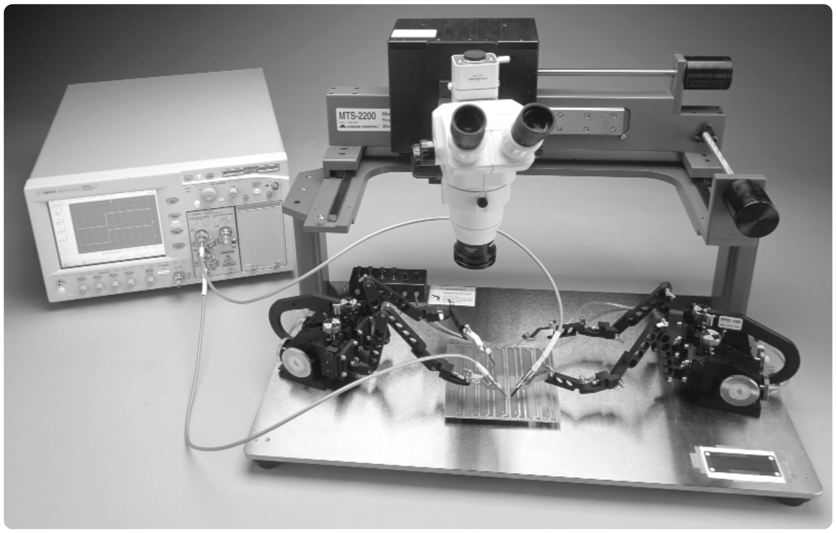
# Microprobing with the Agilent 86100A Infiniium DCA

## Application Note 1304-3



A guide to making accurate measurements with the Agilent 86100A Infiniium DCA and Time Domain Reflectometer using Cascade Microtech high frequency probes.

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## Introduction

The characterization of packages and interconnecting lines has become increasingly important to the performance of today's high-speed integrated circuits. Traditionally, measurements on IC packages have been made in the frequency domain with network analyzers. The high-bandwidth DCA incorporating a time domain reflectometer (TDR) was occasionally used, but the TDR system was not flexible enough to resolve the impedance discontinuities presented by the small geometry of the IC packages. A major obstacle was to obtain a high fidelity connection between the test equipment and the device under test (DUT). This application note describes a test system that overcomes these previous limitations.

By using proper equipment and test methodology, spatial resolution in the sub-millimeter range is achieved. Other parametric measurements yield accuracy in the range of milliohms, femtofarads, picohenries, and picoseconds.

The test system consists of two parts: the Agilent 86100A Infiniium DCA with the Agilent 54754A time domain reflectometer; and the Cascade Microtech MTS-2200 module test station with high frequency air coplanar probes (see Figure 1). Notice that the setup is simple and the number of separate pieces of equipment is small. The same setup can be used for both reflection and transmission measurements. The addition of the second probe and the associated coaxial cable is all that is required to perform transmission measurements.

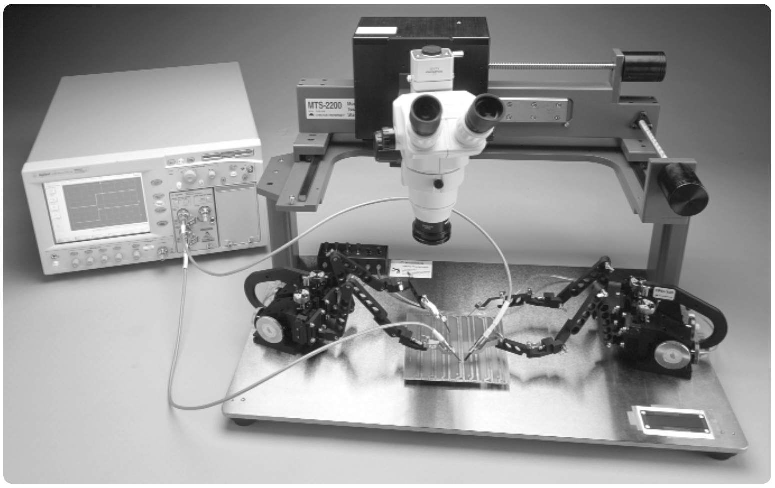


**Figure 1.** Typical test setup

To show the flexibility of this test system, both reflection and transmission measurements are made on a pin grid array (PGA) integrated-circuit package. The results show that a standard setup can be used to characterize a variety of packages and how TDR with normalization can be used to accurately predict package behavior at real world speeds. A complete list of test equipment is given in Appendix 1.

## Digital Communications Analyzer

The 86100A Infiniium DCA with the 54754A differential time domain reflectometer plug-in module is a system consisting of two parts: a digitizing oscilloscope and a TDR/sampler head. The 86100A uses a powerful microprocessor to control the oscilloscope and TDR functions. It is an easy-to-use, precise measurement system with an interface to printers, plotters, computers and other instruments via the IEEE-488 bus. A floppy disk drive is built into the mainframe allowing convenient data transfer of screenshots into reports. The internal microprocessor and DSP filter allow simulation of a wide range of TDR rise times without changing the setup.

Signal paths or transmission lines can be designed according to mathematical models. Then, time domain reflectometry (TDR) can be used to make final adjustments on the prototype, compensating for hard-to-model parasitics. A TDR cursor simplifies measuring impedance, distance, and percent reflection. A key capability of the 86100A system is a feature called "Excess Reactance". This allows the user to accurately quantify the amount of excess inductance or capacitance created by a package structure (with picohenry and femtofarad resolution). This is extremely important when attempting to improve the signal integrity of high-speed IC packages.

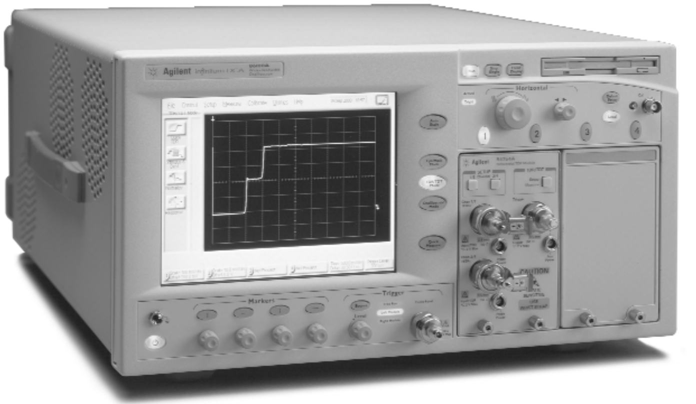


**Figure 2.** The Agilent 86100A Infiniium DCA

Other capabilities of the 86100A system include normalizing the error sources and calibrating the system to any reference plane desired. Normalization minimizes TDR measurement errors caused by imperfect connections, test fixtures and cables. It also measures the real effect of discontinuities on the circuit by matching the rise time of the normalized stimulus with the circuit's operating conditions.

The 86100A accepts both optical and electrical plug-in modules. The Agilent 54753A Single-ended TDR module and Agilent 54754A Differential TDR combine the functions of a step generator and an oscilloscope in one instrument chassis. The 86100A can also measure time domain transmission (TDT). Instead of measuring reflected energy, TDT looks at the energy incident at the far end of the structure under test. Crosstalk, propagation delay, and gain through a device are measured automatically with just a few clicks.

## Probe Station

Cascade Microtech manufactures probe stations for a variety of applications. Probe stations are available for R&D, analysis, production and engineering. For this application note, the MTS-2200 model test probe station was used.

The MTS-2200 probe station below features FPD-100 adjustable arms that allow quick positioning of the probes. This application can be used with up to four microwave positioner assemblies. Each positioner assembly individually controls a microwave probe in the x, y, z axes and adjusts the contact planarity. Also the adjustment range of the Cascade Microtech positioners allow the ACP series and FPC series probes to be used simultaneously. Needle probes can be mixed with coplanar probes if desired.

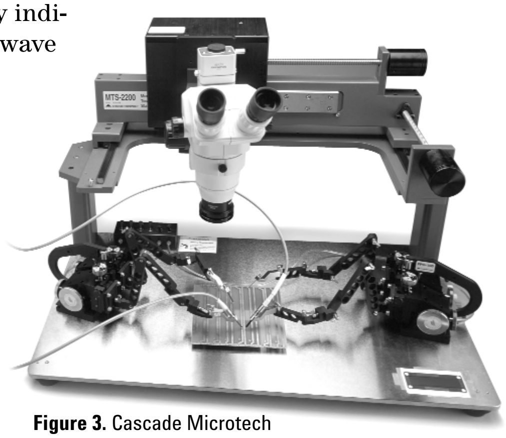


**Figure 3.** Cascade Microtech MTS-2200 probe station

## Probe Heads

All tests used either Cascade Microtech ACP40-GSG-250 wafer probes or FPC-GSG-250 package probes. The ACP40 and FPC probes have a frequency range of 40 GHz and 20 GHz respectively. They are capable of resolving elements as small as 0.01 pF and 50 pH. Calibration repeatability has been demonstrated to be –50 dB (0.3%) and an unprecedented 50 femtoseconds. Therefore, the measured values show the actual parameters of the DUT. Figure 4 illustrates a typical ACP series probe head. Figure 5 shows a FPC series package probe head.

**Figure 4.** ACP-40 Probe

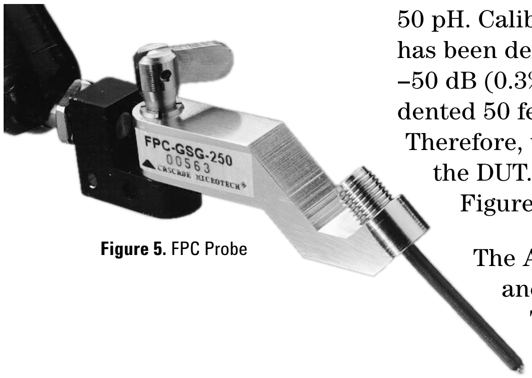


**Figure 5.** FPC Probe

The ACP40-GSG-250 probe has three contacts, one signal and two grounds, and a pitch of 250 microns (10 mils). The ACP40 series have available pitches to match various integrated-circuit package bonding pads.

Cascade Microtech high-frequency coplanar probes provide a reliable connection from the Agilent 86100A to the DUT over a wide bandwidth, adding only sub-picofarad parasitics. The connection is repeatable and temporary, and it will not damage the DUT. The small footprint of the probe aids measurements in confined spaces, such as the cavity of an integrated circuit package. Multi-contact probes allow contacts to be made with a pitch as small as 50 microns (2 mils). The transition from a coaxial to a coplanar structure is internal to the probe and is therefore controlled and reliable.

Probe heads are available in a variety of forms and probe spacing (pitch). High frequency probes usually pair a ground contact with each signal contact, or places a signal contact between two ground contacts. The three most common configurations are:
- GS (ground-signal)
- SG (signal-ground)
- GSG (ground-signal-ground)

## Impedance Standard Substrate

In order to calibrate and set the reference plane at the probe tips, a precision 50-ohm probing substrate is required. The Cascade Microtech impedance standard substrate (ISS) is a small alumina substrate containing multiple sets of the three standards required for setup calibration: a 50-ohm termination, one short and one through line. In addition, a variety of components, structures, and thin film resistors are included. The ISS includes 500 femtofarad capacitors, 400 picohenry inductors, a variety of transmission line segments, and other structures. The ISS family is shown in Figure 6.

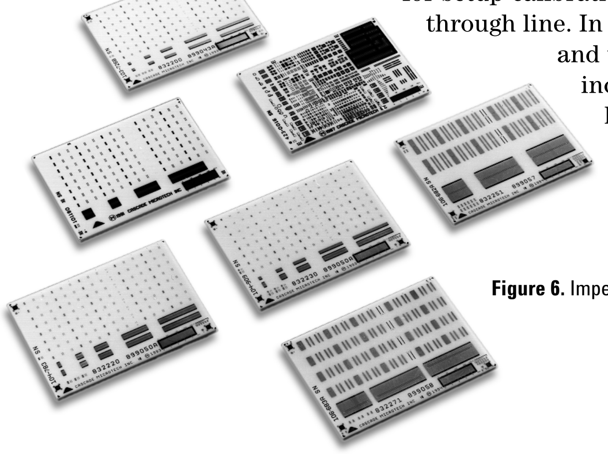


**Figure 6.** Impedance standard substrates

## Surrogate Chip Test Substrate

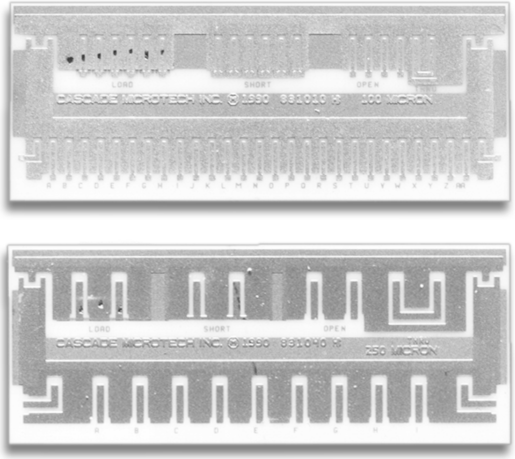


**Figure 7.** Surrogate chip substrate

Another tool that makes measurements easier and more repeatable is the Cascade Microtech surrogate chip test substrate. This IC die substitute mounted inside and wired bonded to a package cavity provides probe test points from inside the package. The surrogate chip, shown in Figure 7, contains all the structures required to calibrate a test system and to measure the characteristics of the IC package. The structure measures 0.25" by 0.118" and contains shorts, through calibrations, 50-ohm loads, and 19 bonding pad/probe landing sites. Several models are available with spacing for standard probe pitches.

## IC Package Test Fixture

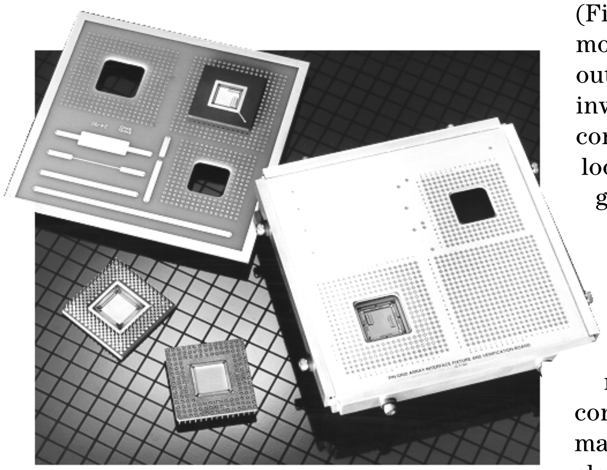


**Figure 8.** PFX-50 IC package test fixture

The Cascade Microtech PFX-50 package test fixture was used for the interface of the high-frequency probes to the PGA package (Figure 8). The PGA was mounted and tested from outside the package looking inward. It could also have been configured from the inside, looking outward with a surrogate chip. The PFX-50 offers 20 GHz bandwidth and uses a continuous electrical connection around the enclosure to provide a stable electrical environment. The interior cavity contains microwave absorber material, minimizing spurious electrical responses detrimental to repeatable measurements. The PFX-50 is held to the chuck by vacuum allowing the probe station X, Y, Z and micrometer controls to place the probes on all fine pitch test structures.

## System Cables

The coaxial cables used in making the measurements were high quality, 40 GHz flexible cables. Like the probes, these cables were used to minimize the contribution of parasitics to the measurements. With this setup, rise times as fast as 15 picoseconds can be used. Cable such as RG-58 with BNC adapters will cause rise time degradation because of losses in the cable and obscure many details of the structure under test from the reflections of the connectors.

## TDR Basics

To better understand the data presented in this application note, a brief discussion of time domain reflectometry will be given. Time domain reflectometry measurements are made by applying a step to a transmission system and measuring the ratio of incident (Ei) and reflected (Er) voltages on the transmission system. Figure 9 illustrates the general concept. Figure 10 shows the TDR response with a transmission line terminated in an ideal open, short, 2 x ZO, and 1/2 ZO. For an open (no) termination, current must be zero at the load so the voltage wave must reflect back in phase. In the case of a short termination, the voltage must be zero at the load, so the voltage wave must reflect back out of phase.

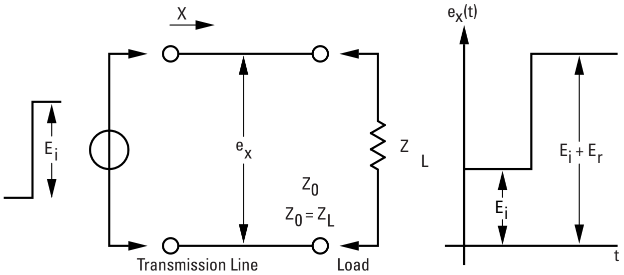
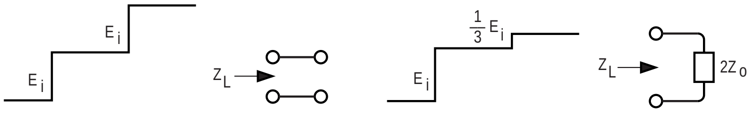


**Figure 9.** TDR Measurement System

Time domain transmission (TDT) measurements are made by applying a step function to the DUT from channel one of the 54754A modules and then applying the DUT output to the channel 2 input of the module. Using TDT methods, gain, distance, crosstalk and propagation delay can be easily determined. Again, the cursor allows the easy measurement and display of important features in the DUT.



(A) Open Circuit Termination ($Z_L = \infty$)

(C) Line Terminated in $Z_L = 2Z_0$

(B) Short Circuit Termination ($Z_L = 0$)

(D) Line Terminated in $Z_L = \frac{1}{2} Z_0$

**Figure 10.** TDR displays for basic loads

## Normalization

Using a process called normalization, it is possible to achieve higher accuracy measurements in the time domain (see Agilent's 86100A on-line help). Normalization can remove test setup errors, establish a measurement reference plane for both distance and impedance, and simulate the response of the DUT to actual system edge rates. Normalization is equivalent to de-embedding in the frequency domain. The reference plane is established by calibration with a short and a 50-ohm load. By use of the calibration procedure and FFT processing, the measured time domain response is converted to the frequency domain. The frequency domain data is processed by a digital filter that removes errors associated with imperfections of the scope, pulse step, and test setup. The corrected response is converted back to the time domain, and then displayed. The actual normalization filter function, F(f), is computed by dividing a sum of the cosines window by the frequency response of the test setup system, S(f):

$$F(f) = W(f)/S(f)$$

The filter allows the calculation of the test system's frequency response deviation from the ideal. If the output of the TDR step

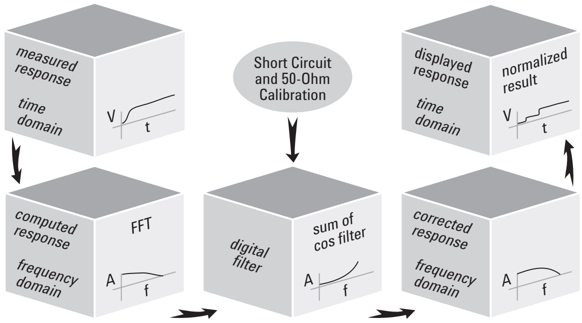
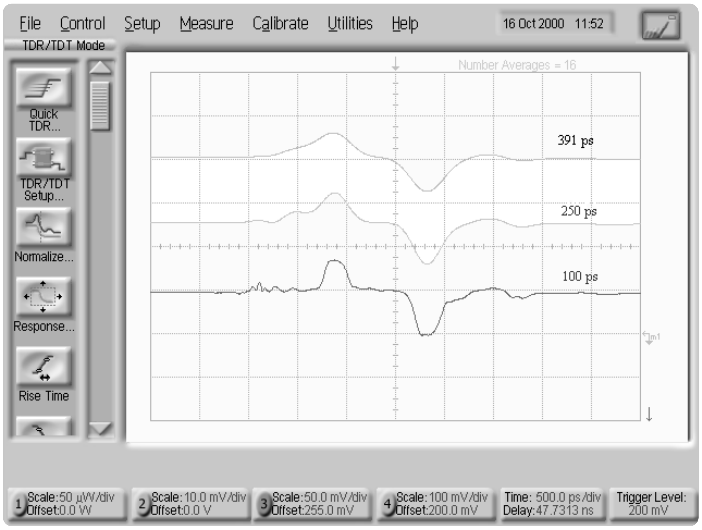


**Figure 11.** Normalization process

generator were to be passed through the filter, the result would be the ideal response. The filter removes errors by attenuating or amplifying and phase shifting components of the frequency response as necessary. For example, cable losses are removed by boosting high-frequency components. Figure 11 shows the process schematically.

Because the scope's response contains useful information much beyond its 3-dB bandwidth, the normalization system can be used to extend the bandwidth for increased resolution. Increasing bandwidth of the TDR is a very important consideration in many applications where dimensions are very small or the spatial difference between two features is small. In air the spatial resolution is about 1.5 mm, but in IC package test applications, where the dielectric constant of the substrate may be as high as 12, the resolution improves to about 0.4 mm.

During TDT measurements, a transmission normalization filter can also be derived. During the TDT calibration, an open and a then a straight through is used (or a standard device) to determine the reference plane, amplitude levels, and propagation times. Then the DUT is inserted and measurements of distance, gain, and propagation delay are made with either the live step or an idealized step with selected rise times.



1 Scale: 50 µW/div Offset: 0.0 W
2 Scale: 10.0 mV/div Offset: 0.0 V
3 Scale: 50.0 mV/div Offset: 255.0 mV
4 Scale: 100 mV/div Offset: 200.0 mV
Time: 500.0 ps/div Delay: 47.7313 ns
Trigger Level: 200 mV

**Figure 12.** Effect of different risetimes

## Launch and measurement considerations

Ground proximity and spacing is a fundamental consideration when launching a TDR step with a high frequency probe. One requirement is that a high-quality ground be placed as close as possible to the point being measured. As the size of the devices and structures decreases and frequency increases, the proximity of a ground becomes more important. High-quality grounds can be realized in several ways. A ground plane beneath a dielectric layer is one option and is known as microstrip. Another system is coplanar microstrip, and is implemented by placing a signal trace on a printed circuit board with two ground traces paralleling the signal trace. In general, the ground traces should be at least three times

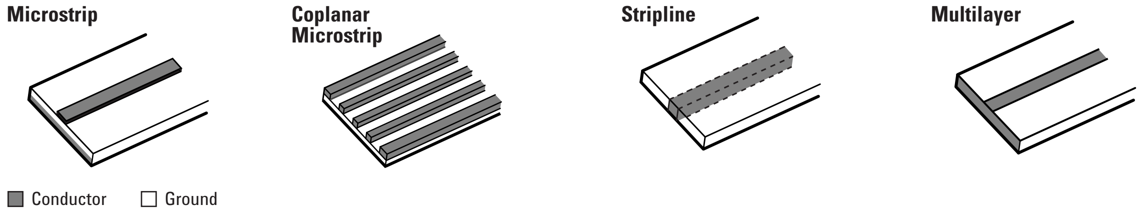


**Figure 13.** Controlled impedance lines

wider than the signal trace to reduce inductance, crosstalk, and fringing effects. A single parallel ground trace also can be used, although the signal trace is subject to crosstalk on the unguarded side. Additionally, the ground line inductance is increased. Besides these standard methods of routing signals on a substrate, stripline and multilayer configurations are also common. Figure 13 shows some of these controlled impedance lines.

The characteristic impedance of these implementations is a function of trace width and spacing, and the dielectric constant and thickness of the insulating material on which the transmission line is mounted. The design and characteristics of transmission lines have been extensively treated in the literature.

## Coaxial to Planar Transitions

The problem of test connections is a serious one for the engineer testing an integrated circuit or printed circuit board. Standard test probes, jigs, and needle probes work well for lower frequencies and large component sizes. As operating frequencies increase, the length and quality of the interconnect between the test equipment and the DUT becomes increasingly important. One major problem with launching a signal to or from a coplanar structure coupled to a coaxial instrument is controlling the impedance at the transition. An uncontrolled transition can mask many of the fine details of the structure under test. Fortunately there is a simple solution to these problems. The 86100A provides the means to extend the reference plane of the measurement down to the DUT terminals or pads. Cascade Microtech high frequency probes handle the problems of coaxial to coplanar transition and small coplanar component size. The input/output terminals of the 86100A system are APC-3.5 precision, 3.5-mm coaxial connectors. In this application note, all connecting cables are high quality, 40-GHz flexible coaxial cables. The coaxial to coplanar conversion is accomplished within the ACP40-series and FPC-series probes.

## DUT, Test Site, and Probe Dimensions

Making contact with the terminals of the device or structure under test may present a challenge to the test engineer. Sometimes the contacts are accessible; at other times the terminals are in a very difficult location.

A good example of a deceptively difficult location is a device within the cavity of an integrated-circuit package. Many packages have fairly deep cavities. The purpose is to prevent mechanical and electrical interference between the lid and the wire bonds. In addition, package designers attempt to control the package size so that wire bonds are not too long. Since a well-designed probe system needs to have a significant horizontal contact component

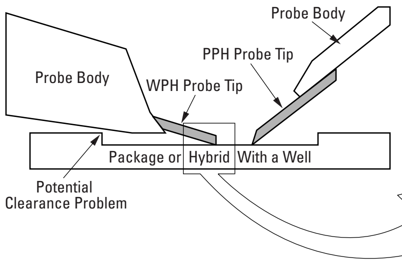


**Figure 14.** Side view of probes

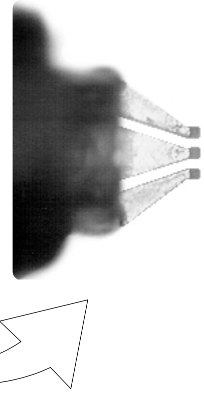


**Figure 15.** Top view of ACP40 tips

and the probe system must occupy some physical space, there is a conflict. Figure 14 illustrates the problem. ACP40 series probes have a 5:1 slope to the device under test so be careful that the underside of the probe clears the opposite wall of the package cavity. Ignoring this detail could result in damage to the probe.

The FPC series probes offer a solution to this problem, providing 45° angle of approach to the DUT. In general, use APC40 series probes for planar structures; use FPC series for DUT's with sidewalls and cavities. Exercise care when probing hybrids or other structures with components that have a significant height above the substrate.

## Planarity Considerations

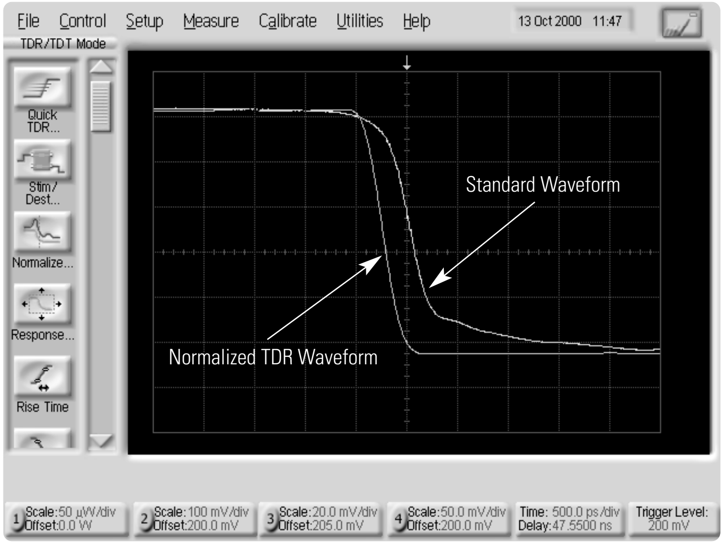
A measurement system based on the use of coplanar probes requires care in maintaining measurement system planarity. The ground-signal-ground probe contact points are shown contacting a substrate that is not perfectly parallel to the probes. This causes one of the probe pads to hit before all the others get a chance. Problems due to this phenomenon include excess skating of the first contact that hits the substrate and deformation of the contact pad. Damage to the substrate is possible if the planarity is too severe. Another, more subtle, concern is the variation in height from contact pad to contact pad. The maximum variation should be 25 microns (1 mil).

## Measurements made on the ISS

The measurements described in this section were made on the Cascade Microtech impedance standard substrate (ISS). The short, resistor, and through are the same as those used during the calibration procedure. The open, capacitor, and inductor are used to show the way the measurement system can be used to measure small value parasitic elements. The ISS also makes a good reference device when making precise measurements on small structures.

## Short and inductor

The trace in Figure 16 was made with a ACP40-GSG-250, a three-contact GSG probe. This illustrates the response of the 86100A system with the probe tips short-circuited. The normalized trace

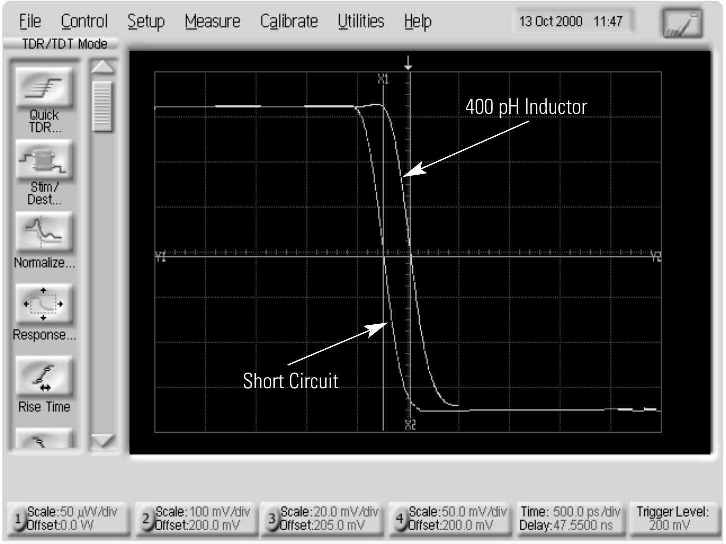


1 Scale: 50 µW/div Offset: 0.0 W
2 Scale: 100 mV/div Offset: 200.0 mV
3 Scale: 20.0 mV/div Offset: 205.0 mV
4 Scale: 50.0 mV/div Offset: 200.0 mV
Time: 500.0 ps/div Delay: 47.5500 ns
Trigger Level: 200 mV

**Figure 16.** Short on ISS

shows a good short at the probe tips. The standard waveform shows the effect of a non-ideal contact that causes a gradual fall of the trace down to a short circuit.

Figure 17 shows two traces: the left trace indicates a normalized short circuit. The right trace is the response of the TDR when the probe is landed on a 400 pH inductor on the ISS. Note that the right trace does not resemble the idealized inductor, or a positive-going response above Ei. Instead, the trace simply appears to have been delayed by about 26 ps. This is due to the rise time of the system. Examples of the ideal response to reactive loads are show below in Figures 18A and B.



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3 Scale: 20.0 mV/div Offset: 205.0 mV
4 Scale: 50.0 mV/div Offset: 200.0 mV
Time: 500.0 ps/div Delay: 47.5500 ns
Trigger Level: 200 mV

**Figure 17.** Short and 400pH inductor

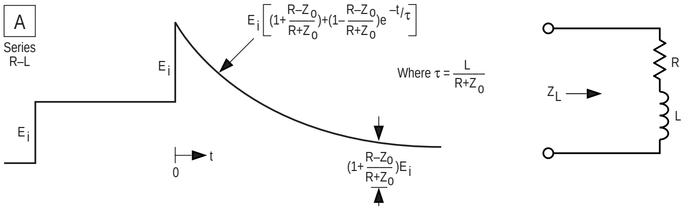


**Figure 18A.** TDR of ideal inductor

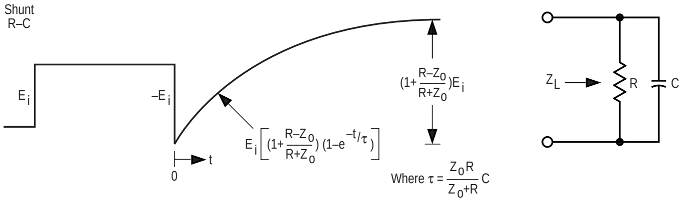
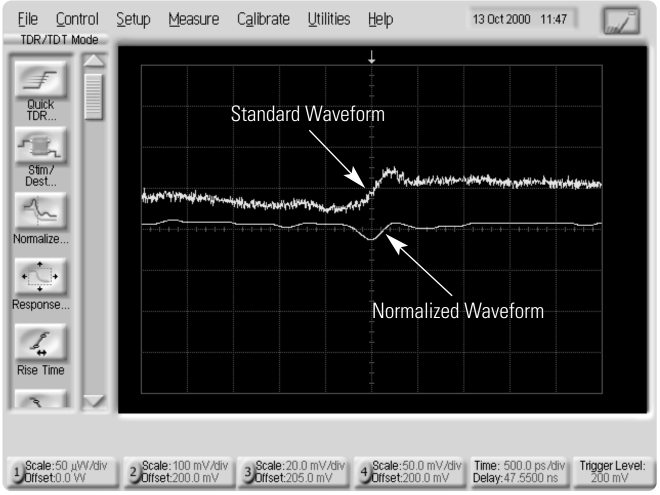


**Figure 18B.** TDR of ideal capacitor

## Resistors

Figure 19 shows the response of an ACP40-GSG-250 probe terminated with a 50-ohm resistor. The vertical scale was chosen at 5 mV/div to show detail. The upper trace, which is not normalized, shows a resistance of 51 ohms. The lower trace is normalized and shows a small impedance error dipping to 49 ohms, most likely due to a small amount of capacitance at the probe tips. Note, however that the normalized trace has stabilized within 50 ps (2.3 mm) and the normalized trace shows that the 50-ohm resistance correlates well with the expected values. This illustrates the tight control of the launch mechanism that can be obtained with this equipment.



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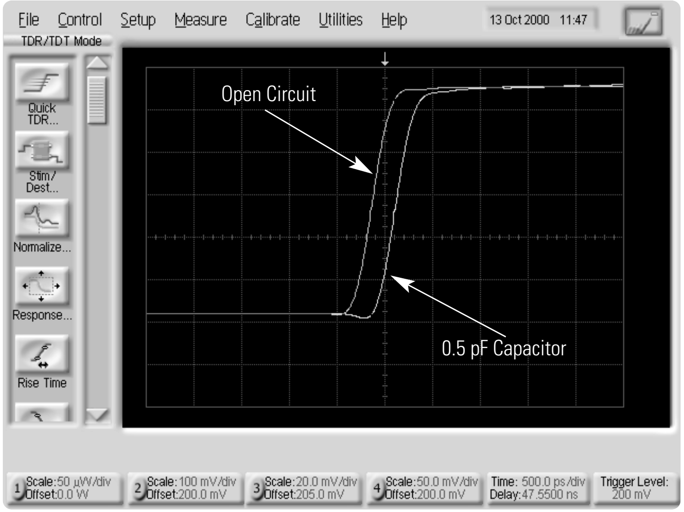
2 Scale:100 mV/div Offset:200.0 mV
3 Scale:20.0 mV/div Offset:205.0 mV
4 Scale:50.0 mV/div Offset:200.0 mV
Time: 500.0 ps/div Delay:47.5500 ns
Trigger Level: 200 mV

**Figure 19.** 50-ohm resistor on ISS

## Open and 500 fF capacitor

Figure 20 compares the normalized trace of an open circuit with that of a 0.5 pF capacitor on the ISS. The open circuit was achieved simply by raising the probe tips a few mils above the substrate. Open circuits often present a problem for TDRs because the calculation for the resistance is rational and the voltage difference between several tens of Kohms and an open circuit is very small. Note that the rise time approximates that of the probe applied to a short circuit. The measurement of a capacitor shown



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2 Scale:100 mV/div Offset:200.0 mV
3 Scale:20.0 mV/div Offset:205.0 mV
4 Scale:50.0 mV/div Offset:200.0 mV
Time: 500.0 ps/div Delay:47.5500 ns
Trigger Level: 200 mV

**Figure 20.** Open and 0.5pF on ISS

in the right trace gives excellent correlation with the measured values of the substrate capacitor as measured by a network analyzer. Although the display does not resemble the ideal capacitor display, this can be explained (or justified) by clarifying that the rise time of the system (35 ps) causes a delay and therefore only the relative amplitudes of the waveform are examined. The traces correlate with the expected response.

## Ceramic 155 pin grid array

Figure 21 shows a cavity-down Pin Grid Array (PGA) package mounted inside the PFX-50. This fixture allows measurements to be made either from the cavity or from the outside with equal accuracy. A surrogate chip (Figure 22) was mounted in the cavity. The surrogate chip was also used in these measurements. In this case, the surrogate chip was placed against the cavity wall to minimize the wire bond length.

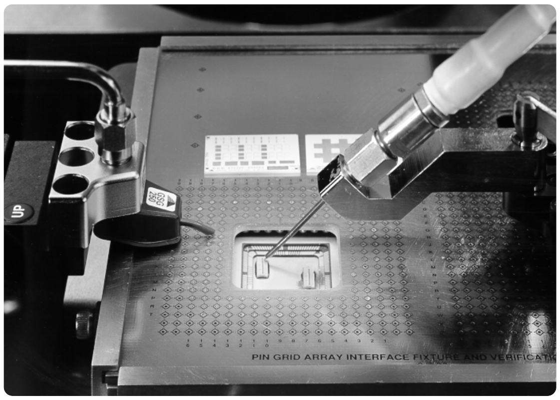


**Figure 21.** Pin Grid Array (PGA) fixture

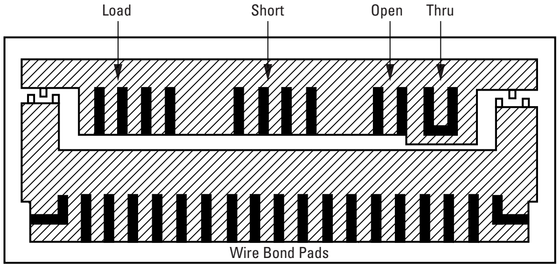
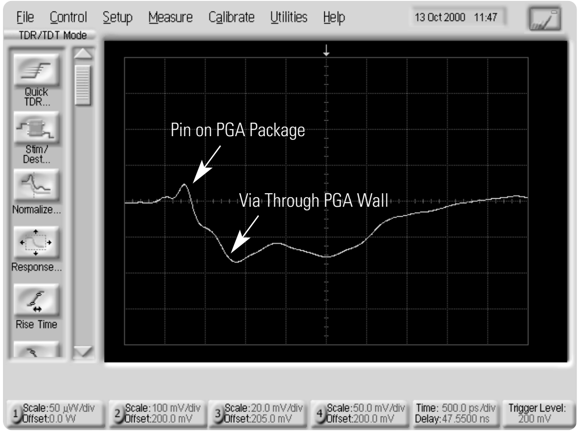


**Figure 22.** Surrogate chip

Figures 23 and 24 show reflection measurements made on two adjacent pins separated by 200 mils terminated into 50 ohms on the surrogate chip. The impedance of each pin is near 80 ohms. Inductance of the pins (3 mm in length) is the same for both estimated to be 3 nH. Each signal trace exhibits fairly low impedance between 20 and 24 ohms with variations due to the vias and the surrounding package planes. These pins appear to have a signal path to its termination resistor of about 12 mm. Lacking an internal layout drawing, the length was estimated to be close to that number. The difference in the delay (60 ps) times the propagation velocity (3.45 mils/ps) yield 207 mils which agrees closely to the physical pin separation.

Figures 25 and 26 show crosstalk of two adjacent lines. The pin pair in Figure 25 terminated into 50 ohms exhibits similar delay characteristics to



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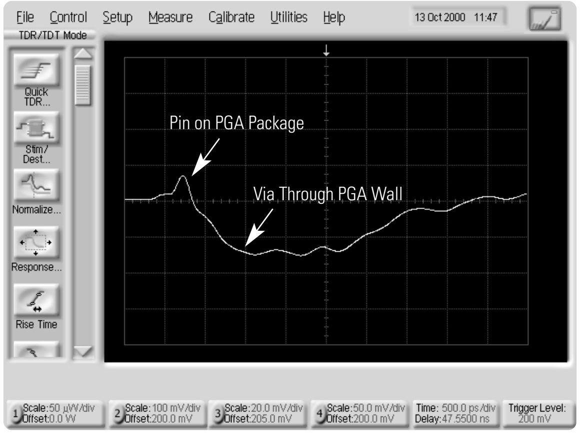
2 Scale:100 mV/div Offset:200.0 mV
3 Scale:20.0 mV/div Offset:205.0 mV
4 Scale:50.0 mV/div Offset:200.0 mV
Time: 500.0 ps/div Delay:47.5500 ns
Trigger Level: 200 mV

**Figure 23.** Pins H16 terminated (PGA)



1 Scale:50 µW/div Offset:0.0 W
2 Scale:100 mV/div Offset:200.0 mV
3 Scale:20.0 mV/div Offset:205.0 mV
4 Scale:50.0 mV/div Offset:200.0 mV
Time: 500.0 ps/div Delay:47.5500 ns
Trigger Level: 200 mV

**Figure 24.** Pin H18 terminated (PGA)

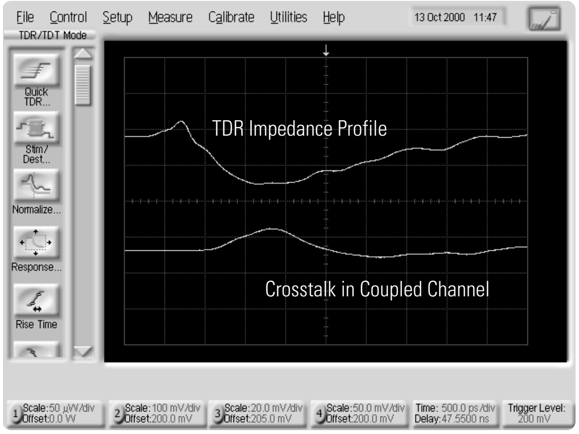
the open terminated pair in Figure 26. The difference is the 2 x peak-to-peak voltage swing of the high impedance pair, which could lead to timing errors in high-speed IC applications.

## Conclusion

As the operating frequencies of integrated circuits increase, the accurate measurement and characterization of all parts of the signal path become very important. Network analyzers perform this function in the frequency domain. With the Agilent 86100A Infiniium DCA and time domain reflectometer, and the use of Cascade Microtech high-frequency probes, similar measurements can now be made in the time domain. Measurements with this equipment can be made on very small structures and are very repeatable. The first three sections of this paper described the setup, measurement considerations and calibration required to make the measurements.

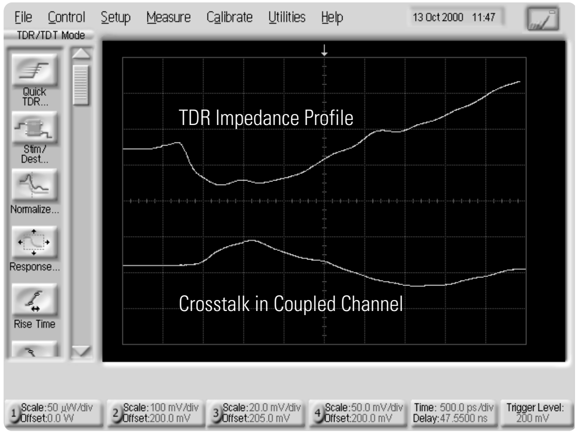
Finally, a number of small structures were measured on the impedance standard substrate and then measurements were made on a commonly used PGA integrated-circuit package.

The results were presented in a series of scope traces. Wire bonds, signal line impedance, crosstalk, and other features are readily seen on these displays.



1 Scale: 50 µW/div Offset: 0.0 W
2 Scale: 100 mV/div Offset: 200.0 mV
3 Scale: 20.0 mV/div Offset: 205.0 mV
4 Scale: 50.0 mV/div Offset: 200.0 mV
Time: 500.0 ps/div Delay: 47.5500 ns
Trigger Level: 200 mV

**Figure 25.** Crosstalk with lines terminated (PGA)



1 Scale: 50 µW/div Offset: 0.0 W
2 Scale: 100 mV/div Offset: 200.0 mV
3 Scale: 20.0 mV/div Offset: 205.0 mV
4 Scale: 50.0 mV/div Offset: 200.0 mV
Time: 500.0 ps/div Delay: 47.5500 ns
Trigger Level: 200 mV

**Figure 26.** Crosstalk with lines unterminated (PGA)

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## Appendix 1: Equipment Used

### Agilent Technologies

- Agilent 86100A Infiniium DCA
- Agilent 54753A single-ended time domain reflectometer
- Agilent 54754A differential time domain reflectometer

### Cascade Microtech

- MTS-2200 model test probe station
- MH5 microwave positioners with MMM planarizable probe arms
- ACP40-GSG-250 40GHz air coplanar probe
- FPC-GSG package probe
- P/N 005-016 impedance standard substrate (ISS)
- P/N 101-162 40GHz flexible cable assemblies
- PFX-50 package test fixture

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