S2 to values similar to those for the other samples. This improvement was probably due to the reduced effect of sample sway on the measurement: it was observed that when S2 was forced to sway using the new sample holder, the observed TDR waveform was stable. However, the average variation in the measurement, indicated by  $\mu_{\sigma,S}$ , did not change when using the new sample holder. To determine if the values of  $\mu_{\sigma,S}$  shown in Table III are a limitation of the measurement system (and, therefore, unavoidable), additional tests were performed. In these tests, six sets of  $\epsilon_{r,S,n,p}$  values for S2 were obtained using one common sample waveform per set and five unique reference waveforms per set. This group of measurements yielded  $\mu_{\sigma,S} = 0.019$  and  $\sigma_{\sigma,S} = 0.004$ . This value of  $\mu_{\sigma,S}$ , 0.019, is based on one unique waveform in a

measurement pair, whereas in practice both the reference and sample waveforms are unique. If we assume that the variation in measurements can be described by a Gaussian distribution, then the effect of variations in both the reference and sample waveforms should yield a lower limit to measurement variation of approximately  $2^{1/2}\mu_{\sigma,S} = 0.027$ . This value, 0.027, is consistent with that observed (see the two rightmost columns in Table III).

#### IV. CONCLUSIONS

The long-term reproducibility error of this TDR-based PWB dielectric constant measurement method is less than 0.2% for samples S1, S3, and S4 and less than 0.7% for S2 over a period exceeding 400 days. The larger variation by S2 can be attributed to the design of the old sample holder. The short-term repeatability varied between 0.3% and 2.5%, with an average of around 1%, when using the old sample holder and this variation was probably dominated by sample insertion repeatability. The redesigned sample holder improved ground contact repeatability and reduced the effect of sample tilt and sway. With the new sample holder, the short-term repeatability varied between 0.1% to 0.9% with an average of less than 0.5%.

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**N. G. Paulter** received the M.S. degree in chemistry from the University of New Mexico, Albuquerque, in 1988 and the M.S. degree in electrical engineering from the University of Colorado, Boulder, in 1990.

He was with Los Alamos National Laboratory, Los Alamos, NM, from 1980 to 1989, and was involved in the study of fast electrical phenomena and in the development of high-speed photoconductors for use as ultrafast light detectors and sampling gates. In 1989, he joined the National Institute of Standards and Technology (NIST), Boulder, to develop transient pulse measurement techniques and analysis. He is presently with NIST, Gaithersburg, MD. His present research interests include semiconductor physics, materials properties, electrooptics, ultrafast electronic phenomena, and waveform/data processing and analysis.