Comments on "Characterization of Resistive Transmission Lines by Short-Pulse Propagation"

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In the above letter,[1] the authors report measurements of the complex propagation constant γ of a coplanar waveguide and the application of Γ to the determination of the characteristic impedance. The authors state that "the same information could, in principle, be obtained with a network analyzer" by the method described in [1]. In fact, these measurements were reported in [1]. Furthermore, the bandwidth of the network analyzer method is broad, with [1] reporting an upper limit of 40 GHz,[2] well above the 25-GHz limit reported in the letter.

The authors also criticize the method described in [1] because it "would require calibration and de-embedding of probe-to-pad parasitics." However, the determination of Γ using the thru-reflect-line de-embedding technique employed in [1] requires no more than a pair of lines of different lengths. These same two artifacts are required in the letter. With the small additional effort of measuring a reflect, the network analyzer may be calibrated and used to measure the scattering parameters of additional devices.

Fig. 2 of the letter indicates large variations of the measured attenuation constant about the modeled result at high frequencies, behavior that we have not seen in measurements of our coplanar lines. Based on an error estimate, the authors conjecture that these discrepancies are "most likely a consequence of the limitations of the model rather than the experiment."

However, the measurement accuracy was assessed "directly by measuring two waveforms without any sample." In other words, two consecutive measurements of a short thru line were compared to determine the amplitude and time delay resolution of the apparatus [2], [3]. This may be incomplete. For example, the noise floor of the sampling oscilloscope may be high enough to contribute significantly to measurement error, especially at the high frequencies where the energy in the 40 ps pulse is already small. While the short line used to determine measurement accuracy introduces little attenuation, the long coplanar line required in the experiment attenuates the high frequencies by as much as 13.5 dB. This makes their amplitude detection more difficult. Furthermore, coplanar waveguide, even at low frequencies, supports a "slotline" [4] and a "CPW surface-wave-like" [5] mode of propagation, either of which might be excited to some extent by microwave probes. Error due to the propagation of these modes is not considered either.

After determining Γ, the authors use the same method suggested in [1] to determine the characteristic impedance from the measured propagation constant and capacitance. Again, the authors note discrepancies, attributed to the model, at high frequencies. The most significant discrepancy at high frequencies is a systematic offset in the real part of the characteristic impedance of Fig. 3 in the letter. This could be explained by an error in the measurement of capacitance. Although details of the measurement and error estimate are not given, the capacitance was measured only at 1 MHz, perhaps in a capacitance bridge. This may prove to be an inaccurate method. A comparison to measurements based on the techniques described in [6], which utilize broad-band measurements and appear to give consistent and accurate results, may be warranted.

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Authors' Reply[3]

The comments by Williams and Marks [1] regarding our recent letter [2] have both general and specific aspects. The general comments relate to differences between time-domain and frequency-domain techniques for broad-band microwave measurements. Our letter described the basics of a short-pulse propagation technique to completely characterize resistive transmission lines [2]. Frequency-domain techniques to obtain the same information have been the subject of several recent works [3]–[5]. The letter by Marks and Williams [4] also used the measured propagation constant $\Gamma(f)$ to obtain the characteristic impedance, albeit with the calculated capacitance.

The 25-GHz upper limit of the results shown in our letter [2] was set by the relatively inexpensive oscilloscope-cum-differentiator used for those measurements, and not by the technique itself. Indeed, this is one of the central advantages of our technique: namely that useful parameters of a resistive transmission line can be determined with relatively inexpensive equipment and some simple mathematical procedures. Had we used the 70-GHz sampling oscilloscope (Hypres PSP-1000) available in our lab or an optoelectronic pulse generation and sampling technique [6], we would have obtained results covering a much wider frequency range.

While it is true that the method described in [4] does not require calibration and de-embedding to accurately determine $\Gamma(f)$, it is also true that with network analyzers some calibration has to be carried out in order to develop confidence in the measured data. In contrast, with the pulse propagation technique described in our letter most sources of potential error are directly observable in the time-domain waveforms, and can be dealt with easily and conveniently. For instance, small defects in the lines being probed give rise to subpulses which can be eliminated by suitable time windowing.

Concerning more specific comments, Williams and Marks find large variations in our measured loss coefficient and criticize our method for determining measurement accuracies. They are correct

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[1] A. Deutsch, G. Arjavalingam, and G. V. Kopcsay, *IEEE Microwave Guided Wave Lett.*, vol. 2, pp. 25–27, Jan. 1992.

[2] As mentioned in the text of [1], the bandwidth in the figures was truncated for clarity.

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in observing that our error analysis does not properly account for the attenuation of high frequencies on lossy transmission lines. Nevertheless, the variation in $\alpha(f)$ (Fig. 2 in [2]) is within the measured resolution of 0.11 dB/cm, about an average value. We did verify that, for the attenuation data presented in [2], the signal-to-noise ratio was adequate over the frequency range shown.

We maintain that the differences between measured and modelled values of $\alpha(f)$ can be attributed to the incomplete nature of the quasi-static model. Among other sources of discrepancy, our model did not account for any non-TEM modes. In addition, the dimensional variations of ±2.4% were not accounted for either. Again, however, the differences are within the 0.11 dB/cm resolution of our measurement techniques. It is superfluous to repeat that oscilloscope based time-domain techniques have worse amplitude resolution than network analyzer based frequency-domain techniques. The more important point is whether the accuracy is sufficient for specific applications such as chip-to-chip interconnections where fabrication tolerances are on the order of 10–20%. In fact, our measured values for the propagation constant can be used in place of modelled values to accurately predict pulse propagation on such structures.

Regarding the measurement of low-frequency capacitance with a capacitance bridge, we believe it is accurate since our measured values are within 1% of the values obtained by two-dimensional modeling. In fact, our measured per-unit-length capacitance of Williams' sample was within 1% of his value [7]. In [2], we clearly state that our expected accuracy for impedance measurements is 2% for the real part, which is true for our results on the coplanar waveguide sample.

Finally, we illustrate the value of our measured results by investigating the response of the coplanar waveguide sample to logic-like step function voltages. In Fig. 1, we compare the measured step response to two different simulated waveforms [2, [2]]: one used the transmission-line parameters determined with the short-pulse propagation technique; the other used parameters from the quasi-static model. The agreements are generally excellent.

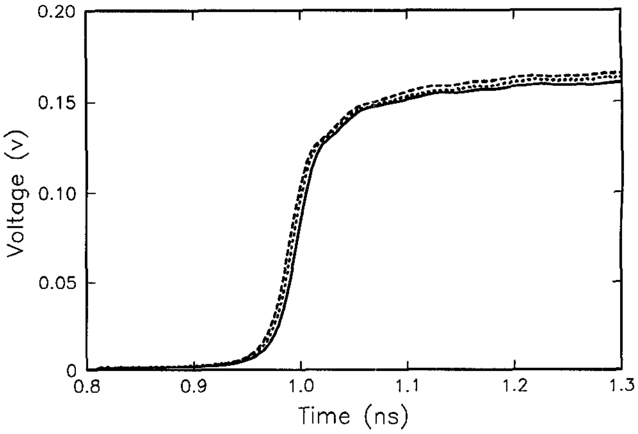

Fig. 1. Response of coplanar-waveguide described in [2] to logic-like pulses. Dotted line is measured with an oscilloscope. Dashed line is obtained when parameters calculated with a quasi-static model are input to a time-domain simulation program. Solid line is simulated with parameters determined by the short-pulse propagation technique.

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