Characterization of Resistive Transmission Lines by Short-Pulse Propagation

A. Deutsch, G. Arjavalingam, and G. V. Kopcsay

Abstract— **A method for completely characterizing resistive transmission lines by short-pulse propagation is described. Using the loss and dispersion of pulses propagated on two different lengths of line, together with the measured low-frequency capacitance, the frequency-dependent propagation constant, attenuation, and the complex impedance are determined. The basic method is demonstrated with results from low-loss cables and a well-controlled coplanar waveguide sample.**

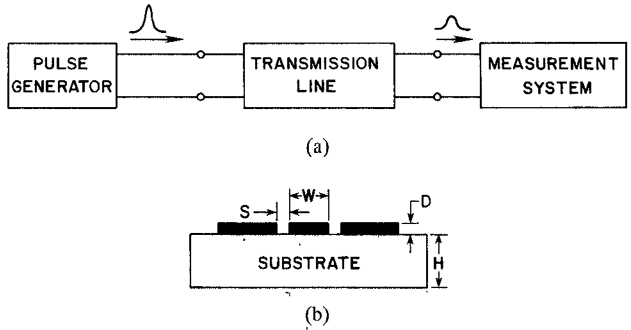

Fig. 1. (a) Schematic diagram of characterization set-up. (b) Cross section of coplanar waveguide sample (W=27.3 μm, S=8.78 μm, D=2.8 μm, H=2.286 μm).

CIRCUIT-TO-CIRCUIT interconnections in today's digital computers include on-chip wiring, thin-film or ceramic multichip carriers, and printed circuit boards. In all cases, it is extremely important to be able to fully characterize these structures since their electrical performance will have a direct impact on the machine cycle time [1]. In most high-performance computers, logic signals are propagated over systems of coupled transmission lines. For a large class of these, series resistance is the primary loss mechanism, particularly so in the high-density thin-film interconnects currently being investigated [2]. As advances in semiconductor technology continue to decrease the risetimes of signals to be propagated on these structures, their transmission-line characteristics need to be accurately known at higher frequencies. For instance, with a pulse risetime of 50 ps the frequency range of interest is from dc up to about 20 GHz.

In this letter, we report a simple short-pulse technique for completely characterizing the frequency-dependent electrical properties of a resistive transmission line. High-speed pulse measurements have previously been used for characterizing the transfer functions of microwave antennas [3] and monolithic microwave integrated circuits [4], the dispersion of microstrips [5] and coplanar striplines [6], and to measure the complex dielectric properties of materials [7]. In the method described here, the measured low-frequency capacitance and the propagation of high-speed pulses are used to determine both the complex propagation constant and the complex impedance of a resistive transmission line, over a wide frequency range. To our knowledge, such a comprehensive pulse characterization technique has not been described previously. Indeed, the same information could, in principle, be obtained with a network analyzer [8], which, however, would require calibration and the de-embedding of probe-to-pad parasitics. Also, while time-domain reflectometry is often used to determine the characteristic impedance of low-loss lines, it does not provide the frequency dependence of the complex impedance for a resistive line [2].

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A schematic representation of our experimental set up is shown in Fig. 1. A short electrical pulse is launched onto the line under investigation and the transmitted waveform is measured at the output end. The source of the pulses could be a pulse generator, the differentiated output of a step generator or a photo-conductive switch [4], [7], while the measurement system could be an oscilloscope or a photo-conductive sampler. For the results discussed here, we used the 40-ps wide pulses obtained by differentiating the step source of a 20-GHz sampling oscilloscope (HP model 54120A). A commercially available passive impulse-forming network (Picosecond Pulse Labs model 5210) was used as the differentiator and custom high-speed probes [9] were used to electrically connect the experimental apparatus to planar transmission lines. Commercially available connectors were used for other experiments.

To characterize the properties of a particular transmission-line, two waveforms are measured with two different lengths, of otherwise identical lines. The digitized waveforms are then numerically Fourier transformed. Since time windowing can be used to eliminate all unwanted reflections, the Fourier spectra contain information about the forward-travelling wave only. The ratio of the two transforms then yields the complex propagation constant

$$\alpha(f) + j\beta(f) = -\frac{1}{(l_1 - l_2)} \ln \frac{A_1(f)}{A_2(f)} + j\frac{\phi_1(f) - \phi_2(f)}{(l_1 - l_2)}, \quad (1)$$

where $\alpha(f)$ and $\beta(f)$ are the frequency dependent attenuation coefficient and propagation constant, respectively. A_i

and $\Phi_i(f)(i=1,2)$ are the amplitude and phase of transforms corresponding to lines of lengths l_1 and l_2, respectively, with $l_1 > l_2$. The effect of interface discontinuities, which are the same for both lines, linearly cancel out making it unnecessary to do any de-embedding.

The complex propagation constant, $\Gamma(f)$, of a quasi-TEM wave on a transmission line is given by

$$\Gamma(f) = \alpha(f) + j\beta(f) = \sqrt{(R + j\omega L)(G + j\omega C)}, \quad (2)$$

where, by the usual convention , L, C, R, and G are the per unit length inductance, capacitance, resistance and conductance, respectively. When dielectric losses are negligible ($G \cong 0$), the corresponding complex characteristic impedance, $Z_0(f)$, can be expressed as

$$Z_0(f) \cong \sqrt{\frac{R + j\omega L}{j\omega C}} = \frac{\Gamma(f)}{j\omega C} = \frac{\beta(f)}{\omega C} - j\frac{\alpha(f)}{\omega C}. \quad (3)$$

While capacitance is in general frequency dependent, it is dominated by the dispersion of the dielectric constant, which in most cases is very small. Consequently, the measured low-frequency capacitance together with the experimentally determined propagation constant and loss coefficient (from (1) and (2)) can be used to determine the complex impedance with (3).

We verified the procedure previously described by measuring the properties of a low-loss coaxial cable (GORE, GD 501501) and a well-controlled coplanar waveguide sample. The measured real impedance of the low-loss cable was 49.5 ± 0.05Ω from low frequencies up to 25 GHz, while its imaginary impedance and loss coefficient were, as expected, negligibly small. The manufacturer's specification for the real impedance was 50 ± 1.0Ω up to 40 GHz. From the measured propagation constant we deduced a dielectric constant of 1.43 for the cable insulator, which is a form of porous Teflon.

Fig. 1(b) shows the schematic of the coplanar waveguide sample. It was fabricated on a 2.29–mm thick fused silica substrate with a single photolithography step.

The 27.3-μm wide center conductor was separated from the 100-μm wide ground planes by 8.78 μm. The copper metallization was 2.8 μm thick with a thickness variation of ±2.3% along the length of the sample. The variation in the center conductor width was 2.4% about its nominal value. The capacitance of the coplanar waveguide was measured to be 0.809 ± 0.005 pF/cm at 1 MHz; its resistance was measured to be 2.32 Ω/cm.

Pulse waveforms were measured at the output ends of 4.5-cm and 9.0-cm long coplanar waveguides. The total span of the temporal waveforms was 368.4 ps resulting in a 0.271-GHz separation in the spectral components. The spectra have appreciable amplitude up to $\sim$ 25 GHz. The frequency dependent propagation constant and loss coefficient, obtained with (10) are shown in Fig. 2. The complex impedance obtained with (3) is shown in Fig. 3. In both Figs. 2 and 3, the points are experimental data while the lines are predictions of a model developed using the measured dimensions and the techniques discussed in [2]. In all cases, the agreement between measured results and theoretical predictions are very good. The resolutions of our experimental procedure was

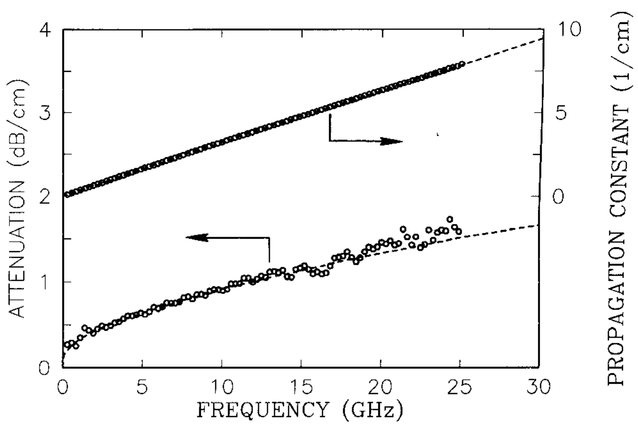

Fig. 2. Top: Phase constant $\beta(f)$ obtained experimentally (dots) and modeled (dashed trace) as a function of frequency. Bottom: Attenuation $\alpha(f)$ obtained experimentally (dots) and modeled (dashed trace) as a function of frequency.

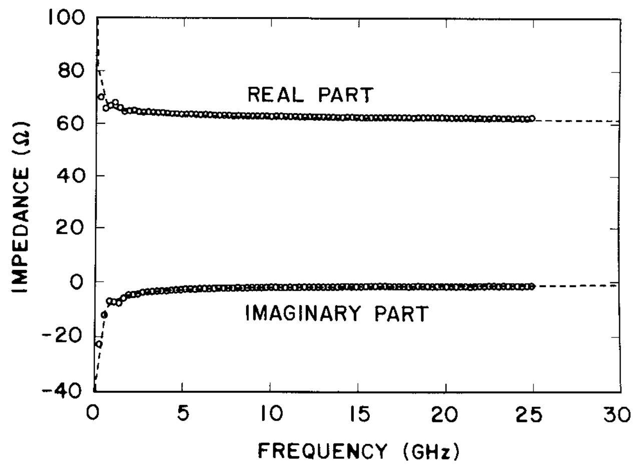

Fig. 3. Real and imaginary parts of the transmission line impedances. Points are experimentally obtained, dashed lines are predictions of modeling.

determined directly by measuring two waveforms without any sample [7]. From these, we deduced that our resolution for loss measurements, which is limited by the resolution for amplitude measurements, is ± 0.11 dB/cm. The accuracy of the propagation constant measurements, which is limited by the accuracy of the time delay, is ± 1.0%. The corresponding accuracy of the impedance measurements was ± 2.0% for the real part and ± 3.8% for the imaginary part. While these limitations come primarily from the instrumentation, the method used here to deduce them includes the effect of our custom fixturing. In our opinion, the discrepancy between measurements and modeling in Figs. 2 and 3, clearly seen at high frequencies, is most likely a consequence of the limitations of the model rather than the experiments.

In summary, we have described a simple time-domain pulse propagation technique for characterizing the broadband electrical properties of resistive transmission lines. The frequency-dependent propagation constant, attenuation coefficient, and complex impedance were obtained without any knowledge of the structural cross-sections or material parameters. The technique offers the direct unambiguous verification of the models used to predict the electrical properties of three-dimensional transmission lines. In fact, we have already applied it to characterize the type of lossy interconnections discussed in [2]. In the absence of a model, the results of these experiments could be input directly into circuit simulation programs.

The results described here can be extended in many ways. The frequency coverage can be increased with the use of shorter pulses and a higher time-resolution measurement system. The technique itself can be extended to the measurement of coupled noise (crosstalk). In that case the transfer function of an N-port network is obtained.

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