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A Wide Bandwidth Printed Wiring Board Transmission Line Probe

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A Wide Bandwidth Printed Wiring Board Transmission Line Probe

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Abstract
An inexpensive, wide bandwidth, high cycle, 50 Ω probe is described for making electrical contact to printed wiring board planar transmission lines. The electrical transfer function of the probe and its contact repeatability are presented.

Introduction

A common method to determine the characteristics of a printed wiring board (PWB) transmission line (TL) is to use time-domain reflectometry (TDR)[1,2,3]; a brief description will be provided in Sec. 1.a. The TL parameter that is of great interest to the PWB manufacturer is the TL's characteristic impedance, which can be used to determine manufacturing repeatability (such as batch-to-batch processing) and accuracy (such as actual conductor dimensions relative to that of the design), and material acceptability (such as thickness and permittivity of the dielectric material).

TDR Measurements Using Commercial Equipment

A TDR measurement system typically uses an equivalent-time, nominally 50 Ω input impedance, TDR-capable, sampling oscilloscope and a computer controller to obtain the captured waveforms from the oscilloscope. The impedance of the sample can be determined if the impedance of the TDR unit is known. In the TDR mode, the oscilloscope's TDR unit delivers a rectangular voltage pulse to the sample and then samples the pulse that is reflected from the sample. An idealized TDR signal for a lossless TL is represented by the trace shown in Figure 1. The reflected pulse is a consequence of the impedance discontinuity between the TDR unit and the sample, where it will be assumed that the sample is a TL. The observed TDR pulse may consist of one or a series of step-like pulses (SLPs). A simple ideal SLP consists of two static (or more realistically, quasi-static) levels, the topline and baseline, that are separated by a transition region. The TDR waveform is the result of the addition of the incident SLP and some of the reflected SLPs and, therefore, contains the toplines, baselines, and transition regions from all these SLPs. The reflected SLPs are a consequence of the incident SLP reflecting from impedance discontinuities. The durations of the static levels in the TDR signal are dependent on the round-trip pulse propagation time of each different characteristic impedance section in the TL and the amplitudes of these levels are dependent on the magnitudes of the impedance discontinuities. For the work described here, the TL has a uniform nominal impedance, Z_c, and the observed reflections are due to the impedance discontinuities at the ends of the TL. For simplicity, we will also assume that the TL length, L, is long enough and the observation period (epoch) is short enough so that at most only two reflections are observed. These observed reflections will be the primary reflections from the impedance discontinuities at the probe-to-TL interface and the TL-to-end of line termination interface. For the work done here, the TLs were unterminated (open circuit).

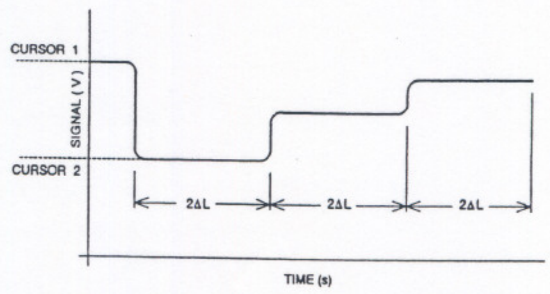

Figure 1 - Idealized TDR Signal

Probe Design

A probe is used to make electrical connection between the TDR and the TL because the connection cannot be permanent. Also, the TDR connector is coaxial whereas the PWB TLs are planar, typically microstrip. The probe affects the duration of the transitions between levels and the stability (lack of ringing) of the quasi-static levels in the TDR waveforms and, therefore, affects the accuracy of the TL Z_c measurement. Consequently, a probe must be designed that provides the fastest transitions and lowest possible ringing. The design of the probe is also dependent on the desired bandwidth of the measurement, the round-trip propagation time of the TL, and the bandwidth of the SLP; the importance of these parameters will be shown later.

The round-trip propagation time of the TL, t_{TL}, is the time it takes a pulse to traverse twice the length of the TL; $t_{TL} = 2L/v_{TL}$ where v_{TL} is the group velocity of the SLP propagating in the TL. The duration of the quasi-static level in the TDR signals obtained for this work is defined by t_{TL}. To determine Z_c of the PWB TL, the bandwidth of the probe must be great enough so that the toplines, baselines, and transition regions of the incident and reflected SLPs can be easily identified (located and measured). Here, the baseline provides information on the reference impedance, Z_0 (usually the characteristic impedance of the TDR or probe), and the topline reflects the difference between Z_c and Z_0. Because we must identify the components of the TDR waveform, the observed TDR waveform should not exhibit excessive ringing or slow transitions. Ringing is caused by the transition between Z_0 and Z_c (the TDR-to-probe and the probe-to-TL interfaces), and the slow transition is due to bandwidth limitations. Optimal probe design can reduce the magnitude and duration of the ringing and improve transition speed.

Our considerations for probe design were the following: the bandwidth must be great enough to ensure existence of quasi-static levels corresponding to Z_c where L can be as short as 7.6 cm (3 in), impedance matched to the TDR, and having an abrupt probe/TL interface to reduce ringing, repeatable and reliable contact, high contact cycle capability, and low cost. Figure 2 contains a sketch of the probe.

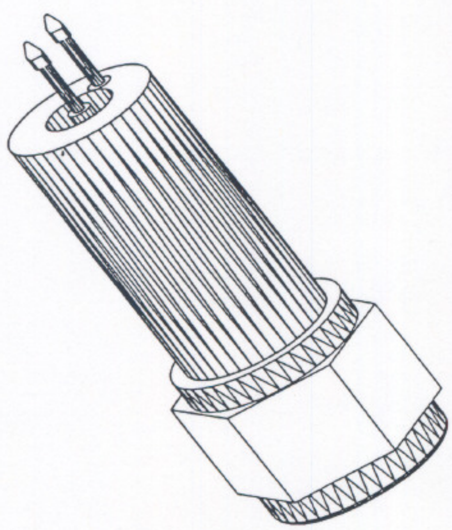

Figure 2 - Diagram of OWB Probe

Impedance matching to the TDR (50 Ω) is achieved by using 3.58 mm (0.141 in) diameter 50 Ω semirigid coaxial cable. A significant advantage of the 3.58 mm cable over cables of other cable geometries is that the inner conductor of the 3.58 mm cable is also the inner conductor of the 3.58 mm cable SMA connector, which reduces physical discontinuities in the probe and their associated ringing.

To further reduce ringing, the transition between the probe and the TL was made as abrupt as possible, about 2 mm (0.08 in). We have observed that the transition with the shortest lived and smallest amplitude ringing in both a coaxial-to-parallel-plate[4] and a coaxial-to-coplanar waveguide transition, has been for the most abrupt transition. The likely reason is that the more abrupt the transition is, the more likely the transition will appear as a lumped element for all frequency components of the pulse and, therefore, less ringing is observed. Although the peak overshoot will be greater for an abrupt transition than for a gradual transition, the duration of overshoot will be very short and can be easily ignored in the observed TDR signal. Also, to avoid ringing and to maintain a high bandwidth, we minimized the physical discontinuities in the probe's conductive paths (signal and ground). The ground is a continuous block of metal and, therefore, has no discontinuities. The center conductor (signal line) of the probe is made by soldering a length of 3.58 mm cable center conductor to a spring-loaded interconnect. Spring-loaded interconnects are used in both the signal and ground lines to make contact to the TL contact pads. These particular interconnects were selected because their contact resistance varied by only 20 m Ω over 10^6 cycles (manufacturer's specification), their outside diameter is similar to that of the inner conductor of the coaxial line, and they have about 2.54 mm (0.1 in) of travel. The spring-loaded interconnect has a barrel length of approximately 12.7 mm (0.5 in) and a diameter of 1 mm (0.04 in), and the tip of the probe extends from the barrel about 4.6 mm (0.18 in) when fully extended and about 2 mm (0.08 in) when fully compressed. The 2 mm probe-to-TL transition is defined by the distance between the barrel and the probe tip under full compression. To minimize the physical discontinuity between the two halves of the signal line, the interconnect and solder were machined to have a nominal diameter the same as that of the inner conductor of the coaxial cable, namely 0.91 mm (0.036 in). The ground contact of the probe is made using an interconnect soldered into the ground block of the probe.

The bandwidth requirement of the probe can be determined using a "root sum-of-squares" approximation, which is, for this application:

$$\frac{1}{BW_{probe}} = \sqrt{\frac{1}{2}}\sqrt{\frac{1}{BW_{sys}^2} - \frac{1}{BW_{scope}^2} - \frac{1}{BW_{SLP}^2}} \quad (1)$$

where BW_{sys}, BW_{scope}, BW_{probe}, and BW_{SLP} are the -3 dB bandwidths of the measurement system, the sampler, the probe, and the SLP, respectively. The $\sqrt{2}$ factor is required because of the round-trip of the pulse through the probe. To measure Z_c for a short TL (approximately 7.6 cm long) requires a BW_{sys} exceeding 7 GHz. For the system used here, $BW_{SLP} \approx$ 12 GHz and $BW_{scope} \approx$ 20 GHz, so that BW_{probe} must be at least 13.5 GHz. Since BW_{SLP} and BW_{scope} are fixed by commercially available instrumentation, the only way to increase BW_{sys} is to increase BW_{probe}. We achieved a high BW_{probe} (-3 dB bandwidth around 18 GHz) by minimizing the number of physical discontinuities within the probe and using high bandwidth connectors (SMA) and coaxial lines.

Results

Our probe and a commercially available probe (50 Ω impedance, nominal –3 dB bandwidth of 3.5 GHz) were tested using three PWB microstrip TLs each having a different nominal Z_c (26 Ω, 56 Ω, and 110 Ω), see Figs. 2 through 4. The lengths of the TL samples were approximately 111 mm (4.375 in). As mentioned earlier, the TDR traces contain several levels and corresponding transition regions. The static levels are labeled in all the figures for identification. For these figures, regions R1 and R2 and the transition between them define the incident SLP, R2 and R3 and their transition define the SLP reflected at the probe TL interface, and R3 and R4 and their transition define the SLP reflected at the TL open interface. The region R2 defines the signal level for a 50 Ω system, R3 defines the signal level for an impedance of Z_c, and R4 defines the level for an open-circuit impedance. For accurate Z_c determinations, it is desirable to have fast transitions between R2 and R3 and between R3 and R4, and R2 and R3 regions that are as flat as possible. From Figure 3, 4 and 5, we can see that the TDR transition regions are shorter and the quasi-static levels more stable for our probe than for the commercial probe. Measuring the 110 Ω TL with the commercial probe, we found it difficult to find a stable R3 level. Furthermore, the commercial probe has an extended unstable R2 region that makes determination of the reference impedance ambiguous. Based on these observations, we can assert that our probe is better suited for measuring Z_c for short PWB TLs than is the commercial probe.

Contact repeatability and reliability and life cycle tests were also performed on our probe. The probe was cycled for over 100000 cycles at a rate of 5 cycles/s and with a compression of approximately 2.5 mm for each cycle. Probe and reference measurements were taken after the following approximate number of cycles: 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10,000, 15,000, 20,000, 25,000, 30,000,

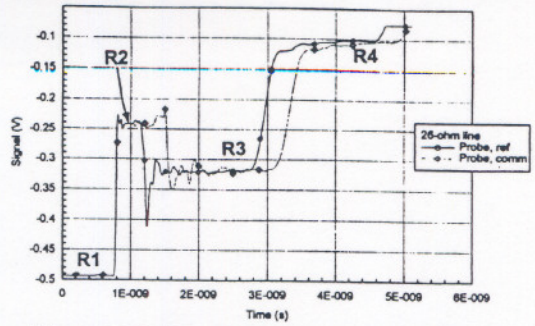

Figure 3 - TDR Signals for 26 Ω Microstrip Transmission Lines Using Our Probe (Labeled "Probe, Ref") and a Commercial Probe (Labeled "Probe, Comm")

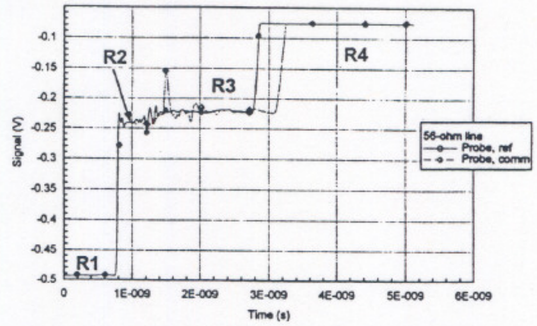

Figure 4 - TDR Signals for 56 Ω Microstrip Transmission Lines Using Our Probe (Labeled "Probe, Ref") and a Commercial Probe (Labeled "Probe, Comm")

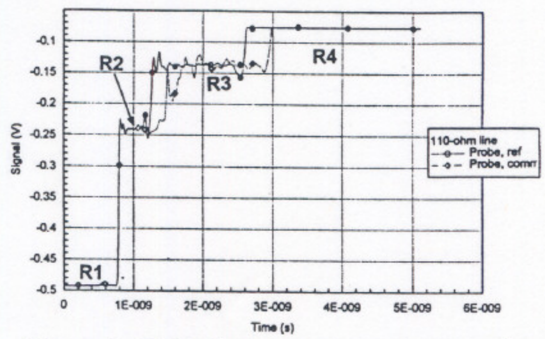

Figure 5 - TDR Signals for 110 Ω Microstrip Transmission Lines Using Our Probe (Labeled "Probe, Ref") and a Commercial Probe (Labeled "Probe, Comm")

35,000, 40,000, 45,000, 50,000, 60,000, 70,000, 80,000, 90,000, and 100,000. Shown in Figure 6 are the mean and standard deviations for the probe cycle measurements which shows that probe behavior did not change appreciably over the 100,000 cycles. The peaks in the standard deviation curve are the result of timebase drift, which causes the transition regions for a given pulse to appear to move over time and which was also observed for the reference measurements (TDR port unterminated).

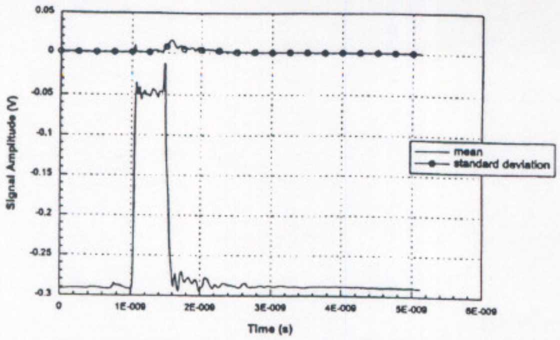

Figure 6 - Mean and Standard Deviation of Probe Waveforms after Repeated Contact Cycling

We determined the transfer function (see Figure 7) of our probe using a short-circuit connected to the TDR port as a reference. The transfer function was obtained by acquiring the reference and probe waveforms and then deconvolving the reference waveform from the probe waveform.[5,6,7] The –3 dB bandwidth for our probe is approximately 18 GHz.

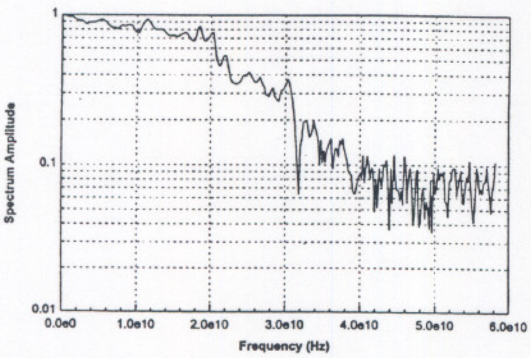

Figure 7 - Probe Transfer Function

We also had our probe tested at a PWB manufacturing facility to determine usefulness and durability in an industrial environment. The short-term gage studies performed by this manufacturer indicated a decrease in reproducibility and repeatability errors of about 50% when using the experimental probe. This improvement is attributed to a more repeatable and stable contact to the PWB transmission line. In addition, users indicate that the experimental probe reduced hand fatigue.

Conclusion

A PWB TL probe was described that provides superior performance compared to a widely used commercially available device: it is inexpensive to make, has a nominal –3 dB bandwidth of 18 GHz, and is expected to survive at least 10^6 cycles. The probe uses two spring-loaded interconnects, one replacing part of the center conductor of a coaxial line for the signal contact and the other soldered to the coaxial outer conductor for the ground contact. Because the signal interconnect replaces the inner conductor of the coaxial cable, it minimizes physical discontinuities that can cause ringing and reduced bandwidth.

Acknowledgements

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