Removal of Cable and Connector Dispersion in Time-Domain Waveform Measurements on 40Gb Integrated Circuits

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***Abstract*— A new instrument for time-domain characterization of circuits is illustrated. We measure output waveshape and rise time of two high-speed digital circuits on wafer, using a 50GHz prototype of the new instrument. It uses vector error-correction to deembed the component under test like a network analyzer but reads out in the time-domain after the fashion of an equivalent-time oscilloscope. With the calibration plane of the instrument set at the tips of the wafer probes, errors arising from dispersion in the connection hardware are removed. A further benefit of this instrument is that random jitter is removed without the convolution penalty usually incurred by averaging, so that anomalies such as pattern dependent jitter are exposed. The system risetime is 7ps, compared to a system risetime of 12–13ps for a conventional equivalent-time oscilloscope of the same bandwidth in the presence of wafer probes, bias networks, and cables.**

I. Introduction

MEASUREMENT of components for 40Gb/s systems presents a new challenge. Circuits are microwave in nature. However, performance specifications typically are made in time-domain terms such as edge risetime. Time-domain information is most useful for designers to visualise circuit operation. No convenient relationship between the time- and frequency-domain performances is available, and measurement of performance in the time domain is thwarted by phenomena such as cable dispersion and wafer probe discontinuities. The eye of a 40Gb/s signal can be closed significantly by a few inches of cable and a few transitions.

We report here crucial time-domain performance measurements made with an instrument called a "Large-Signal Network Analyzer" (LSNA). This instrument is calibrated to a measurement plane just like the familiar Vector Network Analyzer (VNA), yet it yields time-voltage data in a manner similar to an equivalent-time, sampling oscilloscope. The version of the instrument used in this work has a 50GHz bandwidth, and approximately 7ps 20–80% system risetime.

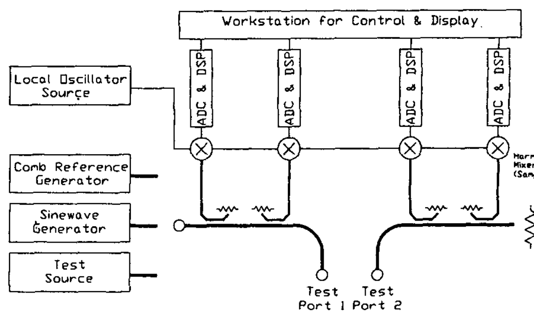

Fig. 1. Block diagram of the Large-Signal Network Analyzer. Switching circuitry used during the calibration procedure has been eliminated in the interest of simplicity.

II. The LSNA Instrument

The Large-Signal Network Analyzer (LSNA) is not a new development, but has previously been seen as a non-linear network analyzer for device or behavioral circuit modeling[1], [2], [3]. Although yielding time-domain data, the instrument internally resembles a vector network analyzer (VNA) or microwave transition analyzer (MTA) that would use a sinewave stimulus. However, it is equally valid to think of it as an *oscilloscope with error correction.* Viewed this way, it can be seen as an ideal tool for making precision, time-domain, wafer-level, waveform measurements in the presence of dispersive cables, imperfect adapters, and unavoidable device probes. This is precisely the need in the case of characterization of 40Gb/s data components such as multiplexers, data amplifiers and retiming circuits.

Figure 1 depicts the block diagram of the LSNA. A practical LSNA contains relays that allow for reconnection during s-parameter, magnitude and phase calibration phases. For ease of description, these have been left out and in this manuscript the calibration procedure will be described in principle only.

The constraints on the use of a LSNA are twofold. Firstly, any waveform to be examined must be periodic, and the period must be known. This is really

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the same condition that exists for equivalent-time oscilloscopes traditionally used for such measurements, since these must normally be provided with a trigger signal at or below the fundamental frequency of the signal being measured.

Secondly, all frequency components present in the waveform must be anticipated. In other words, the LSNA must be calibrated at all the frequencies that might be present in the signal to be examined. A suitable analogy might be the use of an Harmonic Balance (HB) algorithm in a simulator. Unlike a transient algorithm as found in SPICE, the HB simulator also requires that one must specify all frequency orders of the stimulus signal. This constraint exists because the LSNA, though displaying data in the time domain, calibrates at single frequencies selected from a comb. The comb fundamental must be chosen, and wanted members of the comb identified. This is not usually a serious constraint when testing data transmission components, because both the clock rate and the period of any pseudo-random bit sequence (PRBS) are known.

III. Calibrating the LSNA

The LSNA is first connected as a VNA, with a sinewave source, and a small-signal vector calibration performed at the probe tips. All calibrations will be made at the selected fundamental and any desired harmonic frequency. Another calibration is performed using a power sensor and coaxial standards at a convenient location outside of the reflectometer. The VNA is now able to ratio the complex voltage waves and measure absolute power levels at the samplers.

Next, the sinewave source is disconnected and a comb reference generator is connected at the coaxial calibration plane. This generator is driven with a fundamental frequency that is a subharmonic of all the frequencies included in the small-signal calibration. The reference comb provides the absolute phase reference that allows the instrument to relate the phase (timing) of travelling wave signals measured at different frequencies. The corrected magnitude and phase of each harmonic component relative to a known universal subharmonic is now established at the probe tips and an inverse Fourier transform is used to produce the time-domain waveform.

Accuracy of the result relies on knowing the relative phase of all harmonics of the reference comb generator within the bandwidth of the measurement. The reference comb generator is carefully characterized via a nose-to-nose calibration carried out with three samplers[4], [5].

IV. Measured Amplifier Results

We will examine the performance two high-speed integrated circuits tested on a wafer-probe station.

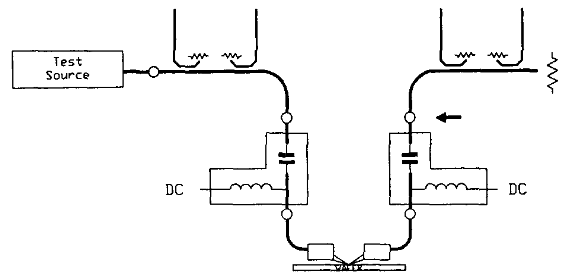

Fig. 2. Actual measurement setup used to compare the LSNA results to those obtained with direct oscilloscope tests of the data amplifier. Note that both a 50GHz wafer probe and a 50GHz bias network are present between the measurement instrument and the DUT. The arrow identifies the closest point at which a conventional sampling oscilloscope can be connected. Had we not sought to carry out a direct comparison with a sampling oscilloscope for the purpose of this report, the bias networks could have been located outside the directional couplers.

Of interest is the performance of the circuits on fast transitions including such characteristics as risetime, overshoot and ringing. The first circuit is a data amplifier that is intended to be run in a limiting mode with output of 3–3.5 Volts peak-to-peak into 50Ω at a fundamental frequency of approximately 21GHz. It can also be used as a clock amplifier with a fundamental frequency of approximately 43GHz. A 4:1 multiplexer (MUX) will also be evaluated. The MUX has current-mode logic (CML, 0 to -0.5V) output into 50Ω suitable for driving the data amplifier.

We are interested in the performance of the circuits on fast transitions, specifically such characteristics as risetime, overshoot, ringing, etc. We wish to measure the performance at the wafer pads, to provide feedback to circuit designers, and to distinguish this from performance measured when fully packaged.

Figure 2 shows the connection used for the amplifier measurement. We are interested in the risetime of the circuit. In the past such a measurement would have been made with a sampling oscilloscope. The presence of the bias networks, wafer probes, and interconnection hardware such as cables and adapters, would progressively degrade system risetime. Using the LSNA, these components will be effectively removed by calibration at the probe tips.

Figure 3 shows the measured output signal obtained from the LSNA. The same plot shows measurements of the input signal, along with the output signal obtained from a 50GHz sampling oscilloscope. With a 700MHz fundamental, the LSNA is measuring 71 harmonics, employing almost the full 50GHz bandwidth. A system with a bandwidth of 50GHz but with a rapid fall in response above 50GHz should theoretically have a 20%–80% risetime of approximately 7ps.[1]

[1]For comparison, a 50GHz system with single-pole rolloff

We may approximately "deconvolve" the response of the system from the response of the device using the rule-of-thumb that risetimes accumulate as the root of the sum of their squares. The LSNA reports a risetime of 11ps, suggesting an actual waveform risetime of $\approx$ 7–8ps.

Allowing for the bias network (5ps), the wafer probe (6ps), adapter (4ps), and the oscilloscope response (7ps), we might expect the oscilloscope system to represent an ideal risetime of $\sqrt{7^2+5^2+4^2+6^2}$, just over 11ps, perhaps 1–2ps larger to allow for some cable loss. Our comparative oscilloscope measurement, taken by breaking the circuit at the point marked with an arrow in Figure 2, gives a risetime of 15ps, implying a system risetime of 12–13ps consistent with this rough estimate, as some 15cm of cable is present. Note that while we are able to go forward through the calculation above, it would be extremely precarious to start with a risetime of 15ps and go backwards to conclude a signal risetime of 7 or 8ps!

Figure 4 shows similar results but with a fundamental squarewave frequency of 2.8GHz, four times higher than the signal used for Figure 3. Unlike the LSNA trace, the oscilloscope trace shows some ringing with a frequency near 9GHz, but the LSNA trace does not. The oscilloscope trace shows a lower amplitude, accounted for by the response of the components (wafer probe, cables, bias network) between the device and its connector. The LSNA waveform is beginning to exhibit Gibb's phenomenon, visible mainly as ringing appearing at the beginning of the transitions.

It is interesting to note that both systems exhibit misleading fine structure in the waveshape, but for different reasons. The fine structure is apt to vary with stimulus frequency content for the oscilloscope case as a consequence of its overall response not being flat. In the LSNA case, the fine structure will vary with fundamental frequency in accordance with Gibb's phenomenon and the relative position of the fundamental and the absence of any data above the highest calibration frequency.

V. Risetime, Jitter and Averaging

The LSNA yields a continuous trace, in the sense that it contains its result in "analytic" form, and can tabulate numeric output with arbitrary point density. It is also capable of analytically reporting measured slope of a transition. In contrast, the sampling oscilloscope has a pre-specified point density, each sample being one measurement made in response to one trigger event. (The oscilloscope has been used with no averaging.) The reported 20%–80% risetimes are $\approx$ 11 and $\approx$ 15ps respectively, but depend a little on

would exhibit a 20–80 risetime of just over 4ps, while a system with a 5^{th}-order rolloff—more representative of an actual oscilloscope—would exhibit around 6ps.

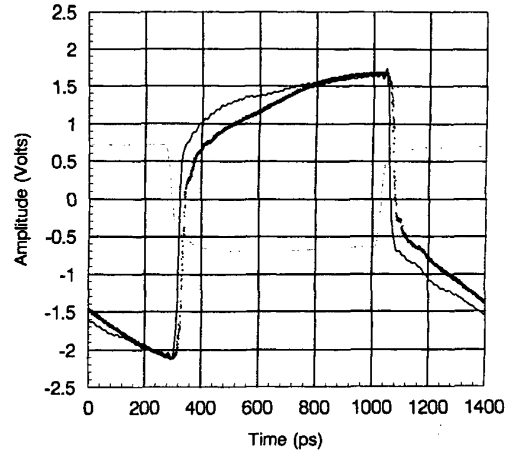

Fig. 3. Measurement results showing the amplifier output waveform obtained using the new instrument. The trace composed of dots shows a measurement carried out with a conventional sampling scope, and the reduced-amplitude waveform is the input signal to the amplifier.

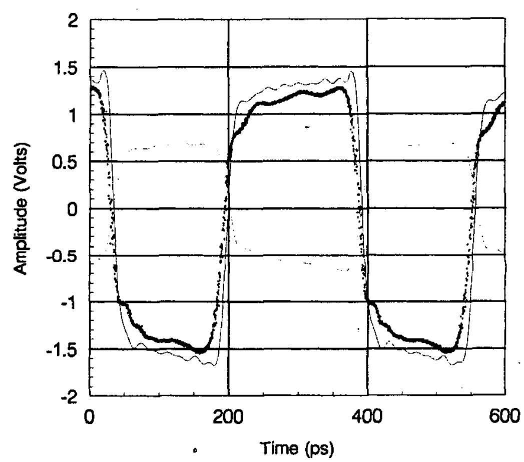

Fig. 4. Measurement results similar to those of Figure 3 but for a fundamental stimulus at 2.8GHz instead of 700MHz.

the end-of-transition levels selected. Peak slopes are around 130 and 90V/ns.

Use of averaging with the oscilloscope can compromise the bandwidth as a consequence of trigger jitter[6]. In the LSNA case, "averaging" is inherently applied to the data, since it is transitioned and then transformed to a frequency domain representation, corrected, and then reconstructed as an analytic, time-domain function. However, random jitter does not compromise the result as in the oscilloscope case. This jitter-immunity is a direct consequence of the architecture of the instrument, and may be discussed in more detail elsewhere. This elimination of random jitter immediately reveals pattern-dependent jitter, a potential cause of intersymbol interference.

Figure 5 shows the eye of a bit pattern as captured by an oscilloscope, where much of the "noise" on the data is jitter, as indicated by its greater magnitude on transitions. Figure 6 shows the measurement using the LSNA. Of note in the comparison of these two figures is the transition crossover asymmetry visible in the LSNA case, but mostly hidden in the scope case. We attribute the apparent rounding or "crunching" of the transitions to cable loss. Note also the 13% difference in apparent amplitude. This is also attributed to interconnection losses, present but uncorrected in the scope case and evident in the earlier data-amplifier measurement.

Figures 7 and 8 compare a measurement of a bit stream using the LSNA with a similar measurement on the same device using an oscilloscope with 1024 averaging. The distortion, loss of detail and reduced amplitude resulting from dispersion and averaging in the presence of jitter are clearly visible.

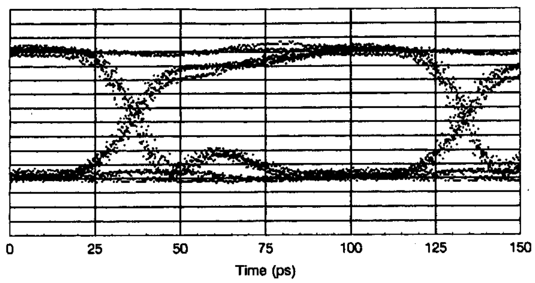

Fig. 5. Output of a MUX running at 10.24GB/s viewed with a 50GHz sampling scope. The data stream is a PRBS of length 16 bits.

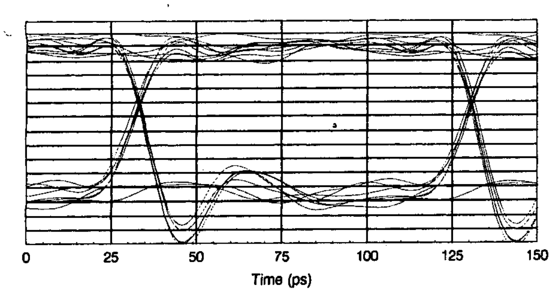

Fig. 6. Output waveform of the same MUX used for Figure 5 but obtained using the 50GHz LSNA prototype, with the calibration reference plane set at the IC output pad.

VI. Conclusions

A new instrument provides reliable time-domain measurements independent of dispersion in the connections to a circuit. As a consequence of this, risetime can be measured with no interference or degradation from wafer probes or connecting hardware, and long connecting cables do not close the eye of a data stream. Random device and measurement system jitter is removed from the displayed results. The 50GHz

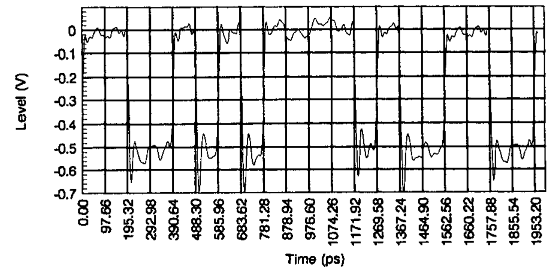

Fig. 7. The MUX output waveform viewed in oscilloscope mode with the LSNA. Pattern-dependent differences in edges are evident. Some of the fine structure on bit levels can be attributed to reflections from the imperfect load presented to the device by wafer probes, adapters, etc.

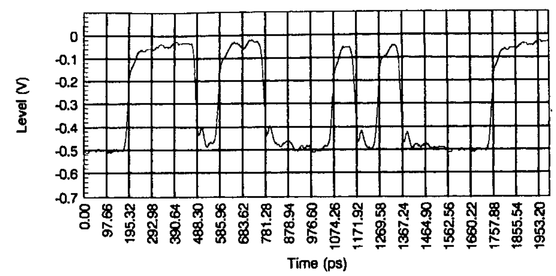

Fig. 8. The MUX output waveform similar to Figure 7 but viewed with an oscilloscope through a wafer probe, half a metre of high-quality cable, and using built-in 1024 averaging.

prototype has a system risetime of 7ps. A 100GHz version could be expected to offer a risetime of approximately 3.5ps.

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