Presented at IPC Printed Circuits Expo® 2002
www.ipcprintedcircuitexpo.org

TDR and VNA Techniques for PCB Characterization

Eric Bogatin, Ph.D.
GigaTest Labs
Sunnyvale, CA

Abstract

A uniform transmission line is described electrically by a characteristic impedance and a time delay. From the length of the line and the time delay, the effective dielectric constant can be extracted. Two instruments are commonly used to measure these properties, a time domain reflectometer (TDR) and a vector network analyzer (VNA). In this paper, these techniques are reviewed. We show that an important factor influencing the quality of the measurements is the way the structure is probed. When using microprobes, the characteristic impedance and effective dielectric constant can be measured to within 1% accuracy. A collection of tips and tricks to improve the measurement accuracy are presented. Finally, the ability to accurately measure the dissipation factor of any laminate material up to 10 GHz, with a VNA, is reviewed.

Introduction

Transmission lines are the key interconnects on printed circuit boards. Measuring their electrical properties plays three important roles: verifying the manufacturing process and that the parts meet specification, intrinsic materials measurements and extracting accurate, high bandwidth models of specific interconnect structures.

There are two principle instruments used to measure the electrical properties of transmission lines, the Time Domain Reflectometer (TDR) and the vector network analyzer (VNA). Surprisingly, both instruments do basically the same thing, just in different domains. In this paper, we describe what the instruments do and offer just a few simple examples of the useful information one can obtain with both instruments.[1]

Impedance

We usually think of impedance as being the ratio of the voltage to the current: Z = V/I. While this is in fact the basic definition of impedance, it can also be defined in terms of how waves interact with a device. If a signal propagates from a region with impedance Z1, and hits a region with impedance, Z2, the incident waveform will reflect. The reflection coefficient, defined as the ratio of the reflected to the incident voltage, is related to the two impedances by:

$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

By measuring the reflected signal and knowing the incident signal and the impedance of the source, the impedance of the second structure, typically the device under test (DUT) can be extracted. When the measurement is done in the time domain by a TDR, the incident waveform is a fast rising step edge and the impedance profile of the DUT is measured as:

$$Z_{DUT} = 50\Omega \frac{1+\rho}{1-\rho}$$

When the measurement is done in the frequency domain by a VNA, the incident waveform is a sine wave and the reflected amplitude and phase is measured at each frequency value. The reflection coefficient, usually referred to as a scattering parameter or S parameter, and specifically S11, is related to the total, integrated overall impedance of the DUT at each frequency by:

$$Z_{DUT} = 50\Omega \frac{1+S_{11}}{1-S_{11}}$$

TDR Measurements

In its simplest form, a TDR emits a fast rising edge waveform, measures the reflected waveform and displays the instantaneous impedance profile of the DUT. If the DUT is a mostly uniform transmission line, the impedance profile will show nearly constant instantaneous impedance as the signal propagates down the line. From this profile, the characteristic impedance of the transmission line can be directly read.

In a production environment, a TDR is most useful in allowing the simple, fast, routine measurement of the characteristic impedance of uniform lines. An example of the measured characteristic impedance of a transmission line is shown in Figure 1.

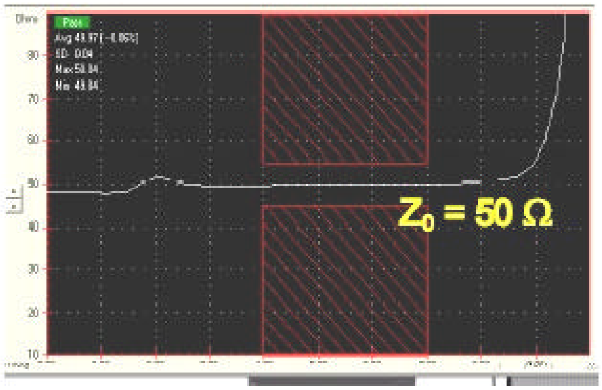

Figure 1 - Typical TDR from a Production Environment[2]

In an R&D environment, i.e., where accuracy and detail is more important than speed, simplicity and robustness, far more useful information can be extracted from measurements than just characteristic impedance.

A key element of high performance measurements is how the transmission lines are probed. It is essential to use probes that can be independently lifted and preferably calibrated, before touching down on the DUT. This allows calibrating or compensating many of the effects of the probe. An example of the microprobes used by GigaTest is shown in Figure 2.

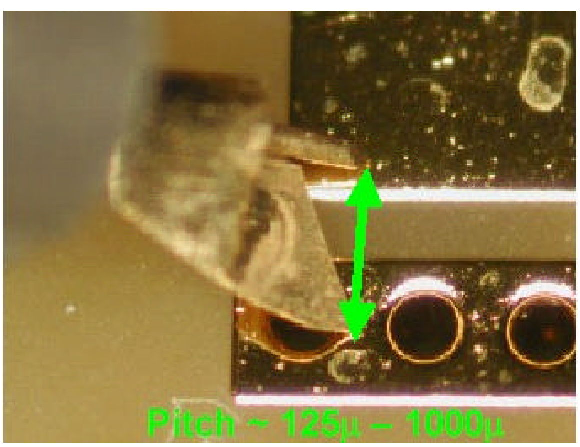

Figure 2 - Close up of Precision Microprobes with Very Small Parasitics and Capable of being Calibrated Right to the Tip

With the use of such probes, a TDR or VNA and software to analyze the measurements, its possible to extract material properties and accurate, high bandwidth models for transmission line structures.

Dielectric Constant

Normally, the way to measure the dielectric constant of a substrate is to measure the time delay (TD) of a trace. When the ends of the lines are not well defined, as when an SMA connector is used, for example, it is sometime difficult to get an accurate measure of TD.

A simple trick can be used to get around this problem.

In the uniform test line, small squares can be added to the trace with a precision spacing between them. These additions will cause a local small drop in the instantaneous impedance. On the TDR, they will show up as small dips. The center position of the dips and their TD can be measured very accurately, to a few psec.

Figure 3 shows the TDR with two small notches spaced 3 inches apart. The measured TD is 441 psec. From the TD, the speed of the signal can be easily calculated. From the speed, the effective dielectric constant can be extracted. In this case, given the length and delay, the effective dielectric constant is 3.05.

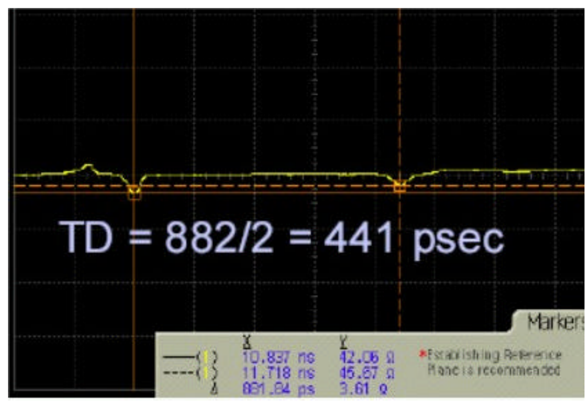

Figure 3 - Profile from a Trace with Two Small Squares Spaced 3 Inches Apary - From the Precision TD Measurement, the Velocity of a Signal can be Accurately Measured[3]

However, it is important to keep in mind that in a microstrip, some field lines are in air, while some are in the bulk material. The measured effective dielectric constant is always less than the bulk dielectric constant. For this particular aspect ratio of about 2:1, line width to dielectric thickness, the bulk dielectric constant is actually 4.0. The relationship between the bulk and effective dielectric constant can only be evaluated with a 2D field solver.

Lossy Line Effects

For lines longer than about 6 inches and clock frequencies above 1 GHz, lossy effects play an important role in FR4 substrates. Knowing the dissipation of the laminate material is critically important to be able to predict signal integrity effects.

Lossy line properties can most easily be analyzed in the frequency domain.

A VNA can be used to measure the sine waves reflected from and transmitted through a short, uniform transmission line. Figure 4 shows the measured S parameters for a 3-inch long stripline test line in FR4.

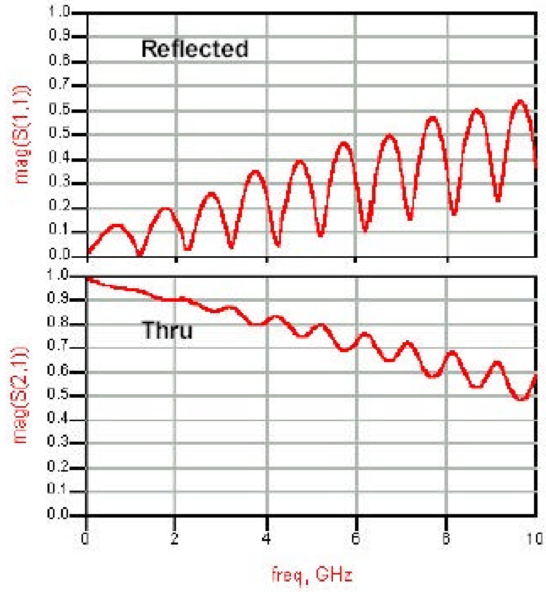

Figure 4 - Measured S11 and S21 of a 3 Inch Long Stripline Only the Magnitude of the S Parameters is Shown Here[4]

In general, it is often difficult to look at the frequency domain plot of either the S parameters or the converted impedance profile and say anything about the electrical properties of the DUT. Rather, the way to extract useful information is to use a process referred to as inverse scattering. In this technique, an ideal model is created to approximate the DUT and the simulated S parameters from the ideal model are compared to the measured values. The parameters in the model are varied until there is good agreement with the actual measured values.

Using this inverse scattering technique, a simple model was created to describe this transmission line. It consisted of a simple pi model of the vias on both ends of the transmission line and a uniform, ideal, lossy transmission line with a constant value of dissipation factor and dielectric constant, and resistive loss proportional to the square root of frequency. Using the best-fit values to the parameters of this simple model, the resulting agreement to the measured S parameters is seen to be excellent. The simulated S parameters, superimposed with the measured S parameters are shown in Figure 5.

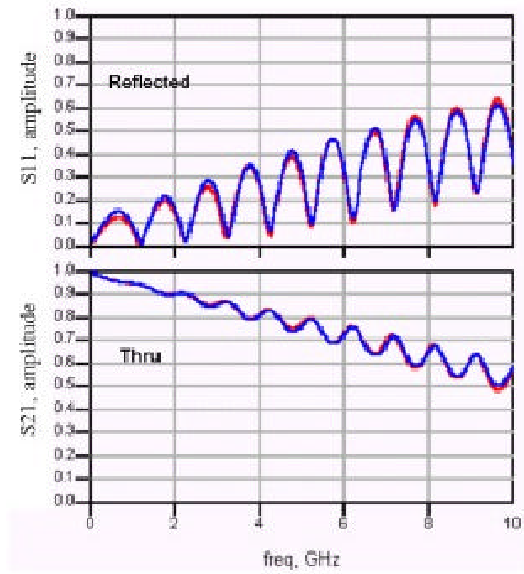

Figure 5 - Comparison of the Measured and Simulated S Parameters for the 3 inch Transmission Line[5]

It is important to keep in mind that the model, which matches the measured performance so well, assumes a constant dielectric constant of 4.0 and a constant dissipation factor of 0.019. We find that for many FR4 samples, these material properties are constant up to 15 GHz.

Extracting Models of Discontinuities

Often times, there are specific PCB features that cause impedance discontinuities that need to be characterized. For example, all transmission lines have vias. Depending on the pad size, a via can be either inductive or capacitive. A gap in the return path will cause the return current to make a jog. This will look like an inductive discontinuity. Both of these effects show up in the measured TDR profile of a transmission line. An example of a line with these two discontinuities is shown in Figure 6.

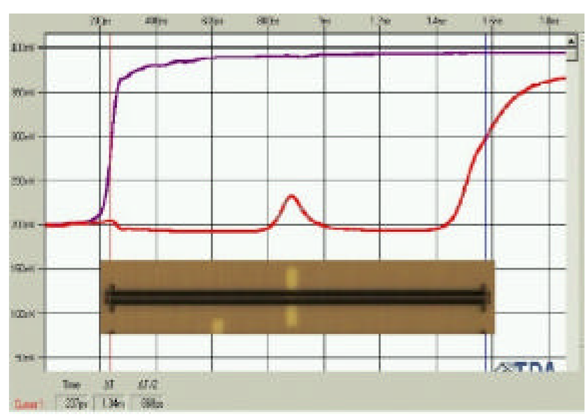

Figure 6 - Measured TDR Profile of a Transmission Line with Initial Via and Small Gap in the Return Path

The inverse scattering technique can be used with TDR data as well as VNA data. An ideal equivalent circuit model is created that describes the uniform transmission line with the two discontinuities. The TDR profile expected from this ideal model is simulated and compared with the measured TDR profile. The parameter values of the model are varied until good agreement is reached between the measured and simulated results.

When there is good agreement, we have confidence in the accuracy of the model. For this transmission line, Figure 7 shows the agreement of the model with the measurement. The excellent agreement provides confidence that the extracted parameters, such as the via inductance of 0.2 nH and the gap inductance of 2.1 nH are accurate values.

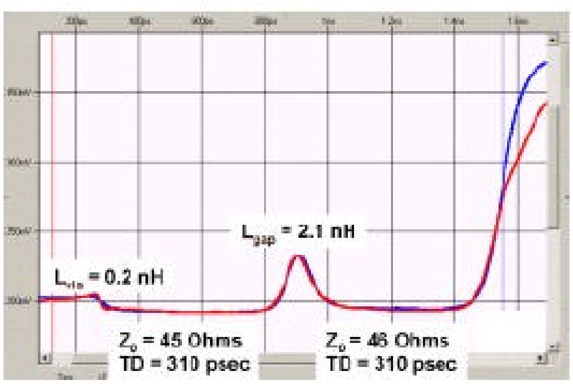

Figure 7 - Comparing the Measured and Simulated TDR Profile for this Transmission Line with a Gap in the Return Path[6]

Conclusions

In this brief report, we have shown that electrical characterization with TDR and VNA can offer valuable detailed information about transmission lines, material properties and physical structures. In addition to the actual instruments, accurate, high bandwidth models require precision probes to the DUT and analysis software that allows extracting the important model parameters. Of course, it also requires understanding and expertise in the electrical properties of interconnects.

References

1. Many of the techniques introduced in this paper are described in great detail in application notes that can be downloaded free from the www.gigatest.com web site.
2. Figure 1 courtesy of Polar Instruments
3. TDR is an Agilent DCA 86100
4. VNA is an Agilent 8510E
5. Analysis done with Agilent ADS Software
6. Analysis done with TDA Systems IConnect Software